

DETERMINATION OF THE THERMAL PROPERTIES AND HEAT TRANSFER
CHARACTERISTICS OF HIGH CONCENTRATION ORANGE PULP

By

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To my wife Carolina who supported and helped me to achieve my goals throughout my graduate studies

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TABLE OF CONTENTS

	<u>page</u>
ACKNOWLEDGMENTS.....	4
LIST OF TABLES.....	8
LIST OF FIGURES	9
LIST OF ABBREVIATIONS.....	12
ABSTRACT.....	15
CHAPTER	
1 LITERATURE REVIEW	17
Introduction.....	17
Theoretical Background.....	18
Orange Pulp and High Concentration Orange Pulp.....	18
Thermal Properties of Foods	20
Specific heat	21
Thermal conductivity	22
Thermal diffusivity.....	23
Principles of Heat Transfer in Fluids.....	23
Heat transfer by conduction	23
Heat transfer by convection	24
Overall heat transfer coefficient	25
Steady-state and unsteady-state heat transfer.....	26
Flow of Fluids – Concepts Relevant to this Study.....	27
The Reynolds number.....	27
Literature Review.....	28
Functional and Nutritional Properties of Citrus Pulp	28
Orange Pulp Industrial Applications.....	29
Pasteurization of Orange Pulp.....	30
Flow Characteristics of HCP and other Viscous Fluids	31
Thermal Properties of Fruit Pulp and of other Viscous Fluids	34
Heat Transfer Coefficient of Fruit Pulp and other Viscous Fluids	36
Alternative Technologies for Pasteurizing Fruit Pulp, Purees, and other Viscous Products	37
Research Objectives	40
Figures and Tables.....	42
2 THERMAL PROPERTIES OF HIGH CONCENTRATION ORANGE PULP	44
Introduction.....	44
Materials and Methods	44

Sample Preparation	44
Pulp Concentration Adjustment	45
Moisture Content	45
Density	46
Specific Heat Capacity	46
Thermal Diffusivity	48
Thermal conductivity	50
Statistical Analysis	50
Results and Discussion	50
Moisture Content and Density	50
Thermal Properties of Orange Pulp	51
Specific heat capacity	51
Thermal diffusivity	52
Thermal conductivity	53
Conclusion.....	54
Figures and Tables	55
3 DETERMINATION OF HEAT TRANSFER COEFFICIENTS AND HEAT TRANSFER CHARACTERISTICS OF HIGH CONCENTRATION ORANGE PULP	59
Introduction.....	59
Materials and Methods	60
Samples Preparation.....	60
Experimental Setup	60
Determination of Local and Overall Heat Transfer Coefficients	62
Temperature Profiles.....	64
Pressure Drop	65
Regression Analysis.....	65
Results and Discussion	65
Determination of Heat Transfer Coefficients	65
Temperature Profiles.....	72
Pressure Drop Determinations	76
Conclusions	78
Significance of this Research	79
Overall Conclusions.....	81
Future Work.....	82
Figures and Tables	84
APPENDIX	
A COMPARISON BETWEEN THE HEAT TRANFER COEFFICIENTS OBTAINED IN THE HEATING AND COOLING SECTIONS OF THE HEAT EXCHANGER ...	100
B COMPARISON BETWEEN THE PRESSURE DROPS OBTAINED IN THE HEATING AND COOLING SECTIONS OF THE HEAT EXCHANGER	102

LIST OF REFERENCES..... 104
BIOGRAPHICAL SKETCH..... 108

LIST OF TABLES

<u>Table</u>		<u>page</u>
1-1	Specific heat capacity and thermal conductivity of viscous fluids and other common liquid foods.	43
1-2	Heat transfer coefficient of viscous fluids and other common liquid foods.	43
2-1	Average (n = 3) moisture content and density of orange pulp at different concentrations.....	57
2-2	Experimental values obtained for the calorimeter's heat capacity	58
2-3	Mean values of the thermal properties of orange pulp at selected concentrations.....	58
3-1	Experimental flow rates and velocities used for determining the heat transfer coefficients for different pulp concentrations.....	87
3-2	Calculated local and overall heat transfer coefficients for different pulp concentrations and velocities, in the heating section of a tubular heat exchanger.	88
3-3	Calculated local heat transfer coefficients for different pulp concentrations and velocities, in the cooling section of a tubular heat exchanger.....	89

LIST OF FIGURES

<u>Figure</u>	<u>page</u>
1-1 Simplified flow diagram for industrial production of orange juice, low concentration orange pulp (LCP), and high concentration orange pulp (HCP). Modified from Braddock (1999).	42
1-2 Combined convective and conductive heat transfer (Singh and Heldman 2009).	42
2-1 FMC Quick Fiber Test instrument used for determining orange pulp concentration.....	55
2-2 Experiment setup for determining specific heat capacity of orange pulp samples.....	55
2-3 Time-temperature graph for determining orange pulp specific heat capacity.	56
2-4 Time-temperature graph for determining the heat loss to the surroundings to calculate the specific heat capacity.	56
2-5 Materials and methods used to determine the thermal diffusivity of orange pulp.	57
3-1 Schematic representation of equipment setup for determination of temperature profiles and heat transfer coefficients of high concentration orange pulp.	84
3-2 Schematic representation of set of thermocouples inserted at different radial directions of the inner pipe and thermocouple attached to the pipe's surface to measure the wall temperature.	84
3-3 Set of thermocouples inserted at different radial directions at the pipe's exit.....	85
3-4 Schematic representation of the temperature profile when orange pulp flows in the heating section of a tubular heat exchanger.	85
3-5 Data acquisition board used to record data	86
3-6 Equipment setup	86
3-7 Local heat transfer coefficients as function of velocity in the heating section of heat exchanger, for pulp concentrations of 516 (◆), 617 (■), 712 (▲), and 801 (X) g L ⁻¹	90

3-8	Local heat transfer coefficients as function of velocity in the cooling section of heat exchanger, for pulp concentrations of 516 (◆), 617 (■), 712 (▲), and 801 (X) g L ⁻¹ .	90
3-9	Overall heat transfer coefficients as function of velocity in the heating section of heat exchanger, for pulp concentrations of 516 (◆), 617 (■), 712 (▲), and 801 (X) g L ⁻¹ .	91
3-10	Local (◆) and overall (■) heat transfer coefficients as function of velocity in the heating section of heat exchanger, for pulp concentrations of 516, and 617 g L ⁻¹ .	92
3-11	Local (◆) and overall (■) heat transfer coefficients as function of velocity in the heating section of heat exchanger, for pulp concentrations of 712, and 801 g L ⁻¹ .	93
3-12	Temperature profiles obtained for 516 ± 6 g L ⁻¹ orange pulp concentration in the heating section of a tubular heat exchanger at flow rates of 4.4 (◆), 5.3 (■), 6.4 (▲), and 7.9 (X) x 10 ⁻⁴ m ³ s ⁻¹ .	94
3-13	Temperature profiles obtained for 516 ± 6 g L ⁻¹ orange pulp concentration in the cooling section of a tubular heat exchanger at flow rates of 4.4 (◆), 5.4 (■), 6.3 (▲), and 7.5 (X) x 10 ⁻⁴ m ³ s ⁻¹ .	94
3-14	Temperature profiles obtained for 617 ± 7 g L ⁻¹ orange pulp concentration in the heating section of a tubular heat exchanger at flow rates of 4.5 (◆), 5.6 (■), 6.4 (▲), and 7.6 (X) x 10 ⁻⁴ m ³ s ⁻¹ .	95
3-15	Temperature profiles obtained for 617 ± 7 g L ⁻¹ orange pulp concentration in the cooling section of a tubular heat exchanger at flow rates of 3.8 (◆), 4.4 (■), 5.3 (▲), and 6.9 (X) x 10 ⁻⁴ m ³ s ⁻¹ .	95
3-16	Temperature profiles obtained for 712 ± 12 g L ⁻¹ orange pulp concentration in the heating section of a tubular heat exchanger at flow rates of 3.9 (◆), 4.4 (■), 5.9 (▲), and 7.4 (X) x 10 ⁻⁴ m ³ s ⁻¹ .	96
3-17	Temperature profiles obtained for 712 ± 12 g L ⁻¹ orange pulp concentration in the cooling section of a tubular heat exchanger at flow rates of 2.7 (◆), 3.7 (■), 6.0 (▲), and 6.7 (X) x 10 ⁻⁴ m ³ s ⁻¹ .	96
3-18	Temperature profiles obtained for 801 ± 13 g L ⁻¹ orange pulp concentration in the heating section of a tubular heat exchanger at flow rates of 2.4 (◆), 3.5 (■), 4.1 (▲), and 5.1 (X) x 10 ⁻⁴ m ³ s ⁻¹ .	97
3-19	Temperature profiles obtained for 801 ± 13 g L ⁻¹ orange pulp concentration in the cooling section of a tubular heat exchanger at flow rates of 2.1 (◆), 2.9 (■), 3.6 (▲), and 4.8 (X) x 10 ⁻⁴ m ³ s ⁻¹ .	97

3-20	Hypothesized mixed flow of HCP	98
3-21	Pressure drop as function of flow rate in the heating section of heat exchanger, for pulp concentrations of 516 (◆), 617 (■), 712 (▲), and 801 (X) g L ⁻¹	98
3-22	Pressure drop as function of flow rate in the cooling section of heat exchanger, for pulp concentrations of 516 (◆), 617 (■), 712 (▲), and 801 (X) g L ⁻¹	99

LIST OF ABBREVIATIONS

A	Area (m^2)
A_i	Inside surface area of the pipe (m^2)
A_o	Outside surface area of the pipe (m^2)
C_p	Specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$)
$C_{p_{ref}}$	Specific heat of the reference liquid ($\text{J kg}^{-1} \text{K}^{-1}$)
D	Diameter (m)
f	Friction factor
g	Gravity acceleration ($9.81 \text{ m}\cdot(\text{s}^2)^{-1}$)
g_c	Proportionality factor for gravitational force ($1 \text{ kg m} (\text{s}^2 \text{ N})^{-1}$)
h	Local heat transfer coefficient ($\text{W m}^{-2} \text{ }^\circ\text{C}^{-1}$)
HCP	High concentration orange pulp
HDP	High density orange pulp
H_k	Heat capacity of the calorimeter (J K^{-1})
K	Consistency coefficient ($\text{Pa}\cdot\text{s}$)
k	Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
L	Length (m)
LCL	Low concentration orange pulp
m	Mass (kg)
m_{ref}	Reference liquid weight (kg)
m_s	Sample weight (kg)
n	Flow behavior index
P_1	Pressure at the inlet of the pipe (kPa)

P_2	Pressure at the outlet of the pipe (kPa)
Q	Heat (J)
q	Rate of heat transfer (W)
Q_f	Total heat content at the final state (J)
Q_i	Total heat content at the initial state (J)
r	Radius (m)
Re	Reynolds number
Re_n	Reynolds number for power law fluids in laminar flow
T	Temperature (°C)
T_{eq}	Final equilibrium temperature (K)
T_f	Outlet temperature of the product (°C)
T_i	Inlet temperature of the cold fluid or product (°C)
T_{hf}	Outlet temperature of the heating media (°C)
T_{hi}	Inlet temperature of the heating media (°C)
$T_{o_{ref}}$	Reference liquid initial temperature in calorimetric analysis (K)
T_{o_s}	Sample initial temperature in calorimetric analysis (K)
T_w	Apparent wall temperature (°C)
t_{eq}	Time required to reach equilibrium temperature (s)
U	Overall heat transfer coefficient ($W\ m^{-2}\ ^\circ C^{-1}$)
U_i	Overall heat transfer coefficient based on the inside area of a pipe ($W\ m^2\ ^\circ C^{-1}$)
u	Velocity ($m\ s^{-1}$)
v	Average velocity ($m\ s^{-1}$)

w	Weight (kg)
x	Length or thickness (m)
z	Elevation (m)
α	Thermal diffusivity ($\text{m}^2 \text{s}^{-1}$)
ΔP	Pressure drop (kPa)
$\Delta P/L$	Pressure drop per unit of length (kPa m^{-1})
ΔT	Temperature difference (K or °C)
ΔT_{LMTD}	Logarithmic mean temperature difference
$\left(\frac{\Delta T}{\Delta t}\right)$	Heat loss rate, temperature variation over time ($^{\circ}\text{C s}^{-1}$)
γ	Shear rate (s^{-1})
ρ	Density (kg m^{-3})
σ	Shear stress (Pa)
σ_o	Yield stress (Pa)
μ	Viscosity ($\text{Pa}\cdot\text{s}$)

Abstract of Thesis Presented to the Graduate School
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DETERMINATION OF THE THERMAL PROPERTIES AND HEAT TRANSFER
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Orange pulp strongly contributes to the sensory and texture properties of fruit juices and other beverages. High concentrated pulp (HCP) is difficult to pasteurize because its high apparent viscosity results in laminar flow regimes. Therefore, heat transfer occurs mostly by conduction. Determination of the thermal properties and heat transfer characteristics of HCP is essential for modeling and optimizing the thermal process of this fluid. Specific heat capacity (C_p), thermal diffusivity (α), and thermal conductivity (k), were determined for orange pulp concentrations of ≈ 500 to 800 g L^{-1} . Specific heat was between 4025 and $4068 \text{ J kg}^{-1} \text{ K}^{-1}$; α ranged from 1.50 to $1.56 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$; and k was between 0.63 and $0.66 \text{ W m}^{-1} \text{ K}^{-1}$. For C_p , α , and k , no significant differences ($p > 0.05$) were found among the different pulp concentrations. Local and overall heat transfer coefficients, radial temperature profiles, and pressure drops were determined by heating and cooling the pulp in a tubular heat exchanger at selected flow rates. The local heat transfer coefficients ranged from 1342 to $7755 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$, while the overall heat transfer coefficients were between 1241 and $6428 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$. These values increased with velocity and decreased with pulp concentration. Pressure drop was between 147 and 244 kPa for a pipe length of 3.4 m . Pressure drop was higher for

more concentrated pulp, and increased with flow rate. The information obtained in this study can be used to optimize equipment design and process conditions to maximize heat transfer and minimize pressure drop, for processing HCP aseptically.

CHAPTER 1 LITERATURE REVIEW

Introduction

The demand for minimally processed and fresh-like foods has continuously increased in recent years. Beverage and juice consumers are demanding products that have closer sensory characteristics and nutritional properties to freshly hand-squeezed juices (Berlinet and others 2007). Orange pulp, a by-product obtained from the industrial production of orange juice, strongly contributes to the aroma, flavor, and texture properties of unprocessed and fresh-like juices (Rega and others 2004). The increase in demand for orange pulp in the market, particularly in Asia, has raised the need to study the product's physical properties and heat transfer characteristics for industrial optimization of handling and pasteurization systems. The types of orange pulp that are commercially available are: unwashed, washed, and wholesome juice vesicles. Washed pulp refers to juice vesicles obtained after the juice and soluble solids have been recovered from pulp or pulpy juice streams by water extraction. Wholesome juice vesicles are very difficult to produce (Kimball 1991). Unwashed pulp, which is the focus of this literature review and this research, will be explained in further detail and will be referred to as orange pulp in this thesis. In 2010/11 season, an estimate of 700 thousand metric tons of orange pulp were produced in the United States (USDA 2011), which correspond to an estimated value of \$520 million.

To-date, many citrus processors produce orange pulp at concentrations around 500 g L⁻¹ as determined by the quick fiber test. Commercializing pulp with higher concentrations is economically more efficient, since reduces shipping and storage costs. However, pulp at concentrations above 500 g L⁻¹, also referred to as high

concentration orange pulp (HCP) or high density pulp (HDP) is difficult to handle in conventional equipment due to its high apparent viscosity. High concentration pulp today is generally not produced aseptically because the pressure drop in tubular pasteurizers is very high. In most cases pulp is pasteurized at around 500 g L⁻¹, then concentrated in a non-aseptic finisher, stored and sold as a frozen product. Storage of frozen pulp involves high energy costs and higher risk of spoilage (Levati 2010; Braddock 1999).

Optimization of equipment design for production of aseptic HCP requires to determine the heat transfer characteristics of this fluid, and to obtain its thermophysical properties. This information has not been published. The overall objective of this study was to determine HCP's thermal properties and heat transfer characteristics at different flow rates, in the heating and cooling sections of a tubular heat exchanger. This information is essential for modeling processing operations involving heat transfer and for designing and optimizing equipment to produce HCP aseptically. This chapter presents the theoretical background on orange pulp processing as well as the fundamentals of thermal properties and heat transfer in tubular heat exchangers, relevant concepts on flow of fluids, and a review of the studies that have been published regarding citrus pulp and other viscous fluids such as juice concentrates, fruit purees and pastes. The specific objectives of this study are also presented in this section.

Theoretical Background

Orange Pulp and High Concentration Orange Pulp

Orange pulp is the dispersion of burst juice vesicles in a small fraction of juice that is obtained from the orange juice finishing and centrifugation process. This fraction of fruit is rich in sugars, and also contains fibers and other residual substances (Tripodo

2004). Orange pulp contains an average of 19.7% of total solids, and represents approximately 5% of the weight of fresh oranges (Martínez and Carmona 1980; Kimball 1991). Figure 1-1 shows a general flow diagram of the industrial process for obtaining orange juice and pulp from the orange fruit.

After extraction, orange juice is pumped to finishers for separation of part of the ruptured juice vesicles, or pulp. The aim of recovering pulp is to manufacture large pulp sacs from the pulpy juice stream, with most of the juice removed (Braddock 1999). Minimum residual juice in the pulp is necessary for transportation purposes. Depending on the market value of pulp and juice, juice processors favor the yield of one or the other product, by adjusting finishing conditions.

When the pulpy juice passes through the first finisher, the pulp in the extracted juice is concentrated to approximately 500 g L^{-1} . In the industry, this semi-concentrated pulp is pasteurized using a tubular heat exchanger. Pasteurization is generally conducted at $90 \text{ }^{\circ}\text{C}$, for 0.5 to 1.0 min, followed by cooling to 2 to $5 \text{ }^{\circ}\text{C}$. Due to the difficulties for pumping the semi-concentrated pulp, heat exchangers with large horizontal tubes and spiral baffles are necessary for efficient pasteurization (Braddock 1999). After chilling, the semi-concentrated pulp-juice mixture can be further concentrated to what is referred as “high density pulp” (600 to 900 g L^{-1}) in a second finisher. Because this finisher is not aseptic, after packaging the concentrated pulp is stored at frozen temperatures to inhibit any residual enzyme activity as well as microbial growth (Kimball 1991). From a practical and economic standpoint, pulp with this concentration level is preferred by the industry, since high concentrated pulp results in lower transportation and storage costs.

The most common process for obtaining high concentration orange pulp has some disadvantages. It requires two steps for concentration, since high concentration pulp is difficult to handle in conventional tubular pasteurizers due to its high viscosity, its rheology and its flow characteristics. Pulp concentrations above 500 g L^{-1} are difficult to mix uniformly resulting in high temperature differences within the fluid; therefore, it is difficult to achieve uniform thermal treatment conditions (Levati 2010). In addition, pumping in conventional tubular heat exchangers results in high pressure drop when handling very viscous fluids. Another drawback of this process is that in the pasteurization of the pre-concentrated pulp (500 g L^{-1}), the carrier juice contained in the mixture juice-pulp (approximately 50% juice) is over-exposed to high temperatures when achieving the required pasteurization conditions for the pulp. This temperature over-exposure may affect the juice's sensory characteristics (Yeom and others 2000; Levati 2010).

Thermal Properties of Foods

Thermophysical properties are necessary for the design and prediction of heat transfer operations during handling, processing, canning, and distribution of food. Theoretical and empirical relations used to design and operate processes involving heat transfer require knowledge of the thermal properties of foods under consideration. Thermal properties can be defined as those properties that control the transfer and storage of heat in a particular food (Lozano 2005). In this research, the thermal properties that are relevant to the design of heat exchangers were studied: Specific heat capacity, thermal diffusivity and thermal conductivity. This section is based on Lozano (2005) and Singh and Heldman (2009).

Water content significantly influences all thermophysical properties. Some thermal properties can be calculated directly from the water content of a food. However, most foods are complex materials, and their contents of proteins, fats, and carbohydrates highly differ from one food to another. Therefore, food composition has variable effects on the thermal properties of a composite food material. Thermal properties are also dependent on the temperature, as well as the chemical composition and physical structure of food. Some models have been developed to predict the thermal properties of foods. Some of these models take into account the food composition, and also assess a physical representation of the food under study. However, often the values estimated by these models have significant discrepancies when compared to experimental values. These differences are mainly due to the complex physicochemical structure of food products; for example the complex interactions that occur between the different components of a food, or the physical changes that some food components undergo with temperature variations. (Mercali and others 2011).

Specific heat

Specific heat is the amount of heat that is gain or lost by a unit of mass of product to achieve a unit change in temperature, without a change in state:

$$Cp = \frac{Q}{m(\Delta T)} \quad (1-1)$$

Where Q is the heat gained or lost, m is the mass, ΔT is the temperature change in the food; and Cp is the specific heat.

Specific heat is an essential part of thermal analysis of food processing and of equipment used in heat transfer operations. Specific heat of food materials is a function of the various components that constitute a food, its moisture content, temperature and

pressure. Specific heat increases as the food's moisture content increases. Since in most food processing applications pressure is kept constant, specific heat at constant pressure is used. Specific heat can be estimated by using predictive equations, which are empirical mathematical models mainly based in the major components of foods. Another method used for specific heat measurement is differential scanning calorimetry (DSC). The advantages of DSC are that measurement is rapid, only a very small sample is needed for analysis, and the results are comparable to those obtained from standard calorimeters. Specific heat can also be determined using a calorimeter, where a known amount of a reference liquid of known specific heat capacity and initial temperature is placed in contact with a known amount of sample at different temperatures, allowing them to reach an equilibrium temperature. An energy balance based on equation 1-1, and that takes into account the heat losses to the surroundings, allows calculating the specific heat of the sample (Hwang and Hayakawa 1979). This method will be explained in detail in Chapter 2.

Thermal conductivity

Thermal conductivity (k) is an intrinsic property of a material, and represents the amount of heat that is conducted per unit of time through a unit thickness of the material if a unit temperature difference exists across the thickness. The SI unit for thermal conductivity is:

$$k = \frac{J}{s \cdot m \cdot ^\circ C} \equiv \frac{W}{m \cdot ^\circ C} \quad (1-2)$$

Most foods with high moisture contents have thermal conductivity values closer to that of water. Several empirical models have been proposed to estimate thermal conductivity of foods. Some of the simplest models consider that the different

components of foods are arranged in layers either parallel or normal to the heat flow. Most of the empirical expressions proposed to calculate the thermal conductivity of foods are functions of temperature, and/or water content.

Thermal diffusivity

Thermal diffusivity (α) is a ratio between thermal conductivity, density, and specific heat:

$$\alpha = \frac{k}{\rho C_p} \quad (1-3)$$

Physically, the thermal diffusivity represents the change in temperature produced in a unit volume of unit surface and unit thickness, containing a unit of matter, by heat flowing in a unit of time under unit temperature differences between opposite faces. The units of thermal diffusivity are $\text{m}^2 \text{s}^{-1}$.

