27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0393
EXPERIMENTAL STUDY TO ANALYZE THE TEMPERATURE PROFILE OF A MASHING PROCESS

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Abstract. *The present study consists in analyzing the mashing process in a simplified wort recirculation system with the objective of emulating the development of the temperature profile during a laboratory scale mashing. The setup was similar to a heat exchanger recirculating mashing system. An experimental setup was assembled, in which, for temperature control, a thermocouple, process controller and a heating element were used. An additional series of thermocouples were used to obtain the discretized temperature profile, which was later compared with theoretical models to verify whether there is reasonable agreement with a real case, even after applying simplifications. With this work, one is also expected to carry out experimental measurements of fermentable sugars concentrations, and enzymatic activity, such experimental results can be used to estimate kinetic parameters of saccharification models.*

Keywords:*brewing, heat transfer, mashing, numerical method*

1. INTRODUCTION

The purpose of the present study is to describe the evolution of the temperature profile throughout a laboratory-scale mashing process, which is one of the primary phases in beer production, by examining a simplified wort recirculation system. When it comes to the relevance of the work, this is significant due to the important position in the world market that beer production occupies, since beer is one of the oldest and most consumed alcoholic beverages in the world. The process analyzed in this study differs from the traditional mashing process by having an assembly where the wort is constantly recirculated through the porous medium formed by the grain bed. The chosen setup was similar to a heat exchanger recirculating mashing system found on automated medium and small breweries, containing a heat exchanger immersed in a vessel with hot water responsible for heating the wort, a pump for recirculation and the vessel where the grain bed is accommodated. The first step was to produce a plant prototype schematic in the standard format used in industrial processes to show the piping, equipment, and instrumentation of a particular process in an industrial plant. The schematic covers the equipment responsible for stages of mashing. After that an experimental setup was assembled, in which, for temperature control, a thermocouple, process controller and a heating element were used. An additional series of thermocouples were used to obtain the discretized temperature profile, which was later compared with theoretical models to verify whether there is reasonable agreement with a real case, even after applying simplifications. The theoretical models consider a series of hypotheses, such as treating the porous bed of grains as a porous medium, uniform flow velocity and obtain a simple formulation from energy and mass transport equations and their respective boundary conditions.

The studies of Marc *et al.* (1983) and Koljonen *et al.* (1995) were some of the first models describing starch saccharification during traditional mashing. In the aforementioned research and Quintanilha *et al.* (2015), the mashing were carried out with different temperature profiles, however the process mostly takes place at constant temperature. The study of Zamboni *et al.* (2017), investigates heat conduction in a traditional mashing process, where is shown the influence of a variable temperature on the saccharification and enzyme activity. The present paper seeks to study how the temperature develops in a recirculating mashing system and to build a setup that allows in the future experimental measurements of fermentable sugars concentrations, such as dextrins, maltotriose, maltose and glucose, and enzymatic activity, specifically alpha and beta amylase, in addition to estimating parameters of mathematical models that predict such carbohydrates extraction.

2. METHODOLOGY

The heat exchanger recirculating mash system (HERMS) prototype schematic is shown in Fig. 1. The setup is a type of system that uses a pump to recirculate the wort in the mash tun through a heat exchanger. The heat exchanger consists of a metal coil inserted into a reservoir with water. The wort is continuously recirculated and a controller maintains the process temperature close to the setpoint temperature by turning the electrical resistance on and off, which causes a change in the temperature of the water, thus changing the temperature of the coil that exchanges heat with the wort, adjusting mashing temperature. The K-001 vessel is the hot liquor tun, the heat exchanger label is W-001. The P-001 pump is responsible for wort recirculation and the mash lauter tun K-002 is where the mashing effectively occurs. The temperature controller TC-1 is responsible for activating the electric heater as the value of the process variable, in this case the mash temperature, gets closer to or farther from the setpoint temperature.