Principles of Heat Transfer in Fluids

Heat transfer by conduction

Conduction is the mode of heat transfer where energy is transferred at a molecular level. One theory that describes conductive heat transfer states that as molecules of a material accumulate thermal energy, they vibrate with higher amplitude of vibration while confined in their lattice. These vibrations are transmitted from one molecule to another without translatory movement of the molecules. Heat is conducted from regions of higher temperature to regions of lower temperature. Another theory states that conduction takes place at a molecular level due to the movement of free electrons, which carry thermal and electrical energy. In conductive heat transfer, there is no movement of the material undergoing heat transfer.

The rate of heat transfer by conduction can be expressed by Fourier's law:

$$q = -kA \frac{dT}{dx} \quad (1-4)$$

Where q is the rate of heat flow in the direction of heat transfer by conduction; k is the thermal conductivity; A is the area through which heat flows; T is the temperature; and x is length.

Heat transfer by convection

When a flowing fluid is heated or cooled by coming into contact with a solid body that is at a different temperature than the fluid, heat exchange will occur between the fluid and the solid body. This mode of heat transfer is known as convection. There are two forms of convective heat transfer: Forced convection, which involves the use of mechanical means to induce the movement of the fluid. And free convection, when there is a temperature gradient caused by density differences within the system; these differences in density produce fluid movement. Both forms of convection may result in laminar or turbulent flow of the fluid, but turbulence generally happens under forced convection heat transfer. Natural convection only occurs in a gravitational field.

When a flowing fluid comes into contact with the surface of a flat plate, the rate of heat transfer from the solid body to the fluid is proportional to the surface area of the solid in contact with the fluid, and the temperature difference between them. The convective heat transfer coefficient can be expressed by an equation called Newton's law of cooling. The heat transfer coefficient is a mathematical explanation of the temperature difference between the fluid and the surface of the solid that arises from the movement of the fluid:

$$q = hA(T_s - T_\infty) \quad (1-5)$$

Where q is the rate of heat transfer; h is the convective heat coefficient; A is the surface area of the solid; T_S is the temperature of the solid surface; and T_∞ is the temperature of the fluid.

The convective heat transfer coefficient is not a property of the material. This coefficient depends on some properties of the fluid such as density, viscosity, specific heat, and thermal conductivity; the velocity of the fluid; geometry and roughness of the surface of the solid body in contact with the fluid.

Overall heat transfer coefficient

Conductive and convective heat transfer may occur simultaneously in many heat transfer applications. For example, when a fluid with a temperature higher than environment temperature flows inside a pipe, heat is first transfer by forced convection from the inside fluid to the inside surface of the pipe, then through the pipe wall material by conduction, and finally from the outer pipe surface to the surrounding environment by free convection. Figure 1-2 shows the temperature profile of combined conductive and convective heat transfer for the described example of the fluid flowing inside a pipe.

Equation 1-6 can be used to calculate the overall heat transfer coefficient:

$$\frac{1}{U_i A_i} = \frac{1}{h_i A_i} + \frac{\ln \frac{r_o}{r_i}}{2\pi L k} + \frac{1}{h_o A_o} \quad (1-6)$$

Where U_i is the overall heat transfer coefficient based on the inside area of the pipe; A_i is the inside surface area of the pipe; h_i is the inside convective heat transfer coefficient; r_i and r_o are the inside and outside radius respectively; L is the pipe's length; k is the thermal conductivity of the pipe material; h_o is the convective heat transfer coefficient at the outside surface of the pipe; and A_o is the outside surface area of the pipe.

The overall heat transfer coefficient (U_i) can also be expressed as:

$$q = U_i A_i (T_i - T_\infty) \quad (1-7)$$

Integrating this equation in order to apply it to the entire area of the heat exchanger, the logarithmic mean temperature difference (ΔT_{LMTD}) is introduced. To use the ΔT_{LMTD} , it is assumed that: the overall heat transfer coefficient is constant; the specific heat of the heating or cooling media and of the fluid are constant; the heat dissipated to the ambient is negligible; and the flow is steady, either parallel or countercurrent (McCabe and others 1985):

$$q = U_i A_i \Delta T_{LMTD} \quad (1-8)$$

Where the logarithmic mean temperature difference is calculated as:

$$\Delta T_{LMTD} = \frac{(T_{h_i} - T_i) - (T_{h_f} - T_f)}{\ln [(T_{h_i} - T_i) / (T_{h_f} - T_f)]} \quad (1-9)$$

Where T_{h_i} is the inlet temperature of the heating media; T_i is the product inlet temperature; T_{h_f} is the outlet temperature of the heating media; and T_f is product outlet temperature.

Steady-state and unsteady-state heat transfer

When studying heat transfer of foods, the conditions may be steady-state or unsteady-state. Steady-state occurs when time does not affect the temperature distribution within the material, although temperature may be different at different locations within the object. Unsteady-state conditions imply that temperature changes with time at a particular location. Even though, strictly speaking, steady-state conditions are not common, their mathematical analysis is much simpler. Therefore, steady-state conditions are often assumed to analyze problems involving heat transfer and to obtain useful information for designing equipment and processes.

Flow of Fluids – Concepts Relevant to this Study

The Reynolds number

The Reynolds number is a dimensionless number used for describing quantitatively the flow characteristics of a fluid flowing in a pipe or on the surface of objects of different shapes. The Reynolds number allows predicting the flow regime, i.e. laminar or turbulent, under selected flow conditions. Reynolds number states that the critical velocity at which laminar flow changes into turbulent flow, depends on the following parameters: The diameter of the pipe (D), and the viscosity (μ), density (ρ) and average velocity (v) of the fluid. These factors were combined in the following expression, which allows obtaining a definite value to specifically identify the kind of flow that a Newtonian fluid will have under certain flow conditions (McCabe and others 1985; Singh and Heldman 2009):

$$N_{Re} = \frac{\rho v D}{\mu} \quad (1-10)$$

The transition from laminar to turbulent flow may occur over a wide range of Reynolds numbers. For Newtonian fluids, below Reynolds numbers of 2100, laminar flow is always identified, but this type of flow can still be encountered up to Reynolds numbers of several thousand under special conditions. Under normal conditions, the flow is turbulent above 4000. A transition region is found between 2100-4000, where the flow can be laminar or turbulent depending upon the conditions at the pipe's inlet and on the distance from the inlet (McCabe and others. 1985).

For non-Newtonian fluids, the generalized Reynolds number for power law fluids (Re, n) can be calculated with the following expression:

$$N_{Re,n} = 2^{3-n} \left(\frac{n}{3n+1} \right)^n \left(\frac{D^n \rho u^{2-n}}{K} \right) \quad (1-11)$$

Where n is the flow behavior index; and K is the consistency coefficient, which are the power law parameters obtained from rheological and viscosity determinations. For non-Newtonian fluids, turbulent flow regimes occur at Reynolds numbers above 2100 with pseudoplastic fluids, for which $n < 1$.

Literature Review

Functional and Nutritional Properties of Citrus Pulp

The increasing market demand for orange pulp in recent years is mainly due to its contribution to aroma, flavor, and texture of unprocessed and fresh-like juices. Pulp has a strong effect on the sensory perception and texture properties of citrus juices and other beverages. It influences aroma and taste perceptions. This may be explained by physicochemical and cognitive effects. The former due to the fact that fresh pulp contains high amounts of key aroma compounds such as acetaldehyde and terpenes. The cognitive effects may be explained by the tactile properties of pulp that impart a particular tactile sensation in the mouth of juice consumers (Rega and others 2004; Berlinet and others. 2007). From the total volatile compounds of fresh squeezed orange juice, it was found that orange pulp represented 80% (Brat 2003). It was also reported that most citrus pulps had relatively high contents of carotenoids, influencing the color of citrus juices (Agocs and others 2007).

Besides its functionality in beverage applications, some nutritional properties have been attributed to orange pulp in a number of publications. The nutritional compounds found in citrus juices were also found in citrus by-products such as pulp. Orange pulp is a source of phenolic compounds, dehydroascorbic and ascorbic acids, which are well-known antioxidants (Gil-Izquierdo and others 2002). There are some discrepancies in literature related to the dietary fiber content in orange pulp. While some authors stated

that orange pulp had relatively low fiber content, others emphasized the nutritional benefits that orange pulp may have on diet, due to its fiber content. Larrea and others (2005) reported that orange pulp contained approximately 24% of solid material, which included 9.8% of proteins, 2.4% of lipids, 2.7% of ash contents, 9.3% of total carbohydrates from which 74.9% was dietary fiber (consisting of 54.8% of insoluble dietary fiber and 20.1% of soluble dietary fiber). Ingestion of foods containing dietary fiber has been recommended for weight loss. According to these authors, pectin, which is the main source of soluble fiber in orange pulp, had effects in reducing the absorption of carbohydrates in the small intestine, thus, reducing the level of serum glucose (Larrea and others 2005). However, orange pulp fiber contribution depends in the amount of pulp that is included in a particular product formulation.

Orange Pulp Industrial Applications

Due to the functional properties of orange pulp, the primary use of this product is for mixing with juice concentrates and beverage bases to impart texture, body, and pulpy characteristics to reconstituted juices and drinks. Some patents have been published detailing product formulation based on citrus pulps and other citrus by-products. A method for producing a clouding agent from orange pulp and orange peel for applications in soft drink beverages was patented (Lashkajani 1999). This clouding agent contributed to the opaqueness and particular flavor of citrus juice beverages. Orange pulp has volatile compounds that contribute to flavor, aroma and also adjusts the viscosity of beverages.

Currently, frozen unwashed pulp containing natural juice solids is the most frequently used material for product formulation. Orange pulp has been proposed as constituent for formulating jams, gel-like desserts, and glaze coatings. Frozen pulp has

also been used for preparing aerated frozen fruit desserts (Braddock 1999). Citrus pulps have a high water and oil holding capacity. For this reason, orange pulp may be used as thickener and gelling agent in beverages and gels-type products, and for formulating low caloric foods. Orange pulp has been used for formulating baked products such as cookies and cakes as a substitute for some of the flour, with good results in flavor, excellent water binding capacity, and less calories than the original formula (Passy and Mannheim 1983).

In other studies, biscuits formulated with 15% of extruded orange pulp had higher preference levels compared to the control, in terms of flavor, texture, and general acceptance. The total fiber content in biscuits formulated with extruded orange pulp was also higher than the control (Larrea and others 2005). The use of extrusion process to improve the functional and nutritional properties of orange pulp has also been reported, making it more suitable for food applications. These and other applications show that there are several potential uses for citrus pulp as a functional ingredient for a variety of food products.

Pasteurization of Orange Pulp

To-date, high concentration orange pulp is generally not produced aseptically due to the difficulties to handle this fluid in conventional tube pasteurizers. In very viscous fluids, heat is transferred mostly by conduction, and radial temperature gradients result in non-uniform process. In conventional tube heat exchangers high pressure drops occur when handling viscous fluids. High concentration pulp is mainly commercialized frozen, which involves high energy costs and lower shelf life compared to aseptic pulp. If the product is abused during manufacture or thawing, microbiological problems may occur, as yeasts and molds can utilize the sugars present in the pulp (Braddock 1999).

The main purpose of citrus products pasteurization is to inactivate the enzyme pectin methylesterase (PME), which is responsible for some undesirable changes during storage. Pectin methylesterase affects the colloidal stability of citrus juices and promotes the browning effect in citrus products during storage (Nikdel and others 1993). This enzyme causes cloud loss of orange juice by deesterification of pectin. Heat pasteurization of orange products is used to inactivate PME, which has higher thermal resistance than vegetative microorganisms. Between 90 and 100% reduction of the PME activity is normally achieved through heat pasteurization (Yeom and others. 2000).

Publications detailing the process conditions for pasteurizing orange pulp and high concentration orange pulp are limited. A standard pasteurization process for low concentration orange pulp was reported by Gil-Izquierdo and others (2002), by heating the product to 95 °C for 30 s, followed by refrigeration at 4 °C. Braddock (1999) reported similar conditions for microbe and enzyme inactivation in orange pulp: Pasteurization at 90 °C for 0.5-1.0 min, followed by cooling to 2-5 °C, using heat exchangers with large horizontal tubes and spiral baffles. For 850 g L⁻¹ concentration pulp, Levati (2010) reported a pasteurization treatment of 98 °C for 90 s using a JBT tubular heat exchanger with static mixers. The product was then filled aseptically. However, Levati stated in his study that it is a current challenge to process high concentration pulp in tubular heat exchangers, due to the high pressure drop resulting from its high viscosity, its particular rheological behavior, and the difficulties to achieve a uniform thermal treatment.

Flow Characteristics of HCP and other Viscous Fluids

For optimum design of continuous heat processing plants, it is fundamental to understand the flow properties of fluids over an adequate temperature range (Cabral

and others 2010). Since the rheological parameters of fluids change significantly with temperature and concentration, modeling and optimization of heat transfer operations is a major challenge (Gabs and others 2003). Studies with high concentration orange pulp showed that the rheological characteristics of this fluid varied significantly with temperature and concentration. High concentration pulp presented a clear non-Newtonian behavior, and showed the behavior of a shear thinning (pseudoplastic) fluid when plotting shear rate and shear stress (Payne 2011). This means that its apparent viscosity decreased with increasing rate of shear stress (Tavares and others 2007). Payne (2011) also found that orange pulp with concentrations between 600 to 900 g L⁻¹ had laminar flow when flowing inside tubular pipes. Levati (2010) also reported that HCP flowed under laminar regime when conducting flow simulations in circular pipes and annular heat exchanger. In laminar flow, time dependence is manifested due to the structural changes that the product has during flow (Gabs and others 2003). For HCP, these structural changes may be explained by the gelation process that occurs in the pulp when heated. The realignment of the pulp inside the pipe, and the separation of fibers and liquid while flowing at high temperatures (above 50 °C) may cause erratic results when measuring and calculating different parameters such as temperature profiles, velocity, and heat transfer coefficients (Levati 2010). It was reported that HCP presented slippage when flowing in tubular pipes. Slippage refers to separation of liquid from the solid particles at the wall surface of the pipe. It was found that the slippage coefficient increased with higher flow rates, and with higher shear stress at the wall (Payne 2011).

In the reviewed publications regarding the rheological and flow properties of viscous fluids, the authors determined which mathematical model was more suitable for describing each fluid's behavior. For non-Newtonian fluids, one of the most widely used is the Ostwald-De Waele model, also known as the power-law model:

$$\sigma = K\gamma^n \quad (1-12)$$

Where σ is the shear stress; K is the consistency index; γ is the shear rate; and n is the flow behavior index.

When fluids are concentrated, an additional resistance flow may affect, which is represented by the yield stress σ_o . This is known as the Herschel-Bulkley model (Telis-Romero and others 1999):

$$\sigma = \sigma_o + K\gamma^n \quad (1-13)$$

For high concentration orange pulp, Levati (2010) reported that the rheological behavior of this fluid was well described by the power law model. However, Payne (2011) stated that HCP was a power law fluid only at very low shear rates. With the presence of slippage, HCP no longer behaved as a power law fluid. Regarding other fluids, Telis-Romero and collaborators (1999) reported that concentrated orange juice behaved as a pseudoplastic fluid with yield stress. Its rheological behavior was best represented by the Herschel-Bulkley model. They also found that as long as there were temperature changes during flow, the rheological properties of the fluid were not constant along the tube length. In another study with frozen concentrated orange juice (FCOJ) with 46.6 to 65.0 °Brix, it was found that the shear rate - shear stress data at all concentrations was best described by the power law model (Tavares and others 2007). In other publications, authors stated that the power law model best described the flow of

tomato concentrates, concentrated orange juice, concentrated kiwi juice, peach and plum puree, and other fruit purees. For guava pulp, the rheological properties were well described by power law with yield stress, exhibiting highly non-Newtonian nature (Harnanan and others 2001).

Thermal Properties of Fruit Pulp and of other Viscous Fluids

Knowing the thermophysical properties of food is necessary for research and engineering applications such as pumping, heating, cooling, freezing, drying and evaporation. Thermal properties are essential for modeling, simulation and optimization of heat transfer operations in food processing (Mercali and others 2011). During processing, properties like density, thermal conductivity and specific heat capacity, may go through significant changes depending on composition, temperature, and physical structure of food. These properties can be predicted as a function of temperature and the major components of foodstuffs: Water, protein, fat and carbohydrates. But significant discrepancies may exist between the estimated and the experimental values due to the complex physicochemical structure of foods (Bon and others 2010). Therefore, experimental methods are necessary to determine the thermal properties of foods more accurately.

Orange pulp's thermal properties have not been reported. Values of specific heat capacity and thermal conductivity for other viscous fluids and common liquids are presented in Table 1-1. In a study with banana puree with an average soluble solid concentration of 22 °Brix, the specific heat and thermal conductivity were estimated using the puree's composition. The estimated value for specific heat was $3642.5 \text{ J kg}^{-1} \text{ K}^{-1}$, and for thermal conductivity was $0.595 \text{ W m}^{-1} \text{ K}^{-1}$ (Ditchfield and others 2007).

In a study with mango pulp, the thermal conductivity was determined using a cell where the heat transmitted by conduction was measured (by electrical resistance) across the sample placed between two concentric copper cylinders. Thermal conductivity was measured at different temperatures and water contents. It was found that thermal conductivity was more dependent of moisture content than of temperature. The values obtained ranged from 0.377 to 0.622 W m⁻¹ K⁻¹, increasing significantly with mango pulp's water content. The specific heat capacity for mango pulp was also determined using the same experimental set-up as for the thermal conductivity, but using a different mathematical solution. The values obtained ranged between 2730 to 4093 J kg⁻¹ K⁻¹, varying significantly with moisture content (Bon and others 2010).

The thermal properties of acerola and blueberry pulps were determined by Mercali and others (2011). The specific heat was determined using a calorimeter. For acerola pulp with 8% solids content, the specific heat was 4172.4 J kg⁻¹ K⁻¹ for an average temperature of 37 °C. There was no significant difference between the values of acerola pulp specific heat and the theoretical values for water. The specific heat for blueberry pulp with 16% of solids was 3720.9 J kg⁻¹ K⁻¹ for an average temperature of 38 °C. There was significant difference between the values found for blueberry pulp and those of water. It was also found that as moisture content increased in the product, its specific heat was higher (Mercali and others 2011).

The thermal diffusivity of acerola and blueberry pulps was determined based on the analytical solution for the heat diffusion equation in a long cylinder. The thermal conductivity of these pulps was calculated using equation 1-3. The thermal diffusivity of acerola pulp was 1.53 x 10⁻⁷ m² s⁻¹, while for blueberry pulp a value of 1.51 x 10⁻⁷ m² s⁻¹

was obtained. The thermal conductivity of acerola pulp at 40 °C was $0.65 \text{ W m}^{-1} \text{ K}^{-1}$, while for blueberry pulps, the values were 0.57 and $0.64 \text{ W m}^{-1} \text{ K}^{-1}$, for pulps with 14% and 16% of solid content respectively. It was found that thermal conductivity was more dependent on moisture content than on temperature (Mercali and others 2011).

Heat Transfer Coefficient of Fruit Pulps and other Viscous Fluids

Determination of heat transfer coefficients is essential to model aseptic processing of fluids that have a complex rheological behavior, such as high concentration orange pulp. The heat transfer coefficients for citrus pulps have not been published. Studies with other viscous fluids have shown that the heat transfer coefficient depends on the fluid thermophysical properties and flow regime, as well as on operating conditions for a particular heat exchanger (geometry and surface roughness) (Ditchfield and others 2007). Several expressions can be found in the literature to determine the heat transfer coefficient, but experimental determinations that include process parameters are few. Equipment design largely depends on reliable equations to explain heat transfer, pressure loss, and energy requirements. Hence, it is imperative to calculate the heat transfer coefficients considering real process parameters (Ditchfield and others 2006) Table 1-2 shows heat transfer coefficients values found in literature for some common liquids and viscous fluids such as fruit purees and pulps.

In a study with orange juice during pasteurization in a plate heat exchanger, the heat transfer coefficients were calculated. The values for orange juice varied from 983 to $6500 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$, while for water (using the same processing conditions as OJ) ranged from 8387 to $24245 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$. The heat transfer coefficient was correlated as a linear function of orange juice viscosity and the channel velocity in the plate heat exchanger (Kim and others 1999). In a study with a model sucrose solution in a falling

film evaporator, the values obtained for the heat transfer coefficient ranged between 1908 to 6168 W m⁻² °C⁻¹. The main source of variation was the stage (effect) of evaporation; the heat transfer coefficient decreased as the sucrose solution became more concentrated (Prost and others 2006). For tomato pulp, the heat transfer coefficients were calculated when heating the pulp in a scraped surface heat exchanger. The heat transfer coefficient varied between 625 and 911 W m⁻² °C⁻¹. The authors found that the values obtained were affected by the flow rate, rotor speed and steam temperature (Sangrame and others 2000).

Ditchfield and others (2007) calculated the heat transfer coefficients of banana puree with a soluble solid concentration of 22 °Brix in a tubular heat exchanger. The heat transfer coefficients obtained ranged from 655 to 1070 W m⁻² °C⁻¹. The authors found that all variables studied: flow rate, steam temperature and length / diameter (L/D) ratio, significantly affected the heat transfer coefficient. The heat transfer coefficient increased at higher flow rates, smaller L/D ratios, and higher heating medium temperatures. It was also found that there was a significant temperature difference between the banana puree that was near the pipe's wall and the product located at the center, and that this difference was smaller at lower flow rates (Ditchfield and others 2007).

Alternative Technologies for Pasteurizing Fruit Pulps, Purees, and other Viscous Products

The use of thermal treatment for pasteurizing citrus products may cause irreversible alterations of the fresh-like flavor, reduction of nutrients, and the initiation of undesirable browning reactions in the juice (Berlinet and others 2007; Yeom and others 2000). In a study where orange pulp was pasteurized at 90 °C for 30 s, it was found that

the thermal process significantly reduced the total phenolic compounds content. Thermal pasteurization of pulp also caused a loss of 58% and 79% of total vitamin C and L-ascorbic acid respectively, and a loss of 47% of pulp's antioxidant capacity, mainly due to the loss of phenolic compounds (Gil-Izquierdo and others 2002). It has also been found that exposure of pulps to high temperatures caused overdrying of pulp and affected the dietary fiber and protein content (Passy and Mannheim 1983).

The use of alternative processing technologies to obtain food products and beverages that are safe for consumption and that retain most of their initial quality in terms of nutrition, sensory characteristics, and functionality is currently being researched. A number of recent studies regarding the denominated emerging technologies as alternatives for pasteurizing diverse food products have been published. Some of these not-conventional processes are: Microwave energy, ohmic heating, and high pressure technology. Currently, most of these technologies are relatively expensive and various technical issues still remain unclear. However, it is important to encompass these technologies and consider them as an alternative for processing viscous fluids and other foods containing solid particles.

The use of microwave energy to pasteurize citrus beverages and concentrated juices has been reported. This technology has the following advantages: Food is directly heated, no heat-transfer films are used, the temperature is easier to control, and foods retain more nutritional components than in thermal processing (Nickdel and others 1993). Nickdel and others (1993) reported that pasteurization of pulpy orange juice with microwave energy gave promising results in terms of enzyme inactivation, microorganism's destruction, and sensory evaluation. In this study, by using microwave

heating, PME was inactivated in 98.5 and 99.5% at temperatures near 75 °C for 10-15 s of residence time. This was compared to 99% of PME inactivation by traditional pasteurization at 90.5 °C for 15 s. The authors concluded that pasteurization using microwave energy in continuous mode was effective for pulpy juice pasteurization. As of most of these relatively new technologies, more research is necessary to apply microwave energy at industrial scales.

Pasteurization of fruit purees by ohmic heating has been studied. Ohmic heating is based on the direct passage of electrical current through the food, with heat generated as a result of electrical resistance. The main advantage of this process over thermal processing, is rapid and uniform heating, resulting in less thermal damage to the product (Rahman 2007). Ohmic heating is suitable for pumpable foods, and it can be used for sterilization of liquid and viscous products (Icier and Ilicali 2005). Ohmic heating has been found to be effective for microorganism destruction in foods such as fruit purees. However, the electrical conductivity of fruit purees depends strongly on temperature, ionic concentration, moisture content, and pulp concentration. Thus, mathematical models have to be developed for determining the optimal process conditions (temperature, voltage) and the properties of different foods (heat resistance, electrical conductivity) to be used for pasteurization of foods (Icier and Ilicali 2005).

The application of high pressure processing (HPP) as an alternative to thermal treatment for inactivation of PME and preservation of citrus products has been studied. It was found that the activation of PME in orange juice and concentrated orange juice depended on the pressure level used, on the pressure holding time, and on the acidity and soluble solids content of the product (Basak and Ramaswamy 1996). In another

study, it was found that stabilization of pulpy orange juice with high pressure processing required a minimum of 500 MPa to sufficiently reduce PME activity. It was also reported that inactivation of PME was enhanced by combining HPP with thermal treatment of 50 °C, and that the orange juice treated with HPP retained its fresh-like quality for several months when stored at 4 °C (Nienaber and Shellhammer 2001). But the use of pressures above 500 MPa may require expensive equipment, which is a drawback for using this technology now days.

The reviewed literature showed that there is potential for the use of these technologies for pasteurization and for aseptically processing highly viscous products such as orange pulp, fruit purees, and pastas. However, most of these emerging technologies are relatively expensive today. In addition, the need for future research in these fields is still very extensive.

Research Objectives

The overall objective of this study was to determine the main parameters needed to optimize the design of a pasteurization system for producing high concentration orange pulp aseptically. The specific objectives of this research were (1) to determine the thermal properties of high concentration orange pulp: Specific heat capacity, thermal diffusivity, and thermal conductivity; and (2) to determine the heat transfer characteristics of HCP in tubular heat exchangers: Calculate the local heat transfer coefficients in the heating and cooling section of a the heat exchanger for different pulp concentrations and fluid velocities; calculate the overall heat transfer coefficients for the selected processing conditions in the heating section of the heat exchanger; and obtain the temperature profiles and pressure drops when heating and cooling orange pulp with different concentrations at selected flow rates.

Determining the specific heat capacity is important for thermal analysis of food processing and of equipment where heat transfer operations are involved, e.g. for determining the amount of energy required to heat a food to pasteurization temperatures. In addition, the specific heat capacity was used to calculate the heat transfer coefficients of HCP. The thermal diffusivity was used to calculate the thermal conductivity. Thermal conductivity is necessary for calculations involving rate of conductive heat transfer in food processing operations and equipment design.

Determining the heat transfer coefficients is necessary to design and optimize equipment dimensions such as the pipe length and diameter of a heat exchanger, or process conditions such as flow rate, required for accomplishing a desired rate of heat transfer. The temperature profiles allowed determining the way heat flowed across the radial layers of HCP flowing in a tubular pipe, and to assess the type of flow regime in which HCP flowed for the selected experimental conditions. This information, combined with the pressure drop determinations, can be used to optimize the design of tubular heat exchangers to produce HCP aseptically, with minimum pressure drop and maximum heat transfer. This information can also be used to assess if tubular heat exchangers are the most suitable equipment to pasteurize highly-concentrated orange pulp.

Figures and Tables

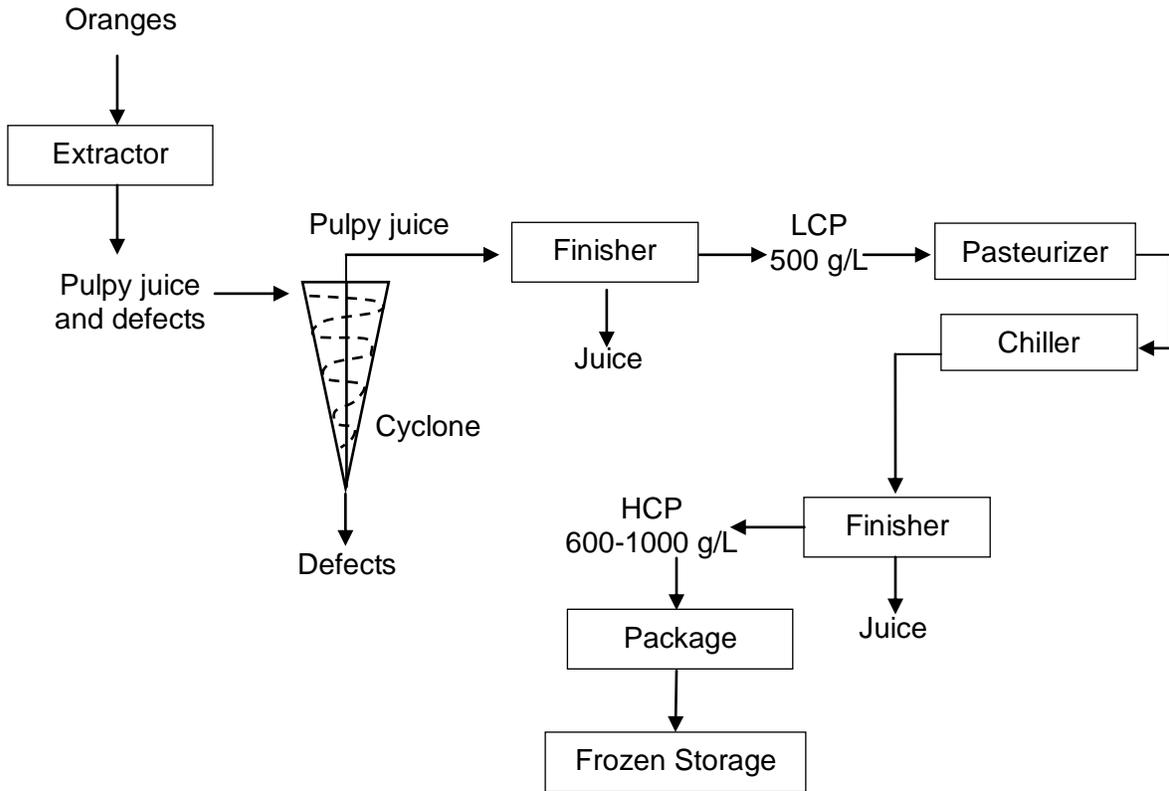


Figure 1-1. Simplified flow diagram for industrial production of orange juice, low concentration orange pulp (LCP), and high concentration orange pulp (HCP). Modified from Braddock (1999).

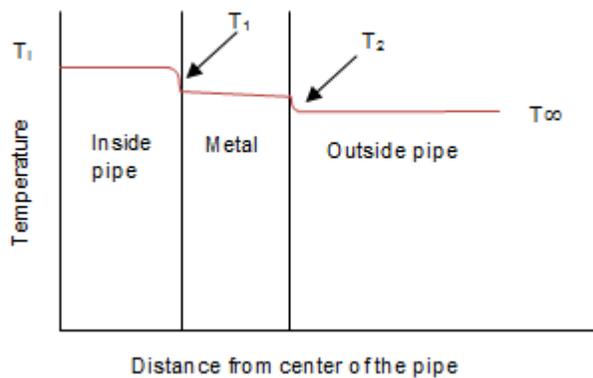


Figure 1-2. Combined convective and conductive heat transfer (Singh and Heldman 2009).

Table 1-1. Specific heat capacity and thermal conductivity of viscous fluids and other common liquid foods.

Fluid	Specific Heat Capacity $\text{J kg}^{-1} \text{K}^{-1}$	Thermal Conductivity $\text{W m}^{-1} \text{K}^{-1}$
1. Banana puree (22 °Brix)	3643	0.595
2. Mango pulp	2730-4093	0.377-0.622
3. Acerola pulp	4172	0.650
3. Blueberry pulp with 14% solids	4050	0.570
3. Blueberry pulp with 16% solids	3721	0.640
4. Strawberry pulp	3755-3967	-
4. Blackberry pulp	3542-3754	-
4. Red raspberry pulp	3528-3836	-
4. Blueberry pulp	3717-3931	-
5. Blueberry syrup	3445	-
5. Tomato soup concentrate	3676	-
5. Honey	-	0.502
5. Apple sauce	-	0.516
5. Apple Juice	-	0.436
5. Orange juice	3882	0.431
5. Water at 20°C	-	0.597
5. Water at 25°C	4181	-
5. Water at 60°C	-	0.658
5. Water at 65°C	4188	-

1. (Ditchfield and others 2007) 2. (Bon and others 2010) 3. (Mercali and others 2011) 4. (Souza and others 2008) 5. (Singh and Heldman 2009)

Table 1-2. Heat transfer coefficient of viscous fluids and other common liquid foods.

Fluid	Flow Rate $\text{m}^3 \text{s}^{-1}$	Heat Transfer Coeff. $\text{W m}^{-2} \text{K}^{-1}$	
1. Banana puree	$2.3-5.1 \times 10^{-5}$	655-1070	Local h , in a tubular heat exchanger
2. Tomato pulp	$6.5-8.5 \times 10^{-4}$	625-911	Overall U , in scrap surf. evaporator
3. Sucrose solution	$6.7-5.2 \times 10^{-5}$	1908-6168	Overall U , in falling film evaporator
4. Orange juice	$1.5-3.5 \times 10^{-4}$	983-6500	Overall U , in plate heat exchanger
4. Water	$2.2-2.6 \times 10^{-3}$	8387-24245	Local h , in plate heat exchanger

1. (Ditchfield and others 2007) 2. (Sangrame and others 2000) 3. (Prost and others 2006) 4. (Kim and others 1999).

CHAPTER 2 THERMAL PROPERTIES OF HIGH CONCENTRATION ORANGE PULP

Introduction

Thermal properties are those that control the transfer and storage of heat in a particular food (Lozano 2005). Thermal properties of most foods are significantly influenced by water content. These properties are also affected by temperature and by the chemical composition and physical structure of food. Therefore, experimental methods are necessary to accurately determine the thermal properties of food. The objective of this study was to determine the thermal properties of HCP that are relevant to the design of heat exchangers for aseptic processing of this fluid. Specific heat capacity, thermal diffusivity, and thermal conductivity, were determined for orange pulp concentrations of $\approx 500, 600, 700,$ and 800 g L^{-1} . The specific heat capacity obtained in this study was used to further calculate the heat transfer coefficients of HCP flowing in a tubular heat exchanger. In addition, knowledge of these properties is necessary for modeling, simulation and optimization of process operations which involve heat transfer.

Materials and Methods

Sample Preparation

Orange pulpy juice was obtained by juicing Valencia oranges in FMC extractors (JBT model 591, Lakeland, Florida) at the Citrus Research and Education Center (CREC) pilot plant. The pulpy juice was pasteurized in a stainless steel tubular heat exchanger (Feldmeier Equipment, Inc. Syracuse, NY.). Pasteurization was conducted at $90 \text{ }^\circ\text{C}$ for a minimum holding time of 60 s and then cooling to $4 \text{ }^\circ\text{C}$, to inactivate the enzyme pectin methylesterase (PME). Inactivation of PME was important to avoid deesterification of pectin, which caused a rapid separation of liquid from the fibers when

pulp was stored and changes in pulp concentration due to product gelation. After pasteurization, the pulp was separated from the juice using a FMC screw finisher (JBT Model 35, Hoopeston, Illinois) at 50 psi with a J.U. 52 mesh screen. Orange pulp with a concentration of 920 g L⁻¹ was obtained, as determined using a FMC Quick Fiber Test. Sodium benzoate was added to the pulp (0.5%) as an anti-mold agent. Pulp was stored in a cold room at 8 °C before taking samples for conducting the different tests.

Pulp Concentration Adjustment

To adjust pulp concentration, 920 g L⁻¹ pulp was diluted with pasteurized orange juice to concentrations of 801 ± 13, 712 ± 12, 617 ± 7, and 516 ± 6 g L⁻¹. Pulp concentration was determined using a FMC Quick Fiber Test instrument (Figure 2-1). Approximately 500 mL of pulp were weighted and placed in the 20 mesh screen of the Quick Fiber apparatus. After 2 minutes of mechanical shaking, the pulp and the screen were weighted, and by subtracting the weight of the screen, the weight of the pulp was obtained. Pulp concentration was determined as:

$$\text{Pulp concentration (g/L)} = \frac{\text{Weight of pulp after shaking (g)}}{\text{Volume of juicy pulp (L)}} \quad (2-1)$$

Moisture Content

Orange pulp moisture content was determined in triplicate for each of the pulp concentrations studied. Approximately five grams of sample were weighted in a small aluminum pan using an analytical balance (Denver Instrument Co., Denver, Colorado). The aluminum pan containing the sample was placed in an oven (Central Scientific Co, New York) at 75 °C, and it was weighted each hour until stable weight was reached (seven hours). Pulp moisture content was measured as:

$$\% \text{ Moisture} = \frac{W_i - W_f}{W_i} \times 100 \quad (2-2)$$

Where W_f is the weight of the sample after reaching steady weight, and W_i is the initial weight of the sample.

Density

Orange pulp density for each of the pulp concentrations studied was determined in triplicate at 20 °C using a 25-mL volumetric cylinder (TEKK, USA) and an analytical balance (Denver Instrument Co., Denver, Colorado).

Specific Heat Capacity

The specific heat capacity was determined using a method developed by Hwang and Hayakama (1979) and adapted by Mercali and others (2011) with minor modifications: An insulated stainless steel double wall 0.3 L thermo flask (Thermos, Rolling Meadows, Illinois) was adapted to be used as a calorimeter. A thermocouple type K was inserted into its geometric center. Approximately 200 g of water at 70 °C (reference liquid) were weighted and placed inside the calorimeter. The system was closed and placed on a shaker (New Brunswick Scientific Co, Edison, New Jersey) for 15 minutes, allowing the temperatures of the water and of the calorimeter to equilibrate. Approximately 75 g of pulp, which were previously placed in low-density polyethylene bags and stored in a refrigerator overnight, were placed inside the calorimeter at an initial temperature of ≈ 10 °C, in indirect contact with the reference liquid. The polyethylene bag was used because of the pulp hygroscopic characteristics, which may affect the heat analysis of the experiment as the pulp would dissolve in the reference water and incorporate it into its matrix (Hwang and Hayakawa 1979). In addition, the plastic bag helped drop the sample rapidly and easily into the calorimeter, minimizing heat dissipation during sample addition. The system was maintained with constant agitation until reaching a final equilibrium temperature (Figure 2-2). An energy balance,

based on the law of energy conservation, allowed calculating the specific heat capacity of the sample:

$$Q_{i \text{ calorimeter}} + Q_{i \text{ water}} = Q_{f \text{ calorimeter}} + Q_{f \text{ water}} + \left(\frac{\Delta T}{\Delta t}\right) \cdot t_{eq} \quad (2-3)$$

$$Q = m Cp \Delta T \quad (2-4)$$

Where Q_i is the total heat content at the initial state; Q_f is the total heat content at the final state; and $\left(\frac{\Delta T}{\Delta t}\right) \cdot t_{eq}$ is the heat loss factor (heat dissipation to the surroundings).

Replacing equation 2-4 in 2-3 and rearranging as done by Hwang and Hayakama (1979):

$$Cp_s = \frac{(Cp_{ref} \cdot m_{ref} + H_k) \cdot [T_{eq} - T_{o_{ref}} - \left(\frac{\Delta T}{\Delta t}\right) \cdot t_{eq}]}{m_s [T_{o_s} - T_{eq} + \left(\frac{\Delta T}{\Delta t}\right) \cdot t_{eq}]} \quad (2-5)$$

Where Cp_s is the specific heat of the sample; Cp_{ref} is the specific heat of the reference liquid; m_s and m_{ref} are the masses of the sample and reference liquid respectively; T_{o_s} and $T_{o_{ref}}$ are the initial temperatures of the sample and reference liquid respectively; T_{eq} is the final equilibrium temperature; t_{eq} is the time required for the sample to reach an equilibrium temperature with the calorimeter; H_k is the heat capacity of the calorimeter; and $\frac{\Delta T}{\Delta t}$ is the heat loss rate.

The temperature was recorded using a data acquisition board (National Instruments, model NI TB-9214) and a computer program written in LabVIEW 10.0.

The final equilibrium temperature (T_{eq}) and the time required to reach this temperature (t_{eq}) were obtained from the linear portion of the time-temperature graph of each experiment (Figure 2-3). The specific heat capacity was calculated in triplicate for each of the studied orange pulp concentrations using equation 2-5.

To determine the heat capacity of the calorimeter (H_k) and the energy loss rate ($\frac{\Delta T}{\Delta t}$), the method described above was used, but using distilled water as the sample: Approximately 200 g of water at 70 °C (reference liquid) were weighted and placed inside the calorimeter. About 100 g of water at room temperature (sample) were weighted, and its initial temperature was measured. The sample water was poured inside the calorimeter in contact with the reference water. The system was immediately closed and kept in the shaker for constant agitation until reaching equilibrium temperature. To measure the heat loss to the surroundings, the system was left in the shaker for approximately 60 min, and from the slope of the linear portion of the temperature vs. time graph (Figure 2-4), the heat loss rate was obtained as $\Delta T/\Delta t$. The heat capacity of the calorimeter (H_k) was obtained by using equation 2-5 and solving for H_k :

$$H_k = \frac{Cp_s \cdot [m_s [T_{o_s} - T_{eq} + \left(\frac{\Delta T}{\Delta t}\right) \cdot t_{eq}]]}{T_{eq} - T_{o_{ref}} - \left(\frac{\Delta T}{\Delta t}\right) \cdot t_{eq}} - Cp_{ref} \cdot m_{ref} \quad (2-6)$$

Using the mean value of H_k obtained from 10 replicates, the experimental apparatus was validated by conducting experiments to determine the specific heat capacity of distilled water, and comparing these values with the ones obtained in the literature. These results are presented in the Results and Discussion section.

Thermal Diffusivity

The thermal diffusivity was determined based on the method used by Mercali and others (2011). This technique is based on the analytical solution for the heat diffusion equation in a cylinder. A copper cylinder (40 mm length and 20 mm diameter) was used for this experiment (Figure 2-5a). At one end of the cylinder, a thermocouple type K was inserted into its geometric center through a rubber stopper and sealed with marine

epoxy. On the other end, the cylinder was filled with pulp sample and a rubber stopper was placed to seal the system.

The cylinder filled with pulp sample was immersed in a water bath at $\approx 25\text{ }^{\circ}\text{C}$ until reaching constant temperature. After reaching equilibrium, the initial temperature was recorded, and the system was transferred to another thermostatic bath with a temperature of $\approx 55^{\circ}\text{C}$. The cylinder was immersed in this bath until reaching equilibrium temperature with the water. Throughout the experiment, the temperature was recorded using the same data acquisition system and program as for the specific heat capacity determination.

Integrating as a function of radius the analytical solution of the energy conservation equation for cylindrical coordinates in a non-steady state, as done by Mercali and others (2011), the following equation was obtained:

$$\ln\left(\frac{T(r,t)-T_{eq}}{T_o-T_{eq}}\right) = \ln k - \alpha\left(\frac{2.405^2}{r^2}\right) \cdot t \quad (2-7)$$

Where $T(r,t)$ is the temperature as function of time and radius of the cylinder; T_o is the initial temperature, T_{eq} is the equilibrium temperature; α is the thermal diffusivity; r is the radius of the cylinder; t is the time to reach equilibrium temperature; and k is a constant.

Adjusting the temperature data versus time to equation 2-7, a linear correlation between $\ln\left(\frac{T(r,t)-T_{eq}}{T_o-T_{eq}}\right)$ vs. time was obtained. By determining the slope of the linear portion of this curve, the thermal diffusivity of the sample can be calculated:

$$\alpha = -\frac{\text{Slope}}{2.405^2 / r^2} \quad (2-8)$$

The thermal diffusivity at 40 °C was calculated in triplicate for each of the studied orange pulp concentrations. The temperature of 40 °C was the average between the initial bath temperature (25 °C) and the second bath temperature (55 °C). Figure 2-5b shows a time vs. dimensionless temperature graphs used for determining the slope and calculating the thermal diffusivity of orange pulp.

Thermal conductivity

Thermal conductivity of the studied orange pulp concentrations was calculated using equation 1-3 and solving for k :

$$k = \alpha \cdot \rho \cdot C_p \quad (2-9)$$

Where k is the thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$); α is the thermal diffusivity ($\text{m}^2 \text{s}^{-1}$); ρ is the density (kg m^{-3}); and C_p is the specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$).

Statistical Analysis

To determine the effect of pulp concentration on specific heat, thermal diffusivity, and thermal conductivity, 1-way ANOVA ($p < 0.05$) was carried out using statistical software (JMP® Version 9.0.2, SAS Institute Inc., Cary, NC, USA). If the effect was found to be significant, Student's t-test with 95% confidence level was carried out to determine significant differences among pulp concentrations.

Results and Discussion

Moisture Content and Density

Orange pulp moisture content and density for the different pulp concentrations are presented in Table 2-1. The moisture content and density values obtained were very similar for all concentrations. For pulp concentrations of 617, 712, and 801 g L^{-1} , the moisture content was between 82.0 ± 0.001 and 82.1 ± 0.002 %, while for 516 g L^{-1} , it was slightly higher: 82.7 ± 0.001 %. These values were in agreement with the literature.

Martinez and Carmona (1980) reported that orange pulp had an average moisture content of 80.3%, while Kimball (1991) reported a range of 80-85% moisture content for this product. Compared to other fruit pulps, the values obtained were also within the same range. Blueberry pulp had an average moisture content of 82% (Mercali and others 2011), while mango pulp had an average moisture content of 83.7% (Bon and others 2010). Moisture content did not vary with pulp concentration. Since orange juice contains approximately 12% of soluble solids (similar soluble solids content as in pulp), when pulp was concentrated in the finisher, the soluble solids contained in the juice were also removed from the concentrated pulp. This may explain why the water content was similar for the different pulp concentrations.

With all pulp concentrations having almost the same moisture content, similar density values were expected for the different pulp concentrations. Orange pulp density at 20 °C ranged between 1.03 ± 0.004 and 1.06 ± 0.001 g mL⁻¹. The values were close to the density of water. It was expected that orange pulp had slightly higher density than water, due to its solid content of $\approx 18\%$. The density values obtained were also similar to that of other fruit pulps. Mercali and others (2011) reported density values between 0.97 and 1.03 g mL⁻¹ for acerola pulp, and between 0.98 and 1.05 g mL⁻¹ for blueberry pulp. In this study, the values varied with temperature and the product's water content.

Thermal Properties of Orange Pulp

Specific heat capacity

The results obtained for the calorimeter's heat capacity (*Hk*) determination are shown in Table 2-2. The average value of *Hk* was 60.1 ± 10.2 J K⁻¹. This value was validated by determining water's specific heat capacity at ≈ 30 °C using the calorimeter. An average value of 4187.3 J kg K⁻¹ was obtained for water, which deviated by less

than 0.1% from water's C_p values reported in the literature (Table 1-2). Therefore, the calorimeter was validated for determining orange pulp's specific heat capacity.