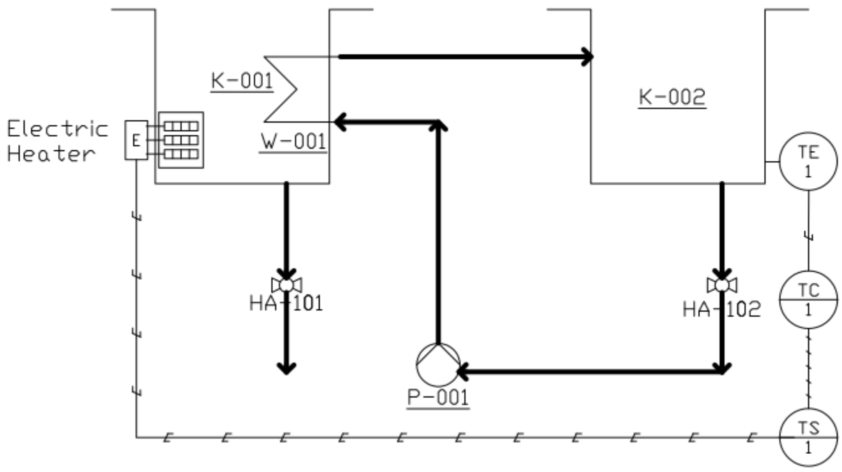

Figure 1. Piping and instrumentation diagram for HERMS prototype.

2.1 Heat Transfer Model

For comparison purposes, a mathematical model is proposed for the temperature profile. The model follows from unidimensional heat equation for fluid flow in a porous medium and simplifying hypotheses such as homogeneous porous medium, uniform flow velocity and insulated reactor wall (Bejan, 2013):

$$(\rho\, c)_b \,\frac{\partial T}{\partial t} + (\rho\, c)_l \, v_z \,\frac{\partial T}{\partial z} \;=\; \frac{\partial T}{\partial z}\left(k_b \,\frac{\partial T}{\partial z}\right) \tag{1}$$

with $(\rho\, c)_b$ and $(\rho\, c)_l$ corresponding to the porous bed and solution thermal capacity respectively, and k_b is porous medium thermal conductivity. Initial and boundary conditions are described as follows:

$$T(z,0) \;=\; T_0, \tag{2}$$

$$k_b \,\frac{\partial T}{\partial z} \;=\; h_{in}\,(T_{in} - T), \qquad \text{for} \quad z = H_b, \tag{3}$$

$$k_b \,\frac{\partial T}{\partial z} \;=\; h_{out}\,(T - T_{out}) \qquad \text{for} \quad z = 0, \tag{4}$$

where h_{in} and h_{out} are convective heat transfer coefficients with the portion of liquid above and below the porous bed respectively. Inlet temperature is set to start from T_0 and reach T_{aq} at the end of the mashing (t_f), according to the following equation:

$$T_{in}(t) \;=\; T_{aq} - (T_{aq} - T_0)\left(\frac{t_f - t}{t_f}\right) \tag{5}$$

The control volume that demonstrates the porous medium, z-coordinate origin and the fluid flow direction is represented in the Fig. 2.

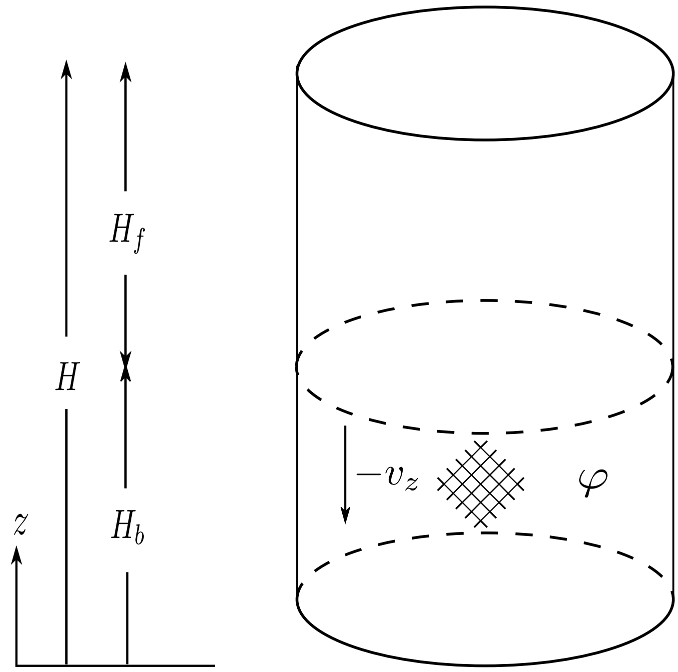

Figure 2. Mash tun control volume.

2.2 Materials and Methods

The equipment used in the project are listed in Tab. 1. The hot liquor and mash tuns are aluminum vessels, however globe valves, temperature sensor well and other connections are made of stainless steel. The experimental setup is shown in Fig. 3.

Table 1. List of equipment used in the project.

Equipment	Tag	Specification
Hot liquor tun	K-001	45.2l aluminum
Mash lauter tun	K-002	38l aluminum
Heat exchanger	W-001	Aluminum coil
Pump	P-001	Chugger brewing pump
HLT Valve	HA-101	Stainless steel valve
MLT Valve	HA-102	Stainless steel valve
Temperature sensor	TE-1	J type thermocouple
Temperature controller	TC-1	programmable temperature controller

The process variable was monitored by a J type thermocouple, this signal is sent to a temperature controller that compares the process value with the setpoint and activates or deactivates the heating resistance. The pump that keeps the wort circulating and promotes heat exchange between the wort and the hot liquor tun water is kept operating throughout the process. The thermocouple, control panel and temperature sensor position are shown in Fig. 4. A heating resistance of 1500 W was selected as control element, Fig. 5 presents both the mash lauter tun and the hot liquor tun with the heat exchanger.

The experiment was carried out with operational conditions and raw materials whose properties are summarized in the table 2. Water initial temperature and setpoint temperature were respectively 26°C and 57°C. An Arduino Uno microcontroller board and Max31856 module with K type thermocouple were utilized for data acquisition, in this case mash lauter tun outlet temperature as a function of time. The experimental temperature profile of the HERMS prototype was then be compared to mathematical models in order to verify how well the model was able to estimate the temperature evolution during the mashing process.

Figure 3. Experimental setup.

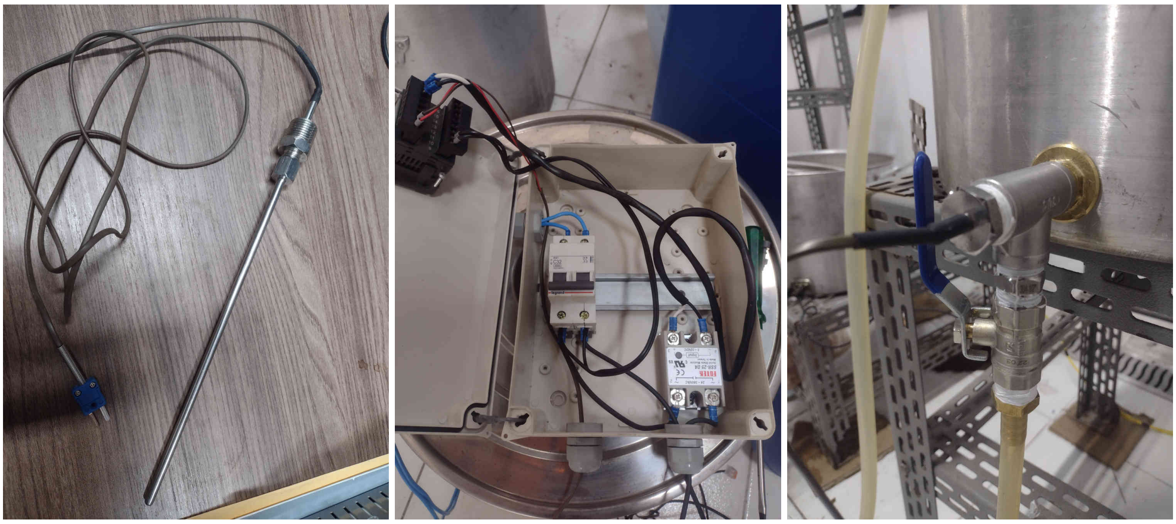

Figure 4. Control elements.

3. RESULTS AND DISCUSSION

In this preliminar experiment the tests were carried out using common Pilsner barley grain, obtaining wort with physical characteristics similar to those obtained in traditional mashing processes. The iodine test was carried out later to verify mash conversion of starch into sugar, obtaining a certain degree of conversion despite not being completely efficient, possibly due to the duration of the process. Alongside the experimental study, the model was used to estimate the temperature profile numerically. The simulation result derived from the solution of the transport equations by the finite volume method are shown in the graph of Fig. 6. According to the model, the temperature does not change for the first few minutes, then rising in the meantime until it reaches the hot liquor tun's temperature.