The experimental results for the determination of orange pulp's specific heat capacity are shown in Table 2-3. The specific heat capacity at ≈ 30 °C for the 4 pulp concentrations ranged from 4025.0 to 4068.4 J kg⁻¹ K⁻¹. The statistical analysis indicated that there was no significant difference ($p > 0.05$) among the specific heat of the different pulp concentrations. However, there was significant difference between the specific heat of orange pulp and water ($p < 0.05$), meaning that it will not be correct to assume the C_p of water as the C_p of orange pulp for further calculations. Since moisture content in all pulp concentrations was between 82 and 83%, and the specific heat capacity strongly depends on water content, it was expected that C_p would be similar for all pulp samples.

Orange pulp's specific heat has not been reported in the literature. Comparing with other fruit pulps, orange pulp's specific heat was similar to some of the reported values for mango pulp (Bon and others 2010) and acerola pulp (Mercali and others 2011), and higher compared to the reported values of blueberry, strawberry, red raspberry, and blackberry pulps (Souza and others 2008). The specific heat capacity for this group of fruit pulps, which are shown in Table 1-2, ranged from 3528 to 3967 J kg K⁻¹. In general, specific heat increased with higher product moisture content.

Thermal diffusivity

The average thermal diffusivity at 40 °C for 516 g L⁻¹ pulp was $1.50 \pm 0.01 \times 10^{-7}$ m² s⁻¹, while for pulp concentrations between 617 and 801 g L⁻¹ the mean thermal diffusivity values were between 1.55 ± 0.07 and $1.56 \pm 0.04 \times 10^{-7}$ m² s⁻¹ (Table 2-3). The thermal diffusivity of water at 30 °C is 1.48×10^{-7} m² s⁻¹ (Singh and Heldman 2009).

Since semi-concentrated pulp ($\approx 500 \text{ g L}^{-1}$) had slightly higher moisture content than higher pulp concentrations, its thermal diffusivity may be closer to that of water. However, statistical analysis indicated that there were not significant differences ($p > 0.05$) between the thermal diffusivity values obtained for the different pulp concentrations.

Orange pulp's thermal diffusivity values were close to the ones reported for other fruit pulps. The thermal diffusivity values for acerola, blueberry, and tomato pulp were: 1.53 , 1.51 , and $1.48 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ respectively (Mercali et al. 2011; Singh and Heldman 2009). As the products' moisture content increased, the thermal diffusivity was lower, becoming closer to that of water.

Thermal conductivity

The calculated thermal conductivity for the different orange pulp concentrations is presented in Table 2-3. The values obtained for pulp concentrations between 516 and 801 g L^{-1} were between 0.63 and $0.66 \text{ W m}^{-1} \text{ K}^{-1}$, showing no significant differences between them ($p > 0.05$). There were no significant differences ($p > 0.05$) either with water.

Thermal conductivity for orange pulp has not been reported. However, the values obtained were within the range reported for other fruit pulps. For mango pulp with 9% moisture content (dry basis), a thermal conductivity ranging between 0.59 and $0.62 \text{ W m}^{-1} \text{ K}^{-1}$ was reported (Bon and others 2010). Mercali and others (2011) reported values of 0.65 , 0.57 , and $0.64 \text{ W m}^{-1} \text{ K}^{-1}$ for acerola, blueberry pulp with 14% solids, and blueberry pulp with 16% solids respectively. As for the other thermal properties, thermal conductivity was dependent on the product's moisture content.

Conclusion

In this study, moisture content, density, specific heat capacity, thermal diffusivity, and thermal conductivity were determined for orange pulp concentrations of ≈ 500 to 800 g L^{-1} . For all pulp concentrations moisture content was between 82.1 and 82.7%. Density values ranged from 1.03 to 1.06 g mL^{-1} . For all pulp concentrations, specific heat capacity was between 4025.0 to $4068.4 \text{ J kg}^{-1} \text{ K}^{-1}$; thermal diffusivity ranged from 1.50 to $1.56 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$; and thermal conductivity was between 0.63 and $0.66 \text{ W m}^{-1} \text{ K}^{-1}$.

The thermophysical properties of food strongly depend on moisture content. Since moisture content was very similar for all pulp concentrations, there were no significant differences ($p > 0.05$) between the mean values obtained for specific heat capacity, thermal diffusivity, and thermal conductivity for the different pulp concentrations. Thermal conductivity of pulp was not significantly different ($p > 0.05$) compared to that of water. However, the specific heat was significantly different ($p < 0.05$) from the values reported for water.

The results of the thermal properties of orange pulp fell in a similar range of values that have been reported for other fruit pulps with similar moisture content. The reproducibility of results in this study (Table 2-3) showed that the methods used for determining the thermal properties of orange pulp are valid and can be used for determining the thermal properties of other food products. The values obtained for thermal conductivity and specific heat capacity of orange pulp can be used to obtain the thermal characteristics of this product, and to optimize process operations involving heat transfer.

Figures and Tables



Figure 2-1. FMC Quick Fiber Test instrument used for determining orange pulp concentration. Photo courtesy of author.



Figure 2-2. Experiment setup for determining specific heat capacity of orange pulp samples. Photos courtesy of author.

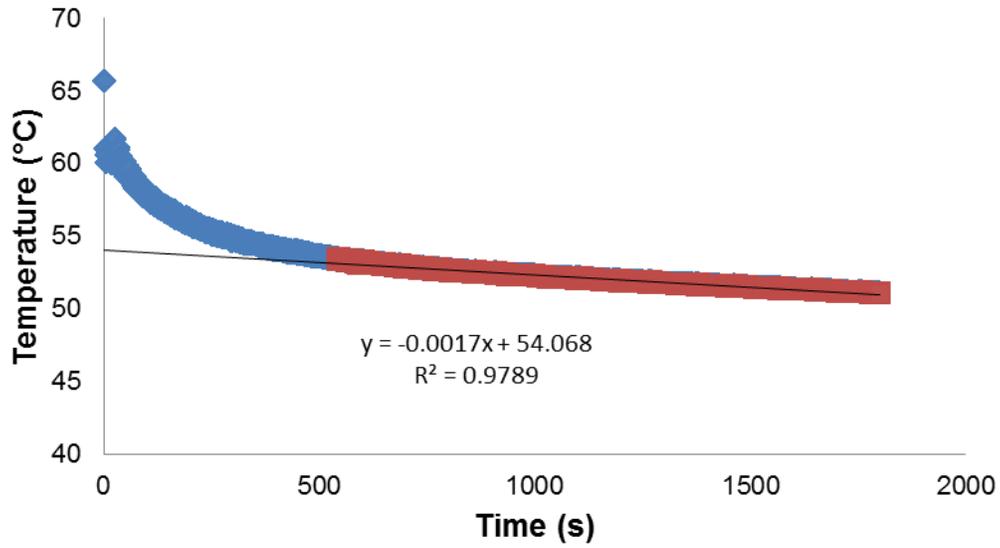


Figure 2-3. Time-temperature graph for determining orange pulp specific heat capacity.

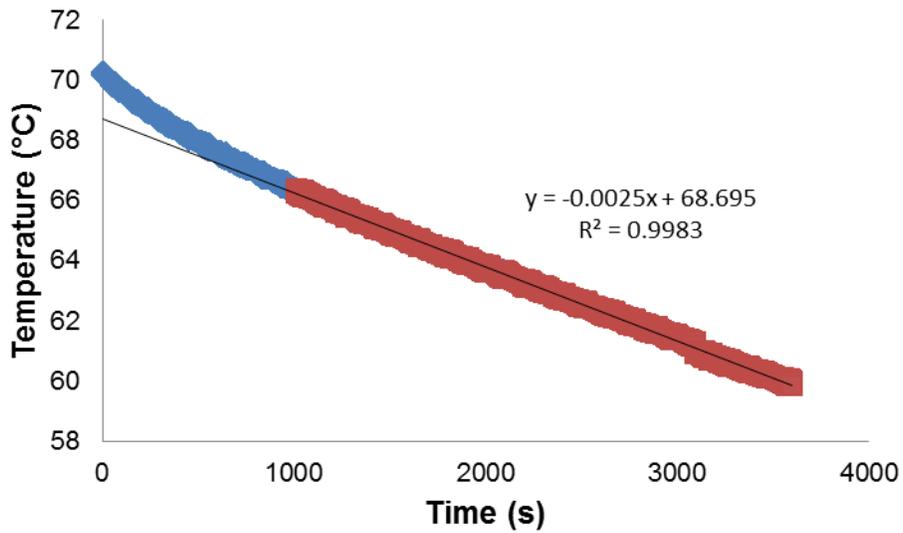
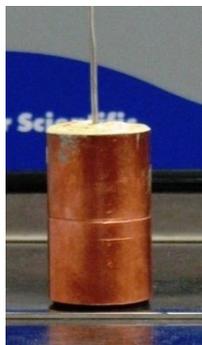
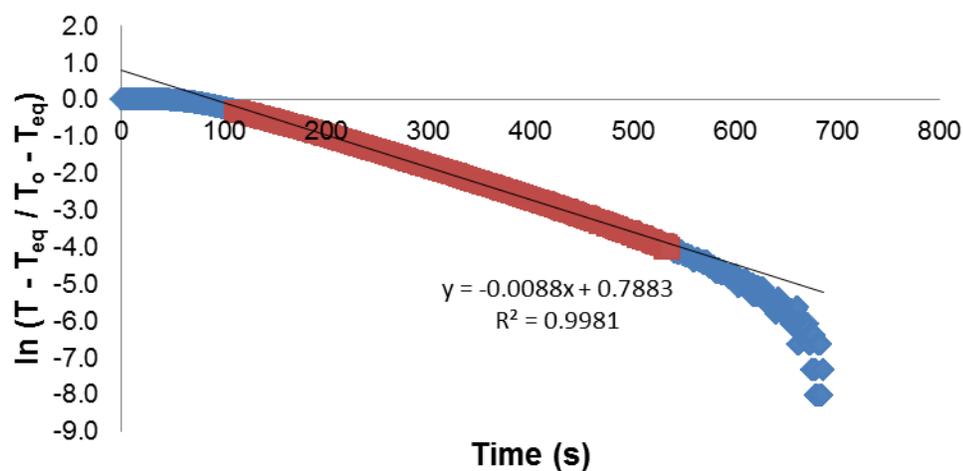


Figure 2-4. Time-temperature graph for determining the heat loss to the surroundings to calculate the specific heat capacity.



a)



b)

Figure 2-5. Materials and methods used to determine the thermal diffusivity: a) Copper cylinder (photo courtesy of the author) and b) Time vs. dimensionless temperature graph. The slope of the linear portion of this curve allowed calculating the thermal diffusivity of orange pulp.

Table 2-1. Average (n = 3) moisture content and density of orange pulp at different concentrations. Errors were calculated as standard deviations.

Pulp Concentration g L ⁻¹	Moisture Content %	Density at 20 °C kg m ⁻³
516 ± 6	82.7 ± 0.001	1037.0 ± 4.4
617 ± 7	82.1 ± 0.002	1056.5 ± 1.0
712 ± 12	82.0 ± 0.002	1038.7 ± 7.5
801 ± 13	82.1 ± 0.001	1033.7 ± 1.5

Table 2-2. Experimental values obtained for the calorimeter's heat capacity (n=10).

Test	Calorimeter's heat capacity (<i>Hk</i>) J K ⁻¹
1	65.98
2	72.10
3	66.86
4	68.93
5	48.31
6	48.82
7	47.57
8	55.41
9	54.08
10	72.67
Mean	60.07
Std. Deviation	10.23

Table 2-3. Mean values of the thermal properties of orange pulp at selected concentrations. Errors represent standard deviations (n=3)

Pulp Concentration g L ⁻¹	Specific Heat Capacity J kg ⁻¹ K ⁻¹	Thermal Diffusivity m ² s ⁻¹	Thermal Conductivity W m ⁻¹ K ⁻¹
516 ± 6	4025.0 ± 37.1	1.50 ± 0.01 × 10 ⁻⁷	0.63
617 ± 7	4051.2 ± 64.1	1.55 ± 0.02 × 10 ⁻⁷	0.66
712 ± 12	4055.7 ± 32.1	1.56 ± 0.04 × 10 ⁻⁷	0.66
801 ± 13	4068.4 ± 12.5	1.55 ± 0.07 × 10 ⁻⁷	0.65

CHAPTER 3
DETERMINATION OF HEAT TRANSFER COEFFICIENTS AND HEAT TRANSFER
CHARACTERISTICS OF HIGH CONCENTRATION ORANGE PULP

Introduction

Determination of heat transfer coefficients is essential to model aseptic processing of fluids that have a complex rheological behavior, such as high concentration orange pulp. The heat transfer coefficients and heat transfer characteristics of orange pulp have not been reported. The heat transfer coefficient is not a property of a material. It depends on thermophysical properties of a fluid such as density, viscosity, specific heat, and thermal conductivity, the velocity and flow regime of the fluid, the geometry and roughness of the surface of the solid body in contact with the fluid (Singh and Heldman 2009). Several expressions can be found in the literature to determine the heat transfer coefficient. However, for equipment design, it is imperative to calculate the heat transfer coefficients considering real process parameters (Goldstein and others 2005).

The objectives of this study were: (1) to determine the local and overall heat transfer coefficients for orange pulp concentrations of approximately 500, 600, 700, and 800 g L⁻¹ at different velocities in a concentric pipe heat exchanger; (2) to obtain the radial temperature profiles when heating and cooling orange pulp at the selected concentrations, in order to explain how heat is transferred in this fluid; and (3) to determine the pressure drop that results from the flow of orange pulp at selected concentrations in tubular pipes, at different flow rates. This information is necessary to optimize equipment design and the process conditions for producing high concentration orange pulp (HCP) aseptically.

Materials and Methods

Samples Preparation

Orange pulp with concentrations of 516 ± 6 , 617 ± 7 , 712 ± 12 , and 801 ± 13 g L⁻¹ was obtained as detailed in the Materials and Methods section of Chapter 2. Since pulp concentration tends to increase with extended processing, its concentration was measured and adjusted, if necessary, after every three experimental runs.

Experimental Setup

Experiments were conducted in a stainless steel double tube heat exchanger (Feldmeier Equipment, Inc. Syracuse, NY) located at the CREC at University of Florida. Figure 3-1 shows the schematic equipment setup used in this study. Approximately 40 L of orange pulp with concentrations of 516, 617, 712, and 801 g L⁻¹ were pumped from a feeding tank into the heat exchanger using a diaphragm pump (Hypro, model 9910-D1064, New Brighton, MN). Tests were run in the heating and cooling sections of the heat exchanger for each pulp concentration. The length and diameter of each section were 3.40 m and 0.0254 m (1 in) respectively. An electromagnetic flow meter (Rosemount, model 8732, Chanhassen, MN) was used to measure the flow rate. Flow rates were adjusted with a glove valve on a by-pass that diverted part of the inlet flow back to the feeding tank. For each pulp concentration and heat exchanger section, experiments were run at minimum five different flow rates. Two pressure transducers (Omegadyne Inc., models PX43EO-060GI and PX44EO-500GI, Sunbury, OH) were mounted at the inlet and outlet of the heat exchanger's experimental section to measure the initial and final pressure.

Pulp initial temperature (T_i) was measured with a thermocouple type K, placed in the bottom of the feeding tank. To measure pulp average final temperature, a set of five

thermocouples ($T_0 - T_4$) type K were inserted at the exit of each section (heating and cooling) using multiconductor feedthroughs (Omega, Stamford, CT), as shown in Figures 3-2 and 3-3. These thermocouples were inserted at a radial distance of 12.7, 10.0, 7.0, 4.0, and 1.0 mm from the pipe wall. At first, a static mixer with a thermocouple attached to its end was placed at the exit of the pipe to mix the pulp uniformly and measure its final temperature. However, the static mixer did not produce a uniform temperature and pulp average final temperature measurements were not accurate. Therefore, we removed the static mixer and determined pulp final temperature as the arithmetic mean of the temperatures obtained with the set of five thermocouples described above. For experiments conducted in the heating section, hot water (heating media) temperature was set at 76 ± 1 °C; for tests conducted in the cooling section water temperature was set at 4 ± 1 °C. Due to the heat exchanger design, the flow of the heating media was countercurrent to the product's flow, while the flow of the cooling media was parallel.

To measure the apparent wall temperature (T_w), an exposed junction thermocouple type K was well attached to the inner pipe's external surface at the exit of the heating and cooling sections. The whole tube at the exit was insulated with foam pipe insulation to avoid heat losses to the surroundings and reasonably approximate the actual wall temperature (Figure 3-2). It was assumed that the temperature difference between the internal and external surfaces of the pipe was negligible. Figure 3-4 shows a schematic representation of how heat flowed when pulp was flowing in the heating section of the heat exchanger, and where the wall temperature was measured. We selected this point to measure T_w because it was not possible to place the thermocouple

inside the pipe's wall without getting it in contact with the heating media or the product. Hence there was no other practical way of determining such temperatures. However, it is clear that this temperature was only an approximation to the actual wall temperature.

For each experiment run, pulp at room temperature was pumped into the system only once (without recirculation), and temperatures, flow rate, and pressures were recorded after reaching steady state, using a data acquisition board model NI TB-9214, and a computer program written in LabVIEW 10.0 both from National Instruments, (Austin, TX) (Figure 3-5). A total of 48 experiments were conducted, and each condition was carried out once (Table 3-3). A picture of the equipment setup is shown in Figure 3-6.

Determination of Local and Overall Heat Transfer Coefficients

The conventional definition of the heat flow for a fluid flowing in the heating or cooling section of a pipe, and the energy balance equation applied to a section of a pipe, were combined to calculate the local heat transfer coefficients (Gratão and others 2006; Ditchfield and others 2007):

$$dQ = hA(T_w - T_f)dt = C_p \rho V dT \quad (3-1)$$

Where, Q is the heat transferred; h is the heat transfer coefficient; A is the heat transfer area; T_w is the wall temperature; and T_f is pulp average final temperature. C_p is pulp specific heat capacity; ρ is pulp density; and V is the volume of the heat exchanger.

Rearranging and integrating equation 3-1 as done by Ditchfield and others (2007), resulted in the following expression:

$$h = \frac{C_p \rho D u}{4L} \ln \frac{T_i - T_w}{T_f - T_w} \quad (3-2)$$

Where T_i is pulp inlet temperature; D is the pipe diameter; u is the velocity; and L is the tube length.

Orange pulp density and specific heat capacity were determined as explained in Chapter 2. The average velocity was calculated dividing the volumetric flow rate by the pipe's cross section area. To calculate the local heat transfer coefficient using equation 3-2, we assumed the following: Pulp density, thermal conductivity, and specific heat were constant throughout the range of temperatures of the experiments; natural convection effects were negligible; and steady flow was reached. The relationship between the calculated heat transfer coefficients with velocity and pulp concentration was determined.

Due to the difficulties involved in measuring accurately the wall surface temperature to calculate h , the overall heat transfer coefficient (U) was also calculated for each pulp concentration and flow rate in the heating section of the heat exchanger. These values were compared to those obtained for h in order to obtain a more conservative approach for future calculations involving the heat transfer coefficient.

The overall heat transfer coefficient was calculated using equation 1-7 and solving for U :

$$U = \frac{q}{A \Delta T_{LMTD}} \quad (3-3)$$

Where q was calculated using equation 2-4, and the logarithmic mean temperature difference was calculated as follows:

$$\Delta T_{LMTD} = \frac{(T_{h_i} - T_i) - (T_{h_f} - T_f)}{\ln [(T_{h_i} - T_i) / (T_{h_f} - T_f)]} \quad (3-4)$$

Where T_{h_i} is the inlet temperature of the heating media; T_i is pulp inlet temperature; T_{h_f} is the outlet temperature of the heating media; and T_f is pulp average outlet temperature.

The outlet temperature of the heating media (T_{h_f}) was measured for pulp concentrations of ≈ 600 and 700 g L^{-1} with a temperature sensor located at exit of the heat exchanger. This temperature was measured at selected flow rates ranging from 3.1×10^{-5} to $6.5 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$. The T_{h_f} values were plotted as function of flow rate, and an equation obtained from linear regression analysis ($R^2=0.9935$) was used to estimate T_{h_f} values for the rest of pulp concentrations and flow rates covered in this research.

Temperature Profiles

Temperature profiles in the radial direction of the pipe, which is the same direction as heat flow, were determined with the temperatures measured with the set of five thermocouples located at the exit of the heat exchanger's section (Figure 3-2). For each experimental run, these temperatures were plotted as function of distance from the pipe wall. The differences between the curves obtained for the different pulp concentrations and flow rates were analyzed in terms of flow regime and heat transfer.

To assess the flow regimes for each experiment, the Reynolds number was estimated using the friction factor, which was calculated using Bernoulli's equation:

$$0 = \frac{P_2 - P_1}{\rho} + \frac{g z}{g_c} + \frac{v^2}{2 g_c} = \frac{2 f v^2 L}{g_c D} \quad (3-5)$$

$$f = \left(\frac{P_2 - P_1}{\rho} + \frac{g z}{g_c} + \frac{v^2}{2 g_c} \right) \left(\frac{g_c D}{2 v^2 L} \right) \quad (3-6)$$

Where f is the friction factor; P_2 and P_1 are the outlet and inlet pressures; ρ is the pulp density; g is the gravity acceleration; z is the elevation; g_c is the proportionality

factor for gravitational force; v is the velocity; D is the pipe diameter; and L is the pipe length.

Pressure Drop

The pressure drop for each experimental run was determined with the pressure difference between the pressure at the inlet and the pressure at the outlet of the heat exchanger section:

$$\text{Pressure Drop} = \Delta P = P_{inlet} - P_{outlet} \quad (3-7)$$

The obtained pressure drop values were plotted as function of pulp concentration and flow rate, to determine the type of relationship between these variables.

Regression Analysis

Regression analysis was performed to determine the relationship between velocity and the heat transfer coefficients obtained for the different pulp concentrations, in both sections of the tubular heat exchanger.

Results and Discussion

Determination of Heat Transfer Coefficients

Local heat transfer coefficients obtained in the heating section for the different pulp concentrations and flow rates ranged from 1342 to 7765 $\text{W m}^{-2} \text{ }^\circ\text{C}^{-1}$. For the cooling section, the local heat transfer coefficients ranged from 1441 to 7757 $\text{W m}^{-2} \text{ }^\circ\text{C}^{-1}$. The ranges were very similar for both sections. For the heating section, the calculated overall heat transfer coefficient values were between 1241 and 6428 $\text{W m}^{-2} \text{ }^\circ\text{C}^{-1}$, a bit lower than the range obtained for the local heat transfer coefficients. Table 3-2 shows the local and overall heat transfer coefficients obtained in the heating section, and Table 3-3 shows the local heat transfer coefficients obtained in the cooling section for the different pulp concentrations and flow rates. These values were obtained for velocities

between 0.3 and 1.7 m s^{-1} , that correspond to flow rates between 1.6 and $8.5 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$ (Table 3-1).

For all pulp concentrations, the heat transfer coefficient increased with increasing velocities. Figures 3-7 and 3-8 show the calculated heat transfer coefficients as a function of velocity and pulp concentration, for the heating and cooling sections respectively. In the heating section, similar heat transfer coefficient values were obtained for pulp concentrations of 516 and 617 g L^{-1} at similar velocities. For 712 g L^{-1} pulp, the heat transfer coefficients were lower compared to those obtained for lower pulp concentrations at similar velocities, and were close to the values obtained for 801 g L^{-1} pulp at similar velocities. Figure 3-7 shows that the range of heat transfer coefficients obtained for 801 g L^{-1} pulp was very narrow (1342 to $2549 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$) compared to the other concentrations. This was in part due to the fact that at this concentration, it was not possible to reach the same range of flow rates as for the other concentrations. As flow rate (velocity) affects the heat transfer coefficient, the range of h values became narrower as the range of flow rates for a particular pulp concentration was smaller.

Figure 3-8 shows that in the cooling section, a similar trend was obtained as for the heating section. However, the range of local heat transfer coefficients obtained for the 617 and 712 g L^{-1} concentrations was narrower compared to those obtained for these concentrations in the heating section. In addition, in contrast with the heating section, there was a pronounced difference at the higher velocities between the values obtained for the 516 g L^{-1} and for 617 g L^{-1} concentrations. The differences obtained for different pulp concentrations will be explained further in this section. Figures A-1 and A-2 (Appendix A) show a comparison between the local heat transfer coefficients obtained

in the heating and in the cooling section for each pulp concentration. These graphs suggest that for all pulp concentrations, the relationship between heat transfer coefficient and velocity may be described with a linear equation. Linear regression showed that a correlation coefficient R^2 above 0.95 was obtained for all linear fits, except for $\approx 700 \text{ g L}^{-1}$ pulp in the cooling section and for $\approx 800 \text{ g L}^{-1}$ pulp in both sections, where R^2 was between 0.92 and 0.94. At higher pulp concentrations, it was more difficult to achieve steady flow rates due to its higher apparent viscosity, which might explain why the relation was less linear for these concentrations (Payne 2011).

Tables 3-2 and 3-3 also show the slopes and intercepts obtained from the linear regression analysis. In the heating section, the slopes obtained from the local heat transfer coefficient vs. velocity curves (h/u) ranged between 4370 to 5615 for pulp concentrations of ≈ 500 to 700 g L^{-1} , with standard error ranging from ± 233 to ± 405 . For the same concentrations, the slopes obtained from the overall heat transfer coefficient vs. velocity curves (U/u) were between 3410 to 5262, with an error between ± 172 to ± 393 . For $\approx 800 \text{ g L}^{-1}$ pulp, the slopes were considerably lower than for lower concentrations. For h/u and U/u , the slopes were 2024 ± 300 and 1704 ± 361 respectively. The slopes for 800 g L^{-1} pulp were lower because the flow rates reached for this concentration were smaller, hence obtaining a narrower range of heat transfer coefficients. In the cooling section, the slope h/u for $\approx 500 \text{ g L}^{-1}$ concentration was 7235 ± 608 , much higher compared to the slopes obtained for the higher concentrations. For ≈ 600 to 800 g L^{-1} pulp, the slopes obtained were similar; they ranged from 1273 to 2927 with an error between ± 201 to ± 433 . For these concentrations, the range of heat transfer coefficients was narrower compared to $\approx 500 \text{ g L}^{-1}$, which explains why their

slopes were closer. Regarding the intercepts, we expected that these values would be close to zero. However, for some pulp concentrations, large negative or positive values were obtained. This was found for ≈ 600 and 700 g L^{-1} concentrations in the heating section, and for ≈ 500 to 700 g L^{-1} in the cooling section. Probably at very low flow rates, the relationship between the heat transfer coefficients with velocity is less linear, or it varies at a different rate compared to higher flow rates. The intercepts obtained for $\approx 800 \text{ g L}^{-1}$ concentrations were more reasonable, probably because at this concentration very low velocities were reached, which allow predicting better the h and U values that will be obtained when velocity is zero.

In general, the local heat transfer coefficients were lower in the cooling than in the heating section for the same pulp concentrations at similar flow rates. McCabe and others (1985) explained that for very viscous fluids, when heated, the lower viscosity near the wall makes the velocity profile more like a plug flow, with a steep gradient near the wall and a smaller gradient near the center, leading to higher rate of heat transfer. In the other hand, when a viscous fluid is cooled, the velocity gradient at the wall decreases, resulting in lower rate of heat transfer. The differences in the heat transfer coefficients were also due to differences in flow rate. Payne (2011) reported that orange pulp had laminar flow at concentrations between 500 to 850 g L^{-1} . Levati (2010) also reported laminar flow for 850 g L^{-1} orange pulp. As pulp concentration increased, pulp had higher apparent viscosity and behaved more like a paste, making it impossible to achieve the same flow rates with the diaphragm pump compared to the lower concentrations, resulting in lower heat transfer coefficients. At higher velocities, the movement of the product particles inside the pipe was higher compared to lower

velocities, which favored heat transfer from the heating media to the product and within the product. This was evidenced by the wall temperature measurements. At high flow rates, the wall temperature varied considerably after each experiment compared to its initial value. While for low flow rates, the wall temperature after each experiment was close to its initial measurement. This indicated that at higher velocities, the rate of heat exchange between the heating / cooling media and the product increased, causing higher temperature differences in the wall's surface.

Figures 3-7 and 3-8 show that local heat transfer coefficients were higher for pulp concentrations of 516 and 617 g L⁻¹, compared to those obtained for 712 and 801 g L⁻¹ at similar velocities. These graphs also show that for the lower pulp concentrations, at velocities above 1.5 m s⁻¹ the heat transfer coefficients tended to increase faster (higher slope) compared to the other concentrations. This was particularly observed for concentrations of 516 and 617 g L⁻¹ in the heating section, and for 516 g L⁻¹ in the cooling section. Pulp at higher concentrations, especially ≈ 800 g L⁻¹, flowed like a solid block inside tubular pipes. The radial movement of particles and fluid near the wall for this concentration was minimum compared to lower pulp concentrations such as ≈ 500 and ≈ 600 g L⁻¹, which was not favorable for heat transfer. This caused a larger temperature gradient between the pulp at the center of the pipe and the wall, affecting the rate of heat transfer for higher pulp concentrations. However, the lower flow rates that were obtained for higher pulp concentrations played a major role on the differences found for the heat transfer coefficients, as explained previously.

The local heat transfer coefficients obtained for low and high concentration orange pulp were higher compared to values that have been reported for other pulps and

purees. Ditchfield and others (2007) reported local heat transfer coefficients of 654.8 to 1070.4 $W m^{-2} \text{ }^{\circ}C^{-1}$ for banana puree in a tubular heat exchanger. However, the range of velocities used in this study ranged from 0.2 to 0.4 $m s^{-1}$, much lower than the velocities that we used for orange pulp (0.3 to 1.7 $m s^{-1}$). For velocities close to 0.4 $m s^{-1}$, Ditchfield and others (2007) obtained heat transfer coefficients between 800 and 1070 $W m^{-2} \text{ }^{\circ}C^{-1}$. For similar velocities, the heat transfer coefficients obtained for HCP were between 969 and 1441 $W m^{-2} \text{ }^{\circ}C^{-1}$, which were close to the values obtained for banana puree. In our study, these low velocities were only obtained for orange pulp concentrations of 801 $g L^{-1}$. In the same study with banana puree, the authors also found that heat transfer coefficients increased at higher flow rates, smaller L/D ratios, and higher heating medium temperatures. In addition, there was a high temperature difference between the banana puree that was near the pipe's wall and the product located at the center, especially at lower flow rates, which was in agreement to what we found for orange pulp. For tomato pulp, Sangrame and others (2000) reported overall heat transfer coefficients of 625 to 911 $W m^{-2} \text{ }^{\circ}C^{-1}$ in a thin film scraped surface evaporator, for flow rates of approximately 6.5 to 8.5 $\times 10^{-4} m^3 s^{-1}$. These values were considerably smaller compared to the overall heat transfer coefficients obtained for orange pulp at similar flow rates. These differences were probably due to the different equipment and operating conditions used in each experiment, and due to tomato pulp higher apparent viscosity (100,000 to 250,000 cP) compared to orange pulp (33,000 to 234,000 cP for concentrations between 503 and 795 $g L^{-1}$) (Payne 2011). Prost and others (2005) reported overall heat transfer coefficients ranging from 983 to 6500 $W m^{-2} \text{ }^{\circ}C^{-1}$ for sucrose solutions in a falling film evaporator. The obtained values varied with

operating conditions and with sugar concentrations. This range of overall heat transfer coefficient is close to the one obtained for orange pulp.

Figure 3-9 shows the overall heat transfer coefficients obtained in the heating section for the different pulp concentrations and velocities. The range of values obtained was similar to that obtained for the local heat transfer coefficients in the heating section. The overall heat transfer coefficients were very similar for concentrations of 516, 617, and 712 g L⁻¹. For 801 g L⁻¹, the overall heat transfer coefficients were lower, mainly due to the lower flow rates reached at this concentration. Figures 3-10 and 3-11 show a comparison between the local and overall heat transfer coefficients obtained for each pulp concentration, as a function of velocity. These graphs show that the difference between the local and the overall heat transfer coefficients was greater for the lower concentrations, while for 712 and 801 g L⁻¹ concentrations, both heat transfer coefficients were similar. For concentrations of 516 and 617 g L⁻¹, the difference between h and U ranged from 1250 to 2240, and from 802 to 1375 W m⁻² °C⁻¹ respectively. For 712 and 801 g L⁻¹, the difference between h and U was between 184 to 463, and 59 to 278 W m⁻² °C⁻¹ respectively. Since at high pulp concentration the laminar flow regime occurred throughout the cross section of the pipe, the predominant way of heat transfer for these concentrations was conduction. This may explain why the overall convective heat transfer coefficient became very similar to the convective local heat transfer coefficient at high pulp concentrations. Laminar flow and heat transfer by conduction will be discussed in the next section of this chapter. For the local heat transfer coefficient calculation, it was assumed that the flow rate of the heating media was much larger than the flow rate of the product. Hence, it was assumed that the

temperature variation in the heating media was negligible, and it was not considered for the calculation of h . However, the temperature of the heating media did change with the product's flow rate. When pulp flowed at higher velocities, after reaching steady conditions, the inlet and outlet temperature of the hot water changed in relation to its initial values. As concentrations of ≈ 500 to 600 g L^{-1} flowed at higher velocities than lower concentrations, the temperature of the heating media dropped more for these concentrations. For example, for 516 g L^{-1} pulp flowing at $7.9 \times 10^{-4} \text{ m s}^{-1}$, the temperature of the heating media decreased approximately $7 \text{ }^\circ\text{C}$ after reaching steady state, while for 712 g L^{-1} pulp flowing at $3.9 \times 10^{-4} \text{ m s}^{-1}$, the temperature dropped about $1 \text{ }^\circ\text{C}$. This also explains why the overall heat transfer coefficient varied more for lower pulp concentrations in relation to the local heat transfer coefficient. Since for high concentration pulp the values were very similar, either the overall or the local heat transfer coefficients can be used for design and optimization of equipment and process operations.

Temperature Profiles

The temperature profiles in a radial direction of the tubular pipe were obtained for every experimental condition. Figures 3-12 to 3-19 show the temperature profiles obtained for each pulp concentration in the heating and cooling sections of the heat exchanger, at selected flow rates. All graphs show that when the pulp was heated, its temperature was maximum at the wall, and decreased towards the center. And when the pulp was cooled, the temperature was minimum at the wall and increased towards the center of the pipe. This was obviously expected since heat flowed in a radial direction, from the heating media to the wall, from the wall to the product, and within the product (McCabe and others 1985). For all experiments, the temperature of pulp at the

center of the pipe was close to its initial temperature. Since we only used one heating or one cooling section of 3.40 m each, the distance was too short to cause a higher increase in temperature in the center of the pipe at the flow rates reached in this study. In general, the temperature of pulp at the wall was close to the wall's surface temperature at the lower flow rates, but as flow rates were higher, the difference between these temperatures increased. This was expected because at lower flow rates the residence time was longer, allowing the pulp temperature at the wall to become closer to that of the heating surface.

In the heating section, for pulp concentrations of 516 and 617 g L⁻¹, the temperature profile was linear at lower flow rates (4.4 to 5.6 x 10⁻⁴ m³ s⁻¹). At higher flow rates (6.4 to 7.9 x 10⁻⁴ m³ s⁻¹) the difference between the temperatures measured at 1, 4, and 7 mm from the pipe's wall decreased, and the curve became less steep at these points, resulting in a less linear profile compared to the lower flow rates. As flow rate increased, there was more molecular movement in the flowing product, favoring heat transfer and consequently equilibrating more the temperatures measured in a radial direction (Bhamidipati and Singh 1994).

In the cooling section, for all pulp concentrations, the temperature profiles were also more linear for the lower than for the higher flow rates. However, a marked division was observed between the first two points that are closer to the wall (1 and 4 mm from the wall) and the rest. For all pulp concentrations and for most flow rates, the temperature between these two points was relatively close, and after the third point (7 mm from the wall), the temperature curves became steeper. This effect may be attributed to the presence of slippage at the wall that was reported by Payne (2011) for

low and high concentration orange pulp in tubular pipes. When slippage at the wall is manifested, a thin layer of liquid is formed at the interface of the fluid and the wall, causing a “lubrication” effect in a small portion of product that is close to the wall (Barnes 1995). Slippage caused a mixed flow, which may have induced changes in viscosity between both faces and thus, changes in the velocity and temperature profiles. Probably this type of temperature profile was mainly observed in the cooling section because as explained by McCabe and others (1985), the velocity gradient at the wall is different for a viscous fluid that is heated than for a viscous fluid that is cooled.

The temperature profiles obtained for the higher pulp concentrations (712 and 801 g L⁻¹) in the heating section were different compared to those obtained for the lower concentrations. For higher concentrations, the temperature difference between the pulp at the wall and the pulp at the center was larger. This was due in part to the lower flow rates reached at these concentrations, but probably also due to the lower rate of heat transferred within more concentrated pulp. In contrast to the temperature profiles obtained in the heating section for the lower pulp concentrations, for ≈ 700 and ≈ 800 g L⁻¹, the temperature profile became less linear at lower flow rates (2.4 to 3.9 m³ s⁻¹). However, this very low range of flow rates was only obtained for these concentrations. For concentrations of 712 and 801 g L⁻¹, the temperature curve was steep for the points located at 1, 4, and 7 mm from the wall, and then the temperature measurements were close between the points located at 10 and 12.7 (center) mm from the wall. For these latter points, their temperatures were very similar to the pulp’s inlet temperature, indicating that the rate of heat transfer was lower for higher concentrations. This means that at these concentrations, heat was mainly transmitted to the radial space located at

7 mm from the wall, but from this distance to the center, the temperature was almost the same as the initial temperature. This was not observed for the lower pulp concentrations in the heating section. This suggests that for high concentration pulp, heat was transferred mostly by conduction, and that the convective heat transfer to the liquid layer at the surface of the pipe was small.

The Reynolds number was estimated for each condition that was carried out in this study, to assess the type of flow regime that was obtained in each case. All the estimated Reynolds numbers were between 3 and 90, indicating laminar flow for all pulp concentrations. This confirmed what was found by Levati (2010) and Payne (2011), who reported laminar flow for low and high concentration orange pulp. In laminar flow, heat transfer occurs by conduction. In general, most temperature profiles obtained in this study were linear, which is in agreement with laminar flow. As discussed, the temperature profiles became less linear for the highest flow rates at the lower concentrations, or for very low flow rates at the higher concentrations. For the lower concentrations, even though the flows were predominantly laminar, there may be a certain degree of turbulence that allowed reaching higher flow rates and increased the rate of heat transfer. The higher flow rates reached at the lower concentrations caused more movement of particles when the product flowed inside the pipe. This explains why the heat transfer coefficients were higher at these conditions, and this may explain why the temperature profiles were less linear. McCabe and others (1985) explained that flow is truly laminar only in conditions where temperature changes and viscosity gradients are small. But variations in viscosity across the tube distort the velocity-distribution profile of laminar flow. When a fluid is heated, the layer near the wall has a lower viscosity than

the layers near the center, causing an increase in the velocity gradient at the wall. In addition, the temperature “layers” generate density gradients that may cause natural convection to set in, distorting the flow lines of the fluid. Regarding the less-linear temperature profiles obtained for very low flow rates at high pulp concentrations, McCabe and others (1985) stated that in laminar flow at low velocities and at large temperature drops, natural convection may occur to a very high extent. The effects of natural convection in tubes is found almost entirely in laminar flow, since at very low velocities, the fluid is not able to overcome the “soft” currents of natural convection. The different factors discussed: Slippage, probable natural convection, density and viscosity gradients, may have contributed to obtain distorted temperature profiles for some of the conditions carried out in this research. Figure 3-20 shows the hypothesized mixed flow of HCP, where heat was probably transferred by convection at the liquid layer at the wall, and by conduction at the thick “plug” of pulp flowing under laminar regime.

Pressure Drop Determinations

The pressure drops that resulted from pumping orange pulp with concentrations of ≈ 500 to 800 g L^{-1} in the heating and cooling sections of a tubular heat exchanger were plotted as function of flow rate in Figures 3-21 and 3-22. The pressure drop increased with higher flow rates for all pulp concentrations. As shown in the graphs, the pressure drop was higher for lower pulp concentrations. In the heating section, the pressure drop ranged from 147 to 157 kPa for 516 g L^{-1} , from 159 to 175 kPa for 617 g L^{-1} , from 184 to 207 kPa for 712 g L^{-1} , and from 159 to 169 kPa for 801 g L^{-1} . For this last concentration, the pressure drop values were not as high as expected due to the lower flow rates that were reached for this concentration. The same occurred for the cooling section, were

the pressure drops were between 168 to 189 kPa for 516 g L⁻¹, 196 to 220 kPa for 617 g L⁻¹, 217 to 253 kPa for 712 g L⁻¹, and 170 to 210 kPa for 801 g L⁻¹.

Figures B-1 and B-2 (Appendix B) show that for all pulp concentrations the pressure drop was considerably higher in the cooling section than in the heating section. It was expected that pressure drop would be higher in the cooling section, for higher pulp concentrations, and at higher flow rates. At higher temperatures and lower concentrations the apparent viscosity of the liquid phase probably decreased; this facilitated the movement of particles, generating less pressure while flowing. At higher flow rates, there was more interaction of particles within the fluid, generating more friction, and thus, more resistance to flow. Consequently, the pressure drop was higher with increasing flow rates (Singh and Heldman 2009).

Comparing to the pressure drops per unit of pipe length ($\Delta P/L$) obtained by Payne (2011) for orange pulp concentrations between 529 and 870 g L⁻¹ flowing in the same tubular heat exchanger, the values obtained in our study were higher but in the same order of magnitude. In the cooling section of the heat exchanger, Payne (2011) obtained experimental $\Delta P/L$ ranging between 37.9 and 56.3 kPa m⁻¹, while in the heating section, the values obtained were between 8.5 and 50.5 kPa m⁻¹. We obtained $\Delta P/L$ values ranging between 49.4 and 74.4 kPa m⁻¹ in the cooling section, and between 43.2 and 60.9 kPa m⁻¹ in the heating section. The higher pressure drops per length unit obtained in our study can be attributed to the fact that in Payne's experiments, pulp flowed through the heat exchanger at constant temperature, while we heated or cooled the pulp. Since changes in apparent viscosity with temperature are exponential, it is reasonable that the differences in $\Delta P/L$ were larger in the heating than in the cooling

section. In addition, the variability between orange pulp used in each study (e.g. source, different extraction and finishing processes) probably also contributed to the differences found between these studies.

The pressure drops obtained in our study were higher compared to values reported for other viscous fluids such as fruit purees. For apricot, apple, nectarine, and strawberry purees, pressure drops of approximately 55 to 120, 35 to 180, 10 to 50, and 10 to 45 kPa were reported respectively (Yeow and others 2002). The correspondent range of flow rates for these pressure drops was from 2.8×10^{-5} to $1.6 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$. The flow rates used for orange pulp in our study fell in the range of flow rates reported by Yeow and others (2002). In this study, a pipe with 0.025 m diameter and 7 m length was used, which doubled the length used in the experiments with HCP. The authors did not report the apparent viscosity of the purees; probably these values were greater for orange pulp, which may be the main cause for the pressure drop differences found. For 850 g L^{-1} orange pulp, Levati (2010) reported pressure drops between 375 to 500 kPa at flow rates from 1.4 to $1.8 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$ in a tubular pipe with 0.025 m diameter, at 50 °C. These values were higher compared to the values that we obtained for pulp concentrations between 712 and 801 g L^{-1} in the heating section (163 to 207 kPa). However, the flow rates reported by Levati were much higher than the ones reached in this study for HCP. The pressure drops obtained in this research can be used in combination with heat transfer data obtained, for modeling and optimization of heat transfer operations for HCP.

Conclusions

For orange pulp concentrations of approximately 500, 600, 700 and 800 g L^{-1} flowing in the heating and cooling sections of a tubular heat exchanger, the heat

transfer coefficients varied linearly with velocity. As velocity increased, higher heat transfer coefficients were obtained. The local heat transfer coefficients were higher for lower pulp concentrations, mainly due to the higher velocities that were reached at these concentrations, which favored heat transfer. Orange pulp with concentrations close to 800 g L^{-1} flowed like a solid block in tubular pipes. This caused that the flow rates reached for this concentration were very low, hence reducing the rate of heat transfer within the fluid. The overall heat transfer coefficients obtained in the heating section for the different pulp concentrations at different velocities, did not vary considerably compared to the local heat transfer coefficients. The values of h and U were very close for concentrations of ≈ 700 and 800 g L^{-1} . At these concentrations, heat was transferred mostly by conduction, which explained why the local and overall convective heat transfer coefficients were very similar. The temperature profiles and estimated Reynolds numbers indicated that orange pulp with concentrations from 500 to 800 g L^{-1} flowed under laminar regime. These curves also indicated the presence of slippage at the wall surface, which distorts the temperature profiles at the distances located near the wall. The pressure drop measured in the heat exchanger increased at higher flow rates, and was higher for more concentrated pulp. Also, higher pressure drops were found in the cooling section of the heat exchanger.

Significance of this Research

In this research, the thermal properties, heat transfer coefficients, and heat transfer characteristics of HCP in tubular heat exchangers were determined. This information had not been previously published. This data can be used to evaluate process operations which involve heat transfer, to design and optimize equipment dimensions and characteristics for thermal processing of HCP, and to obtain HCP heat

transfer characteristics with different equipment and processing conditions. For example, the specific heat of HCP can be used to obtain energy balances using the conventional definition of heat flow (equation 2-4). We can determine the energy required to heat HCP from an initial temperature to a desired final temperature at a given mass flow rate. With this energy requirement, it is possible to determine the required mass flow rate and temperature of the heating or cooling media in the equipment under evaluation. The specific heat capacity can also be used to calculate the heat transfer coefficients for other types of heat exchangers, or other process conditions. The thermal conductivity is useful to calculate the rate of conductive heat transfer along the radial direction of a tubular pipe. Since in HCP heat is mostly transferred by conduction, the thermal conductivity plays a major role for designing and optimizing thermal processes and equipment for this fluid, *e.g.* to calculate the required heat transfer area to heat HCP from T_i to T_f in a tubular pipe.

The results from this study showed that for HCP, turbulent flow was not possible to achieve under the conditions carried out in these experiments. The relatively low heat transfer coefficients obtained for highly-concentrated pulp, the high temperature gradients within the product, and the high pressure drops, indicated that the heat exchanger dimensions and pump characteristics used in this research were not suitable for pasteurizing HCP. The heat transfer coefficients obtained for HCP can be used to determine the required equipment dimensions and characteristics to pasteurize this fluid. Applying the same equations used in this research, the minimum pipe length and diameter that will allow reaching pasteurization temperatures for HCP flowing in a tubular pipe can be calculated. Nonetheless, the required dimensions might not be

applicable from a practical and commercial standpoint. The obtained temperature profiles suggested that we would probably need a very long pipe to reach the desired temperature in the pulp located at the center of the pipe. In addition, a very high power pump would probably be required to overcome the pressure drop built inside the pipe, and induce turbulent flow to enhance heat transfer. Therefore, tubular heat exchangers are probably not the most suitable equipment to pasteurize highly-concentrated pulp. The heat transfer coefficients and thermal properties obtained in this research can still be used for design and optimization purposes, especially for optimizing equipment to handle orange pulp with lower concentrations ($< 700 \text{ g L}^{-1}$).

Overall Conclusions

The thermal properties of orange pulp with concentrations of approximately 500, 600, 700, and 800 g L^{-1} were determined in this research. The specific heat capacity, thermal diffusivity, and thermal conductivity, were not significantly different ($p > 0.05$) among pulp concentrations. Orange pulp specific heat capacity was significantly different ($p < 0.05$) compared to water, while the thermal conductivity was not significantly different ($p > 0.05$) from to the values reported for water.

The local and overall heat transfer coefficients of low and high concentration orange pulp, increased linearly with fluid velocity, and decreased with pulp concentration. Heat transfer coefficients were lower for highly-concentrated pulp due to its “solid like” flow that caused higher temperature gradients within the product. The radial temperature profiles suggested that HCP flowing in tubular pipes presented slippage at the wall, flowed under laminar regime, and that heat in this fluid was mainly transferred by conduction. The estimated Reynolds numbers confirmed laminar flow for all pulp concentrations. Pressure drop for HCP flowing in a tubular heat exchanger

increased with flow rate and with pulp concentration. Pressure drop was higher in the cooling than in the heating section of the heat exchanger, for same pulp concentrations and similar flow rates.

The process conditions and equipment used in this research did not allow reaching turbulence for HCP. In order to induce turbulent flow and enhance heat transfer, high power pumps and larger equipment dimensions would probably be required. Hence, scraped surface heat exchangers can be an alternative to tubular pasteurizers, for producing highly-concentrated pulp aseptically.

Future Work

In this study, we did not cover the higher range of orange pulp concentrations: from 850 to 1000 g L⁻¹, because it was not possible to pump pulp concentrations above 800 g L⁻¹ with the diaphragm pump used in these experiments. Another type of pump such as a progressive cavity pump, would allow determining the heat transfer coefficients and temperature profiles for this higher range of concentrations, which would be valuable information for citrus processors and equipment designers. For future studies involving heat transfer in tubular heat exchangers, it would be useful to measure the inlet and outlet temperature of the heating or cooling media in order to calculate accurately the overall heat transfer coefficients in both sections.

As discussed in the “Significance of this Research” section, the results obtained in this study will allow calculating the required equipment dimensions and process conditions for pasteurizing HCP in tubular pipes. However, it is possible that these requirements might not be applicable from a commercial and practical standpoint. Therefore, it would be useful to combine the pressure drop, heat transfer data, and thermal properties obtained in this research, to determine the equipment requirements,

utility consumption, potential capacities, in order to minimize pressure drop and maximize heat transfer. This information may lead to conduct further experiments with other types of heat exchangers, or to experiment with different pipe dimensions, in order to find the optimal equipment to produce HCP aseptically.

Figures and Tables

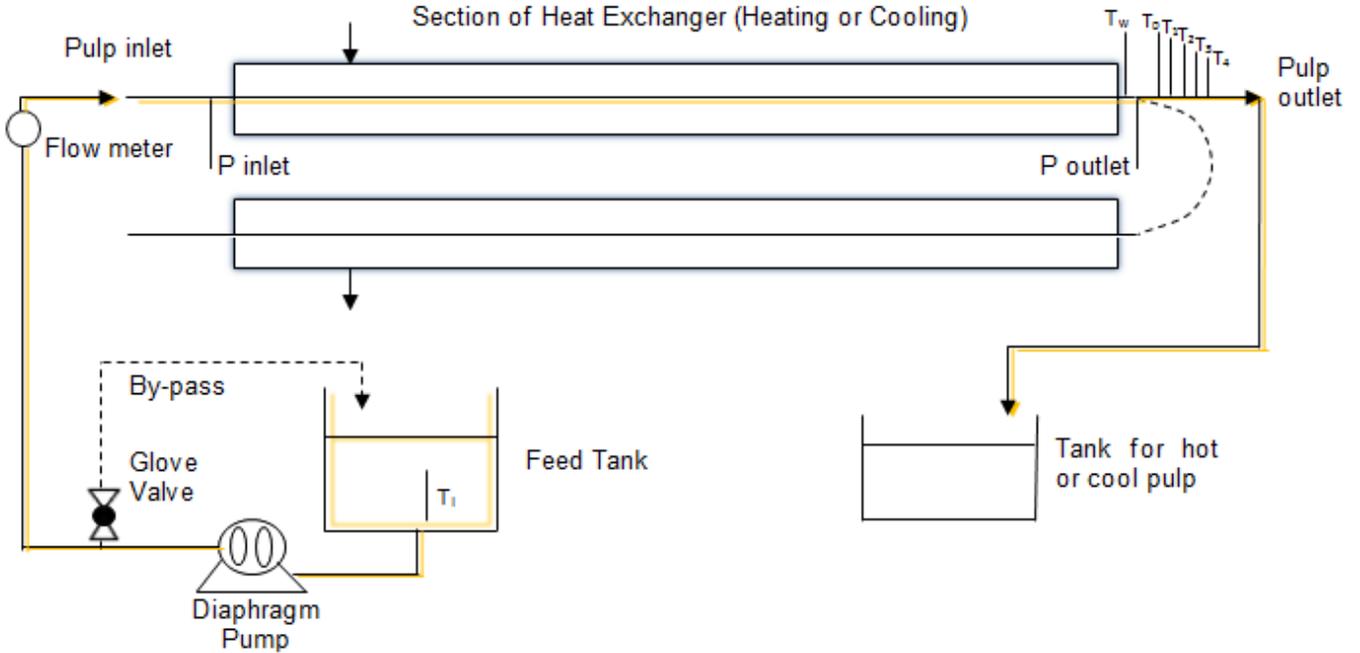


Figure 3-1. Schematic representation of equipment setup for determination of temperature profiles and heat transfer coefficients of high concentration orange pulp.

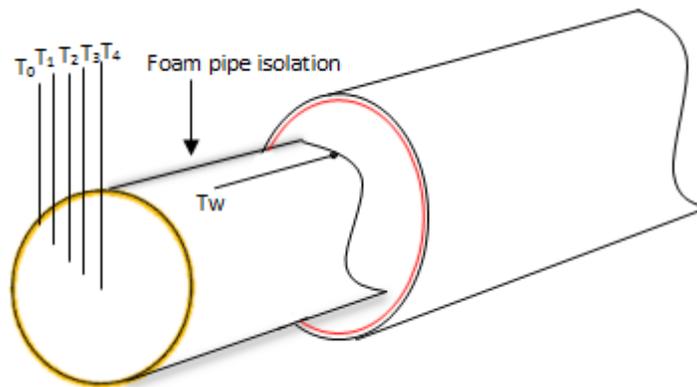


Figure 3-2. Schematic representation of set of thermocouples inserted at different radial directions of the inner pipe (at 12.7, 10.0, 7.0, 4.0, and 1.0 mm from the pipe wall), and thermocouple attached to the pipe's surface to measure the wall temperature.



Figure 3-3. Set of thermocouples inserted at different radial directions at the pipe's exit.
Photo courtesy of author.

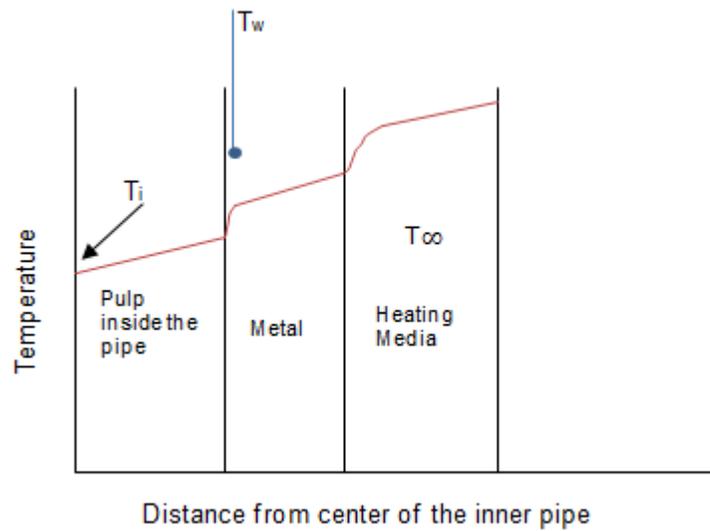


Figure 3-4. Schematic representation of the temperature profile when orange pulp flows in the heating section of a tubular heat exchanger.

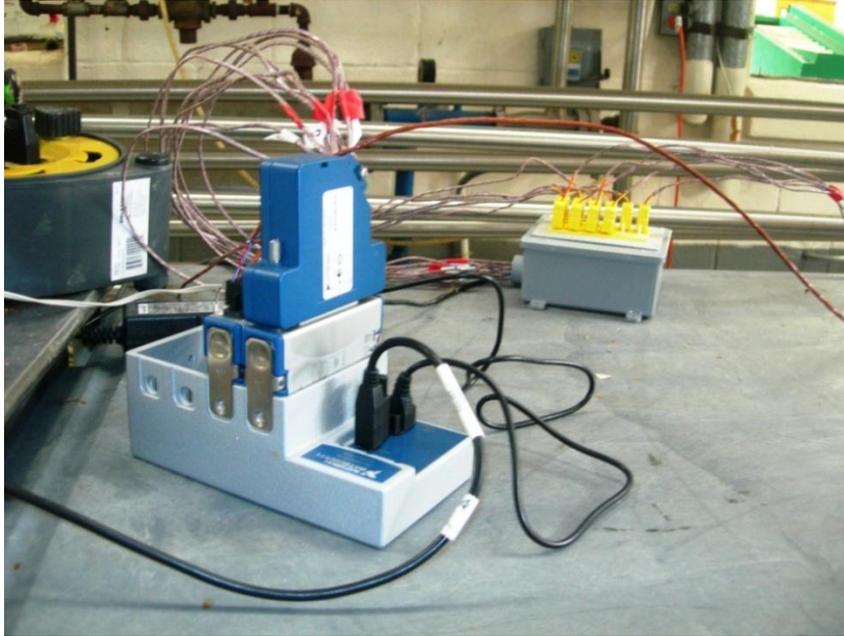


Figure 3-5. Data acquisition board used to record data. Photo courtesy of author.



Figure 3-6. Equipment setup. Photo courtesy of author.

Table 3-1. Experimental flow rates and velocities used for determining the heat transfer coefficients for different pulp concentrations.

Pulp concentration g L ⁻¹	Heating Section		Cooling Section	
	Flow Rate x 10 ⁻⁴ m ³ s ⁻¹	Velocity m s ⁻¹	Flow Rate x 10 ⁻⁴ m ³ s ⁻¹	Velocity m s ⁻¹
516 ± 6 ¹	4.4	0.9	4.4	0.9
	5.3	1.0	5.4	1.1
	6.4	1.3	5.9	1.2
	7.2	1.4	6.3	1.2
	7.9	1.6	7.5	1.5
	8.3	1.6	7.8	1.5
617 ± 7	4.2	0.8	3.8	0.7
	4.5	0.9	3.9	0.8
	4.9	1.0	4.4	0.9
	5.6	1.1	5.3	1.0
	6.4	1.3	5.6	1.1
	7.0	1.4	6.9	1.4
712 ± 12	7.6	1.5	7.3	1.4
	3.9	0.8	2.7	0.5
	4.4	0.9	3.1	0.6
	5.9	1.2	3.7	0.7
	7.4	1.5	6.0	1.2
	8.5	1.7	6.3	1.2
801 ± 13	-	-	6.7	1.3
	2.1	0.4	1.6	0.3
	2.4	0.5	2.1	0.4
	3.5	0.7	2.9	0.6
	4.1	0.8	3.6	0.7
	4.8	0.9	4.8	1.0
	5.1	1.0	-	-

¹ The errors shown for pulp concentration are the correspondent standard deviations.

Table 3-2. Calculated local and overall heat transfer coefficients for different pulp concentrations and velocities, in the heating section of a tubular heat exchanger. Data obtained from regression analysis is also shown.

Pulp concentration g L ⁻¹	Velocity (<i>u</i>) m s ⁻¹	Local heat transfer coefficient (<i>h</i>) W m ⁻² °C ⁻¹	Overall heat transfer coefficient (<i>U</i>) W m ⁻² °C ⁻¹	Slope <i>h</i> / <i>u</i> Intercept <i>h</i> / <i>u</i> R ²	Slope <i>U</i> / <i>u</i> Intercept <i>U</i> / <i>u</i> R ²
516 ± 6 ¹	0.9	4044	2788		
	1.0	5162	3417		
	1.3	5849	4190	Slope 4370 ± 331	Slope 3410 ± 151
	1.4	6414	4718	Interc. 354 ± 440	Interc. -157 ± 200
	1.6	6978	5022	R ² 0.98	R ² 0.99
	1.6	7765	5525		
617 ± 7	0.8	3285	2483		
	0.9	3869	3130		
	1.0	4619	3447	Slope 5615 ± 405	Slope 4582 ± 393
	1.1	5447	3889	Interc. -1092 ± 468	Interc. -1134 ± 455
	1.3	5739	4548	R ² 0.97	R ² 0.96
	1.4	6486	4845		
712 ± 12	1.5	7401	6027		
	0.8	1670	1486		
	0.9	2434	2214	Slope 4693 ± 233	Slope 5262 ± 172
	1.2	3922	3642	Interc. -1725 ± 287	Interc. -2477 ± 212
	1.5	5160	4993	R ² 0.99	R ² 0.99
801 ± 13	1.7	5964	6428		
	0.4	1342	1241		
	0.5	1468	1408		
	0.7	1587	1360	Slope 2024 ± 300	Slope 1704 ± 361
	0.8	2252	2059	Interc. 469 ± 226	Intercept 514 ± 272
	0.9	2348	2070	R ² 0.92	R ² 0.85
	1.0	2549	2301		

¹ The errors shown for pulp concentration are the correspondent standard deviations.

Table 3-3. Calculated local heat transfer coefficients for different pulp concentrations and velocities, in the cooling section of a tubular heat exchanger. Data obtained from regression analysis is also shown.

Pulp concentration g L ⁻¹	Velocity (<i>u</i>) m s ⁻¹	Local heat transfer coefficient (<i>h</i>) W m ⁻² °C ⁻¹	Slope <i>h / u</i> Intercept <i>h / u</i> R ²
516 ± 6 [†]	0.9	2620	Slope 7235 ± 608 Interc. -3826 ± 758 R ² 0.97
	1.1	3979	
	1.2	4273	
	1.2	5105	
	1.5	6518	
	1.5	7757	
617 ± 7	0.7	3158	Slope 1981 ± 201 Interc. 1817 ± 217 R ² 0.95
	0.8	3399	
	0.9	3731	
	1.0	3745	
	1.1	3982	
	1.4	4576	
712 ± 12	1.4	4631	Slope 1273 ± 255 Interc. 1875 ± 258 R ² 0.93
	0.5	2384	
	0.6	2220	
	0.7	2807	
	1.2	3508	
	1.2	3389	
801 ± 13	1.3	3894	Slope 2927 ± 433 Interc. 216 ± 273 R ² 0.94
	0.3	960	
	0.4	1441	
	0.6	1986	
	0.7	2528	
	1.0	2808	

[†] The errors shown for pulp concentration are the correspondent standard deviations.

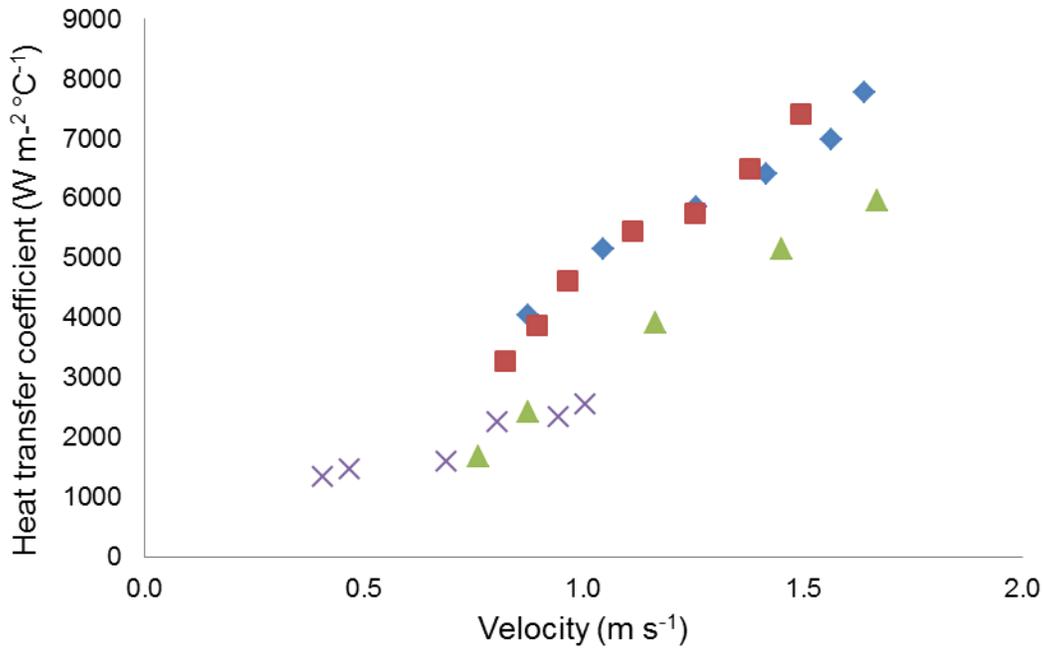


Figure 3-7. Local heat transfer coefficients as function of velocity in the heating section of heat exchanger, for pulp concentrations of 516 (♦), 617 (■), 712 (▲), and 801 (X) g L⁻¹.

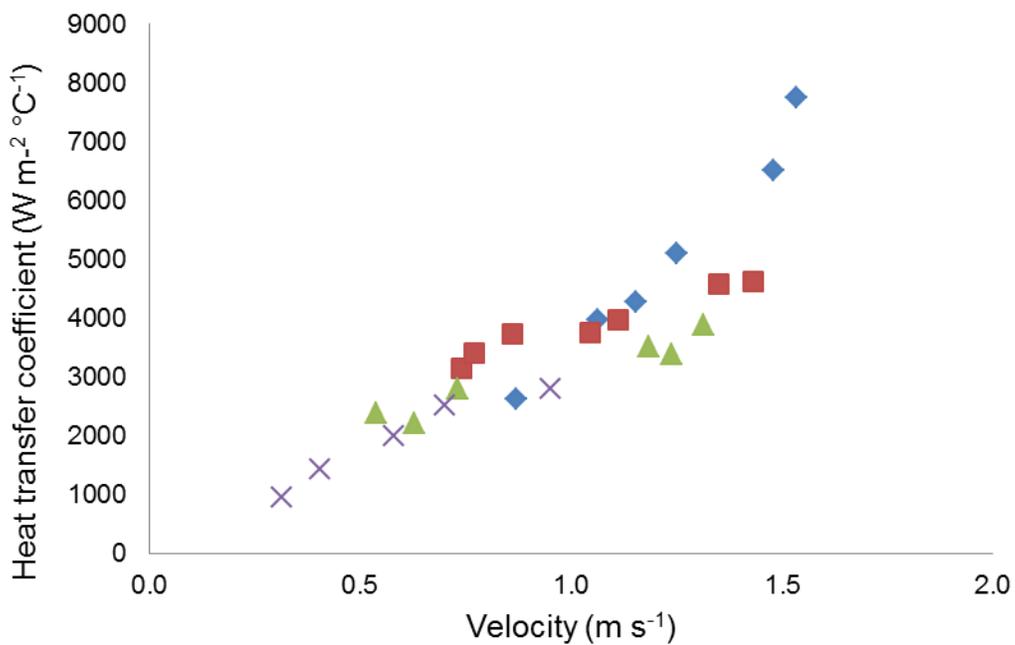


Figure 3-8. Local heat transfer coefficients as function of velocity in the cooling section of heat exchanger, for pulp concentrations of 516 (♦), 617 (■), 712 (▲), and 801 (X) g L⁻¹.

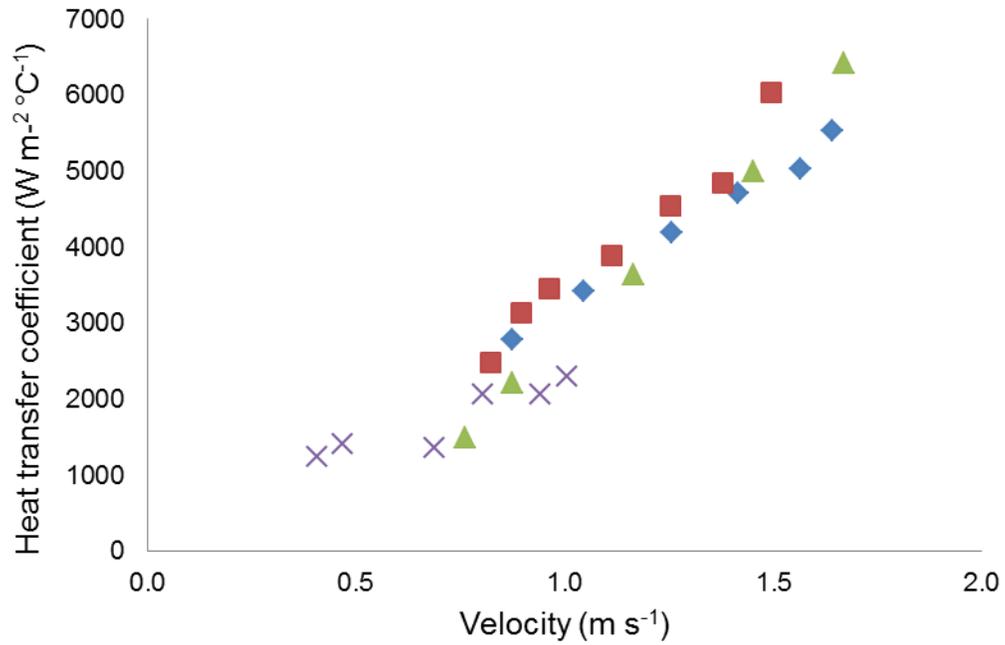
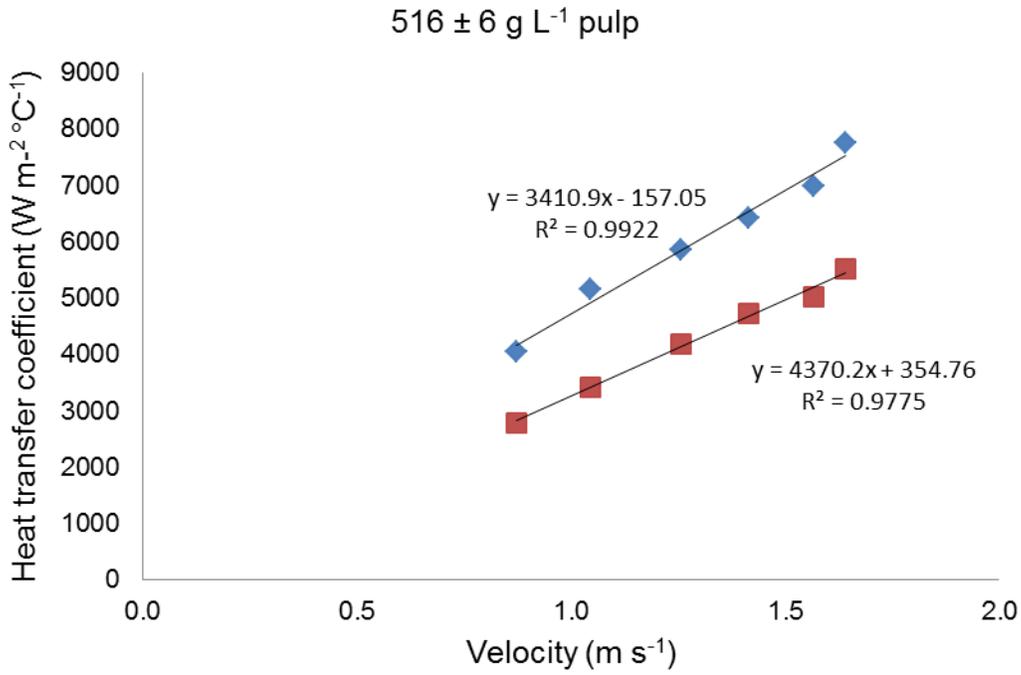
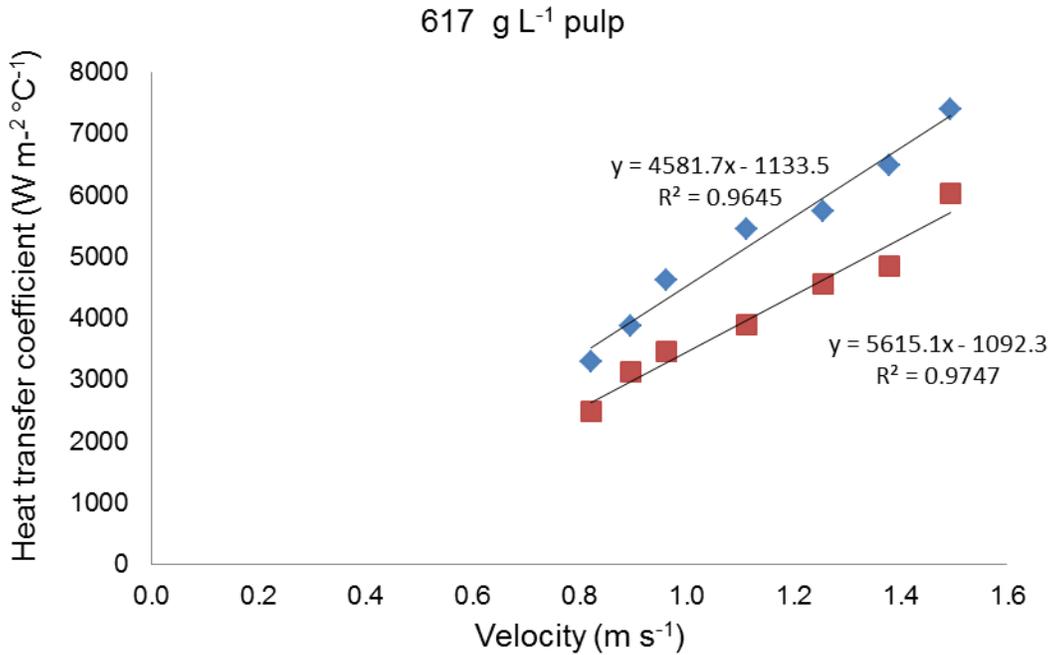


Figure 3-9. Overall heat transfer coefficients as function of velocity in the heating section of heat exchanger, for pulp concentrations of 516 (♦), 617 (■), 712 (▲), and 801 (×) g L⁻¹.

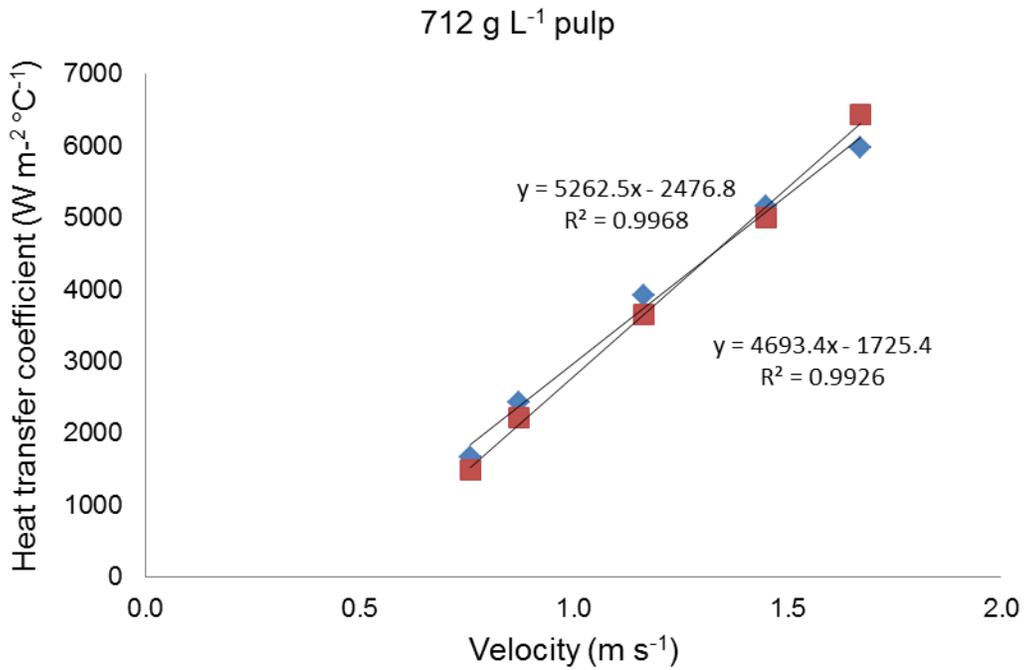


a)

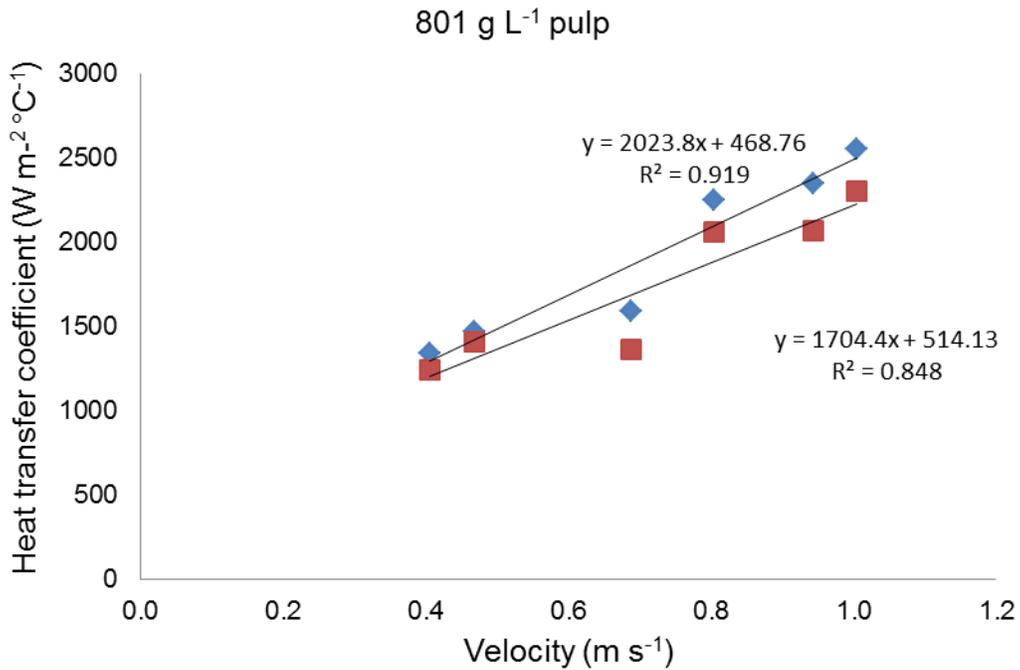


b)

Figure 3-10. Local (♦) and overall (■) heat transfer coefficients as function of velocity in the heating section of heat exchanger, for pulp concentrations of a) 516, and b) 617 g L⁻¹.



a)



b)

Figure 3-11. Local (♦) and overall (■) heat transfer coefficients as function of velocity in the heating section of heat exchanger, for pulp concentrations of a) 712, and b) 801 g L⁻¹.

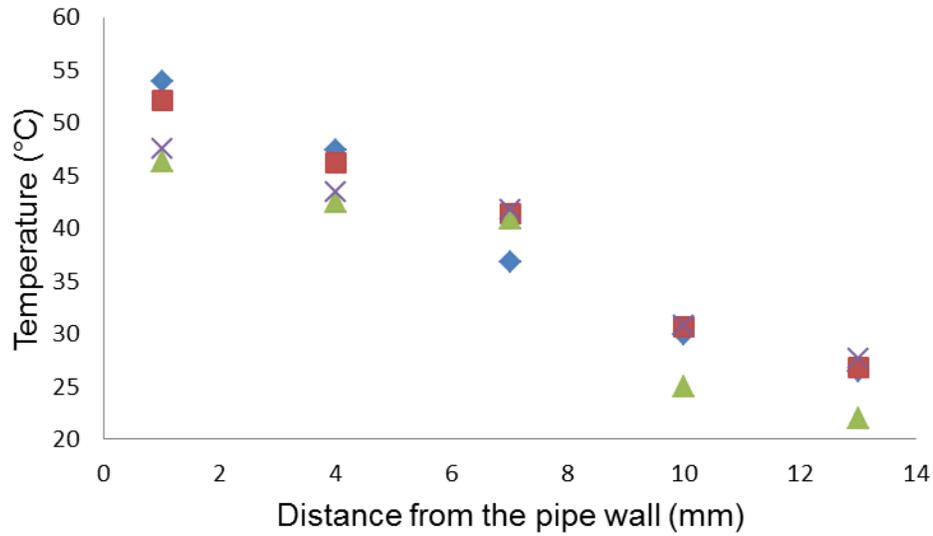


Figure 3-12. Temperature profiles obtained for $516 \pm 6 \text{ g L}^{-1}$ orange pulp concentration in the heating section of a tubular heat exchanger at flow rates of 4.4 (♦), 5.3 (■), 6.4 (▲), and 7.9 (×) $\times 10^{-4} \text{ m}^3 \text{ s}^{-1}$.

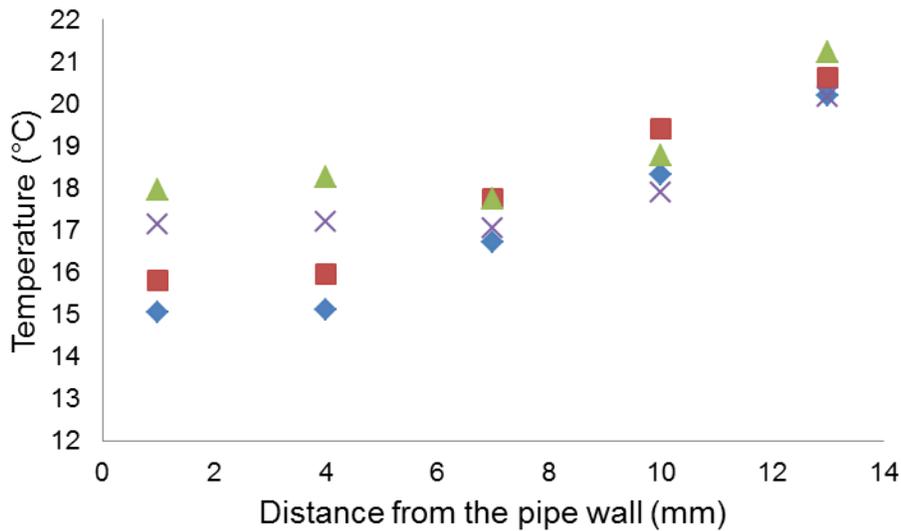


Figure 3-13. Temperature profiles obtained for $516 \pm 6 \text{ g L}^{-1}$ orange pulp concentration in the cooling section of a tubular heat exchanger at flow rates of 4.4 (♦), 5.4 (■), 6.3 (▲), and 7.5 (×) $\times 10^{-4} \text{ m}^3 \text{ s}^{-1}$.

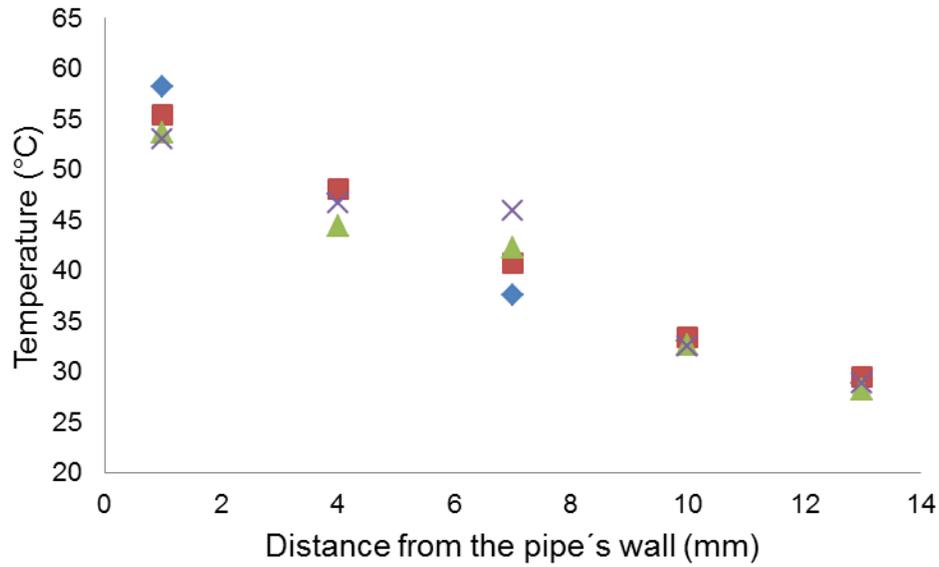


Figure 3-14. Temperature profiles obtained for $617 \pm 7 \text{ g L}^{-1}$ orange pulp concentration in the heating section of a tubular heat exchanger at flow rates of 4.5 (\blacklozenge), 5.6 (\blacksquare), 6.4 (\blacktriangle), and 7.6 (\times) $\times 10^{-4} \text{ m}^3 \text{ s}^{-1}$.

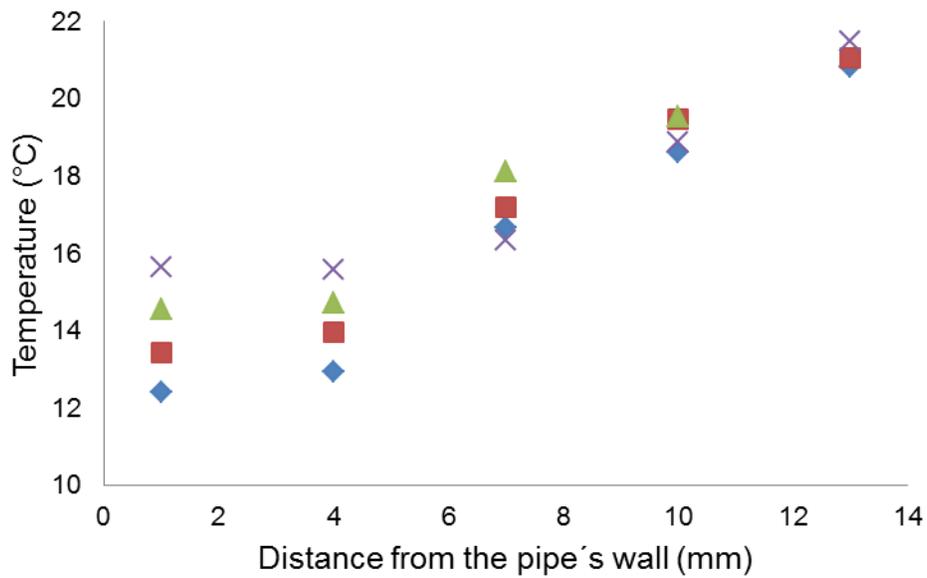


Figure 3-15. Temperature profiles obtained for $617 \pm 7 \text{ g L}^{-1}$ orange pulp concentration in the cooling section of a tubular heat exchanger at flow rates of 3.8 (\blacklozenge), 4.4 (\blacksquare), 5.3 (\blacktriangle), and 6.9 (\times) $\times 10^{-4} \text{ m}^3 \text{ s}^{-1}$.

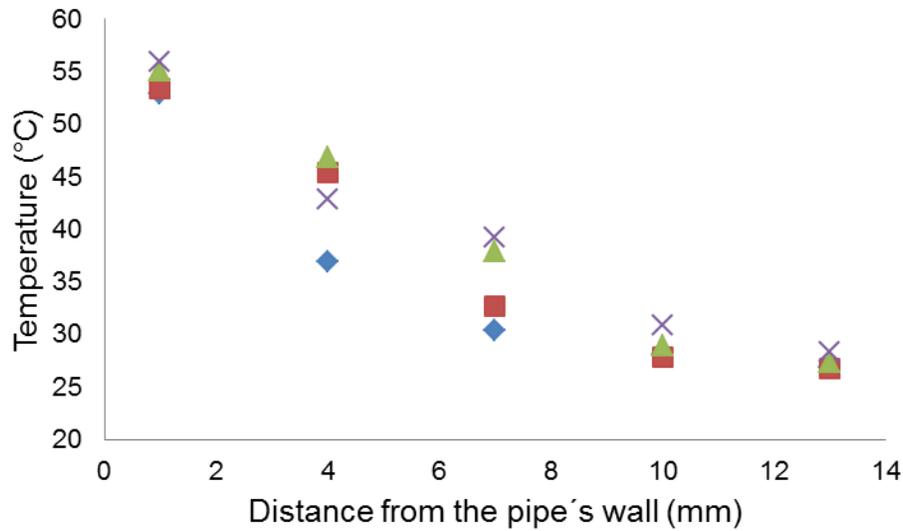


Figure 3-16. Temperature profiles obtained for $712 \pm 12 \text{ g L}^{-1}$ orange pulp concentration in the heating section of a tubular heat exchanger at flow rates of 3.9 (♦), 4.4 (■), 5.9 (▲), and 7.4 (×) $\times 10^{-4} \text{ m}^3 \text{ s}^{-1}$.

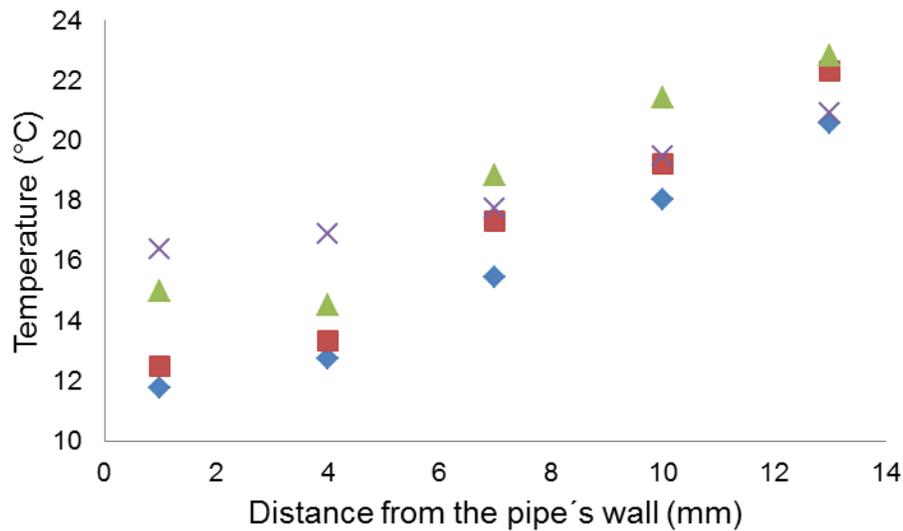


Figure 3-17. Temperature profiles obtained for $712 \pm 12 \text{ g L}^{-1}$ orange pulp concentration in the cooling section of a tubular heat exchanger at flow rates of 2.7 (♦), 3.7 (■), 6.0 (▲), and 6.7 (×) $\times 10^{-4} \text{ m}^3 \text{ s}^{-1}$.

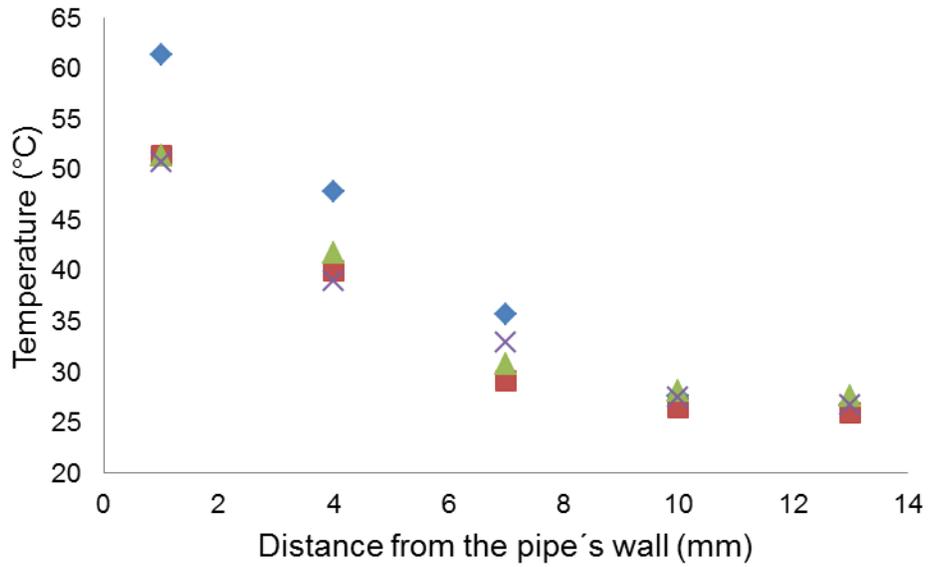


Figure 3-18. Temperature profiles obtained for $801 \pm 13 \text{ g L}^{-1}$ orange pulp concentration in the heating section of a tubular heat exchanger at flow rates of 2.4 (♦), 3.5 (■), 4.1 (▲), and 5.1 (×) $\times 10^{-4} \text{ m}^3 \text{ s}^{-1}$.

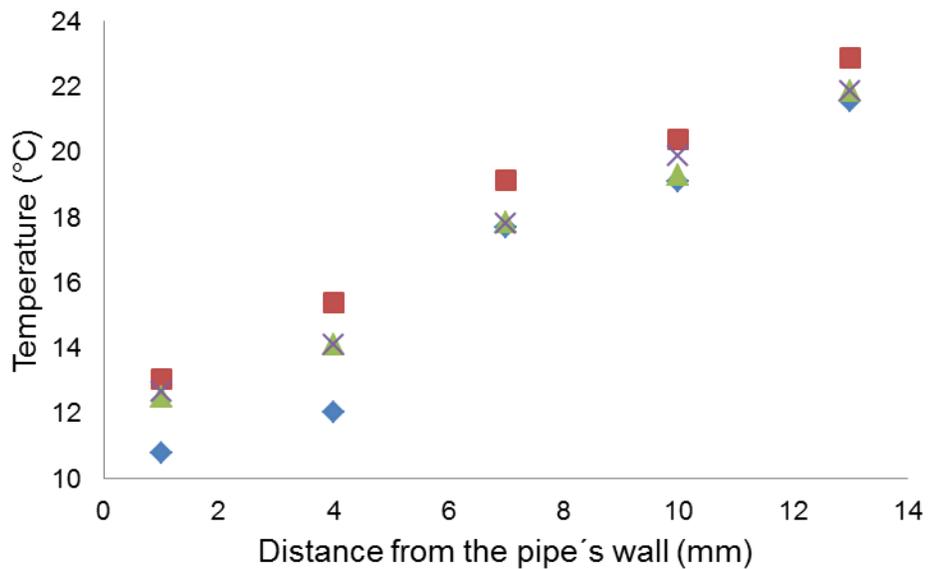


Figure 3-19. Temperature profiles obtained for $801 \pm 13 \text{ g L}^{-1}$ orange pulp concentration in the cooling section of a tubular heat exchanger at flow rates of 2.1 (♦), 2.9 (■), 3.6 (▲), and 4.8 (×) $\times 10^{-4} \text{ m}^3 \text{ s}^{-1}$.

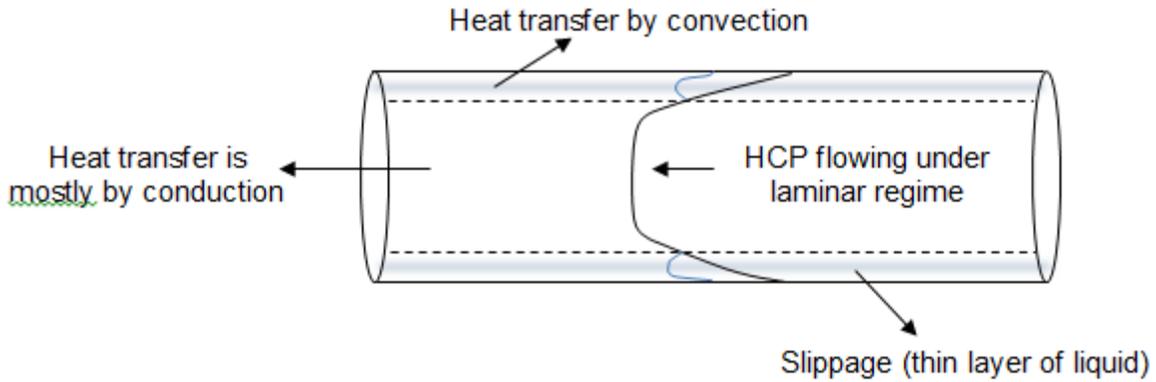


Figure 3-20. Hypothesized mixed flow of HCP. A thin layer of liquid (slippage) was formed close to the pipe surface, where heat was transferred by convection. While a thick plug of pulp flowed under laminar regime and heat was transferred mostly by conduction.

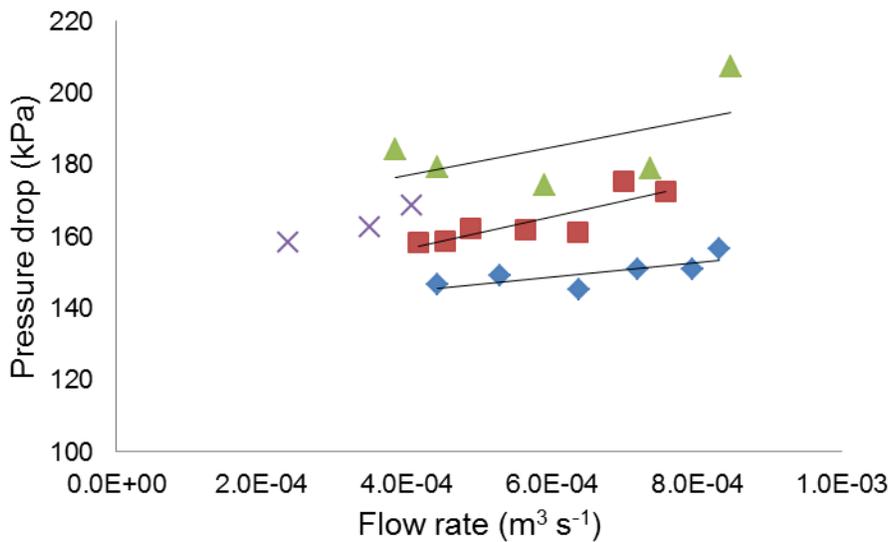


Figure 3-21. Pressure drop as function of flow rate in the heating section of heat exchanger, for pulp concentrations of 516 (◆), 617 (■), 712 (▲), and 801 (×) g L^{-1} .

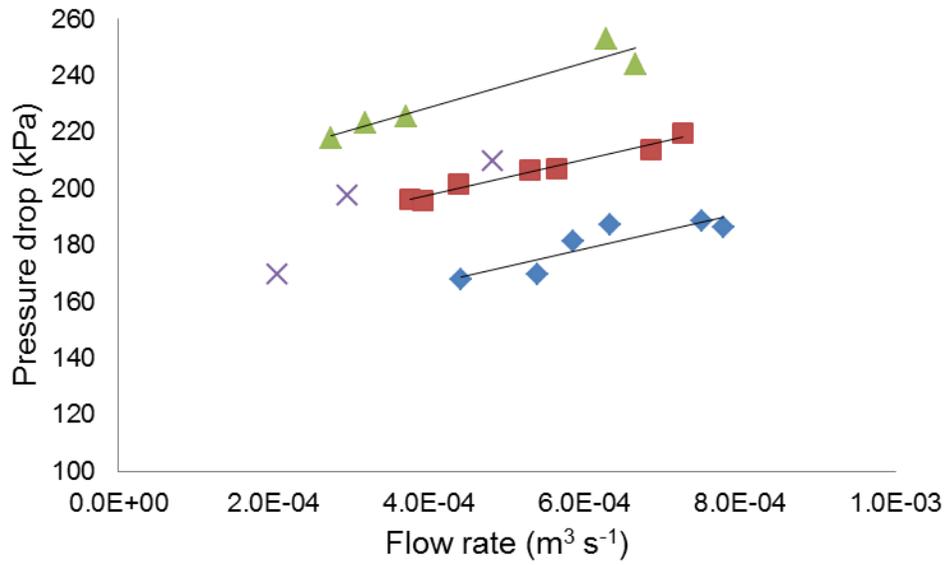
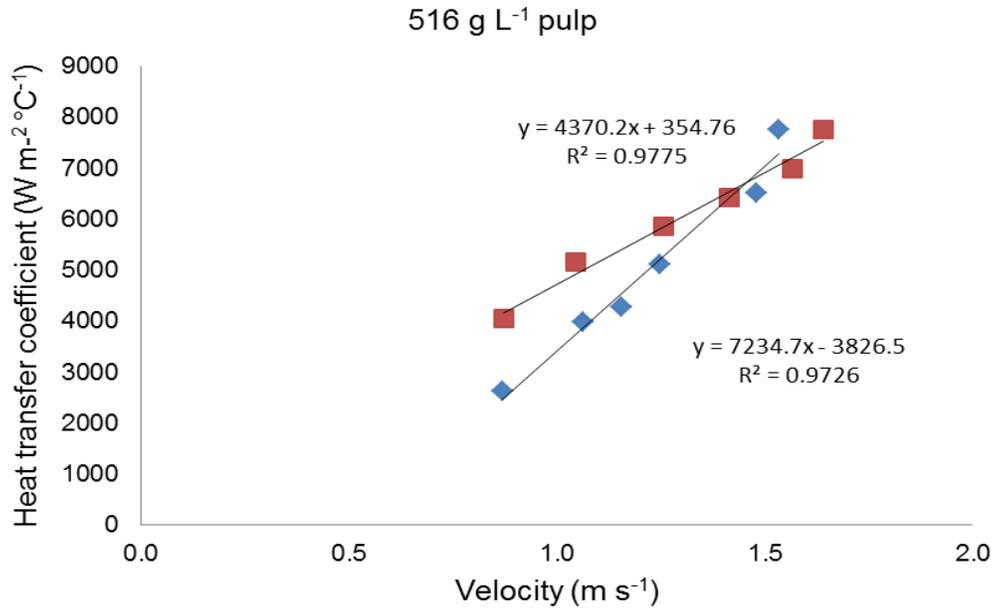
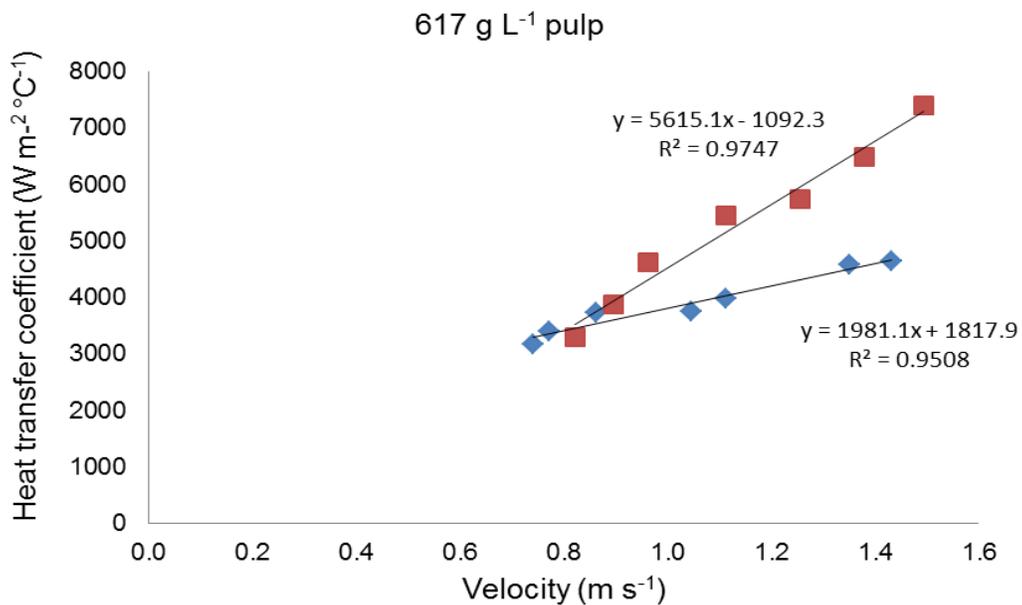


Figure 3-22. Pressure drop as function of flow rate in the cooling section of heat exchanger, for pulp concentrations of 516 (♦), 617 (■), 712 (▲), and 801 (×) g L⁻¹.

APPENDIX A
COMPARISON BETWEEN THE HEAT TRANSFER COEFFICIENTS OBTAINED IN
THE HEATING AND COOLING SECTIONS OF THE HEAT EXCHANGER

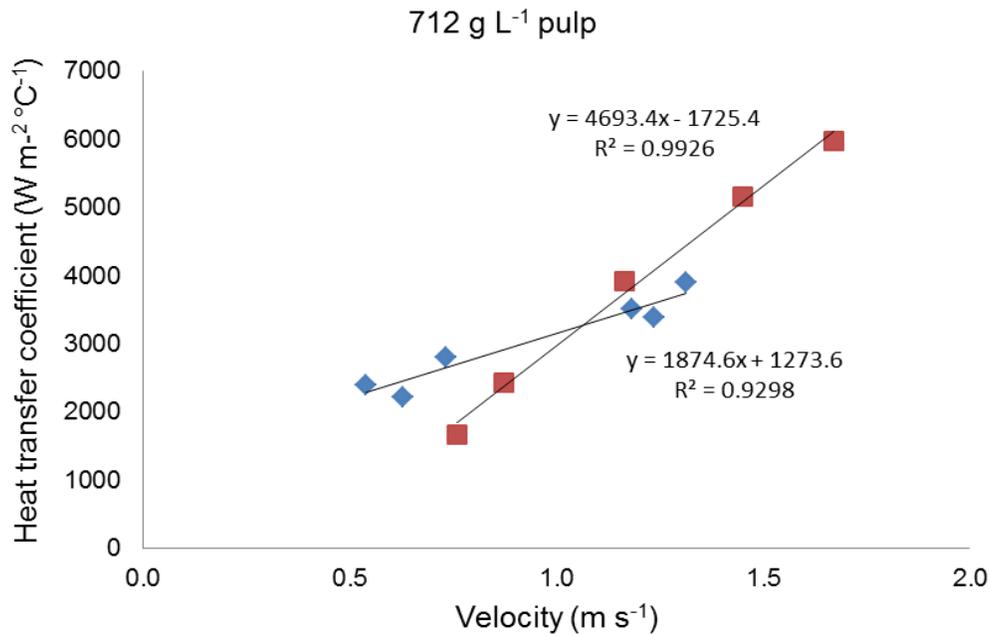


a)

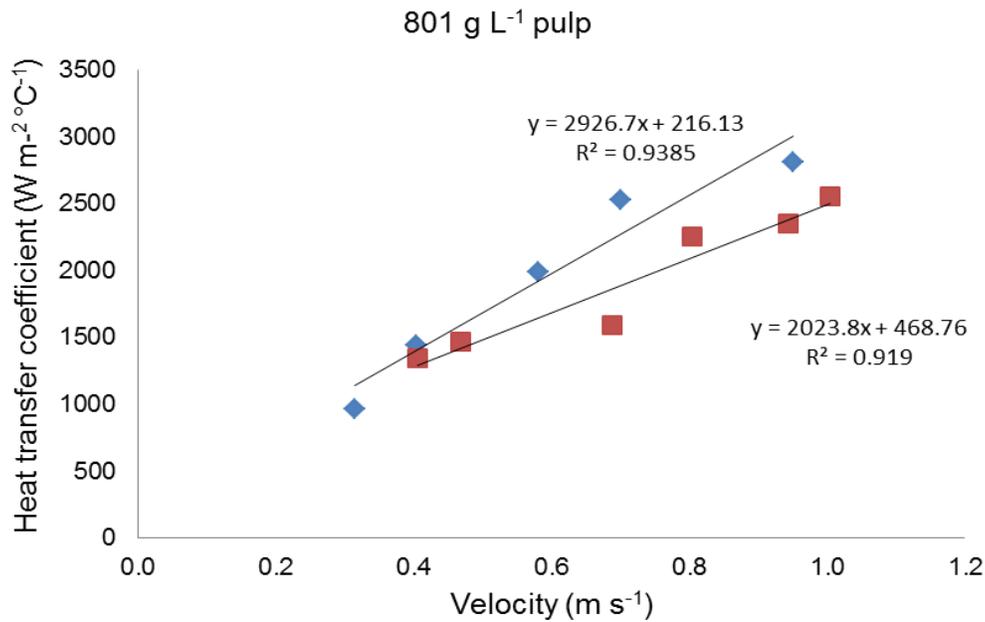


b)

Figure A-1. Heat transfer coefficients as a function of velocity in the heating (■) and cooling (◆) sections of heat exchanger for: a) 516 and b) 617 g L⁻¹ orange pulp concentration.



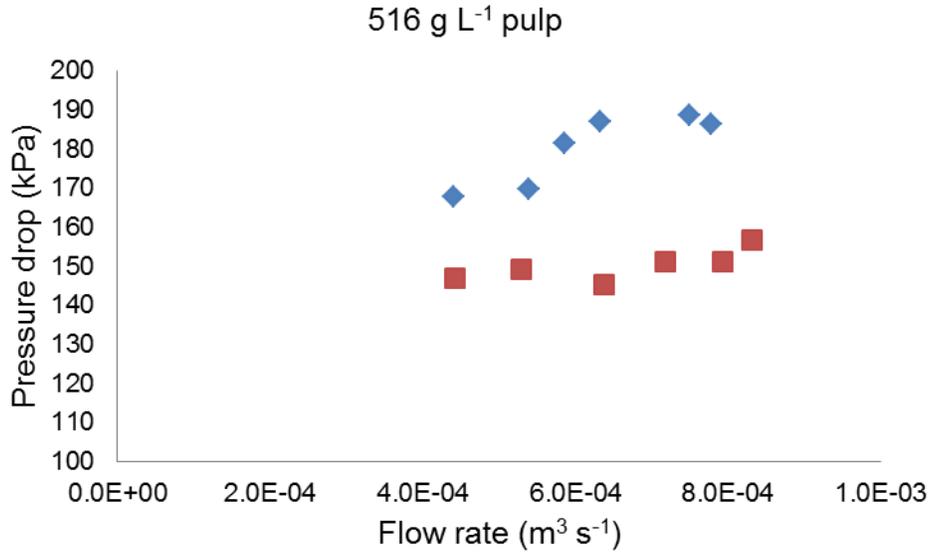
a)



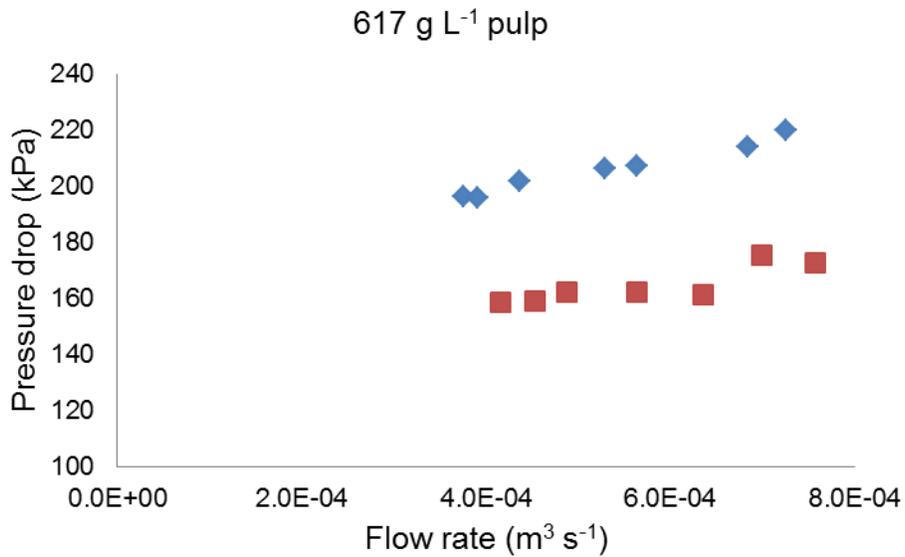
b)

Figure A-2. Heat transfer coefficients as a function of velocity in the heating (■) and cooling (◆) sections of heat exchanger for: a) 712 and b) 801 g L⁻¹ orange pulp concentration.

APPENDIX B
COMPARISON BETWEEN THE PRESSURE DROPS OBTAINED IN THE HEATING
AND COOLING SECTIONS OF THE HEAT EXCHANGER

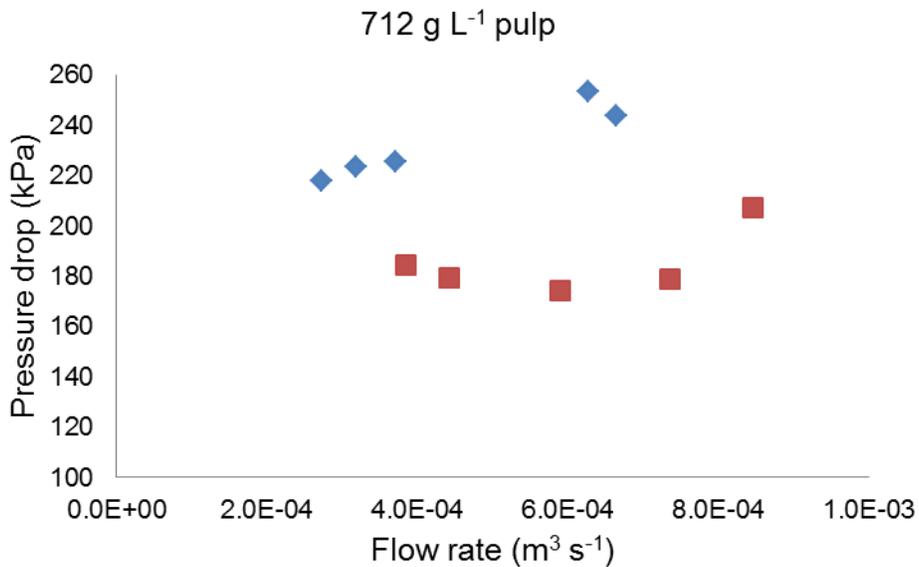


a)

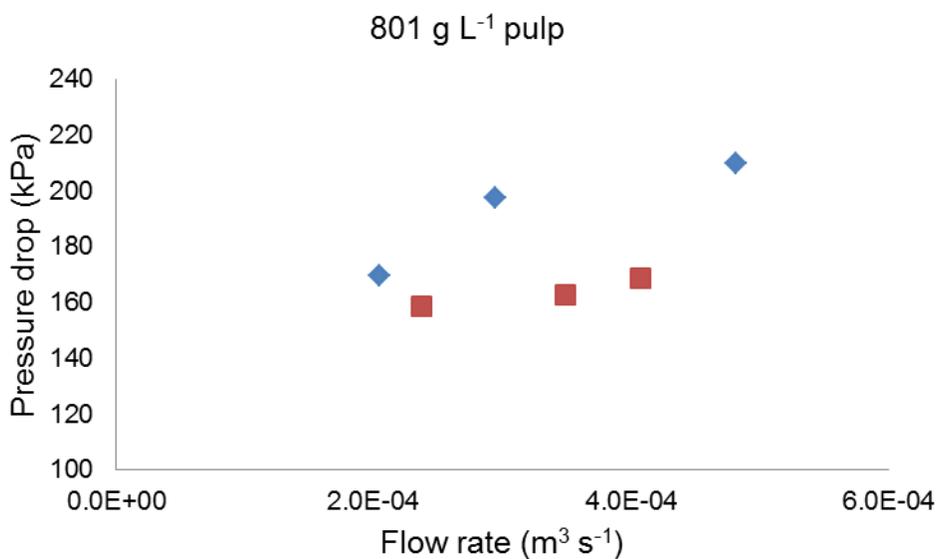


b)

Figure B-1. Pressure drop as a function of flow rate for a) 516, and b) 617 g L⁻¹ pulp concentrations, in the heating (■) and cooling (◆) sections of a tubular heat exchanger.



a)



b)

Figure B-2. Pressure drop as a function of flow rate for a) 712, and b) 801 g L⁻¹ pulp concentrations, in the heating (■) and cooling (◆) sections of a tubular heat exchanger.

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BIOGRAPHICAL SKETCH

Juan Fernando Muñoz was born in Quito, Ecuador. In 2003, he obtained a Food Engineering degree in Universidad San Francisco de Quito. From 2003 to 2010, he worked in the food industry, mainly in the R&D field developing vegetable fats and oils for industrial applications and food products for mass consumption. In 2010, J.F. Muñoz began his graduate studies at University of Florida to pursue a master's degree in Food Science and Human Nutrition. He is expected to complete his studies in August 2012, and intends to return to the industry to work in what he feels more passionate about: Research and development.