The collection of measured data that depicts the temperature profile evolution as a function of time at the outlet of the control volume is shown in Fig. 7, where it can be seen that in this first run the temperature increases slowly. The controller was configured to act with discrete PID heating control. The result obtained was different from the expected for this type of control, showing a slow evolution of the measured temperature. It is possible that this is due to an undersizing of the heating element, oversized mash lauter tun volume or incorrect pump flow. More tests will be performed modifying these variables to validate the hypotheses.

4. SUMMARY AND CONCLUSIONS

The study objective was to propose a temperature profile investigation of the recirculating mashing process. Since the reaction kinetics during mashing are highly reliant on the temperature, it is natural to investigate in a more detailed way how temperature behaves during the process. The study employs a simplified model of heat transfer in porous media and compares it to experimental data acquired from a lab-built HERMS prototype. The preliminary analysis are made

Figure 5. Hot liquor tun and mash lauter tun.

Table 2. Barley grain properties and operational conditions.

Description	Symbol	Value	Reference
Barley grain density	ρ_r	618 kg/m^3	Mujumdar (2014)
Barley grain thermal capacity	c_r	1245 J/kg/K	Mujumdar (2014)
Barley grain thermal conductivity	k_r	13.14 J/min/m/K	Mujumdar (2014)
Water volume	V	2.0×10^{-2} m^3	-
Malt mass	M	5.0 kg	-
Initial temperature	T_0	26 °C	-
Set point temperature	T_{aq}	57 °C	-
Malt-to-water ratio	r_g	4 l/kg	-
Flow velocity	v_z	0.015 m/min	-
Liquid column height	H_f	0.05m	-

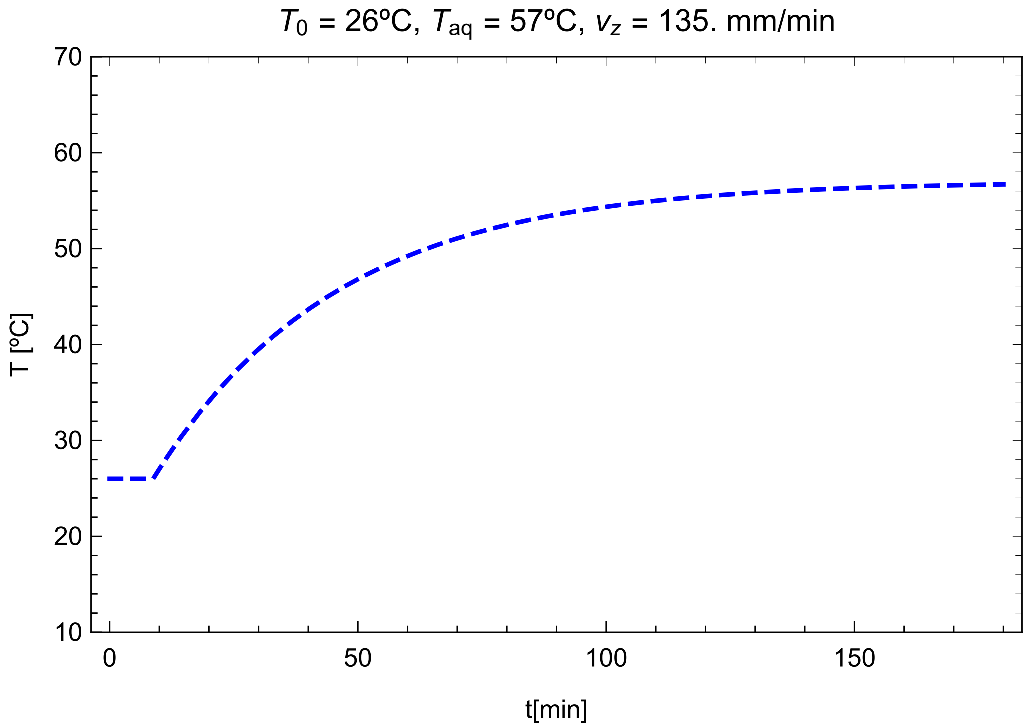

Figure 6. Model prediction of outlet temperature as function of mashing duration.

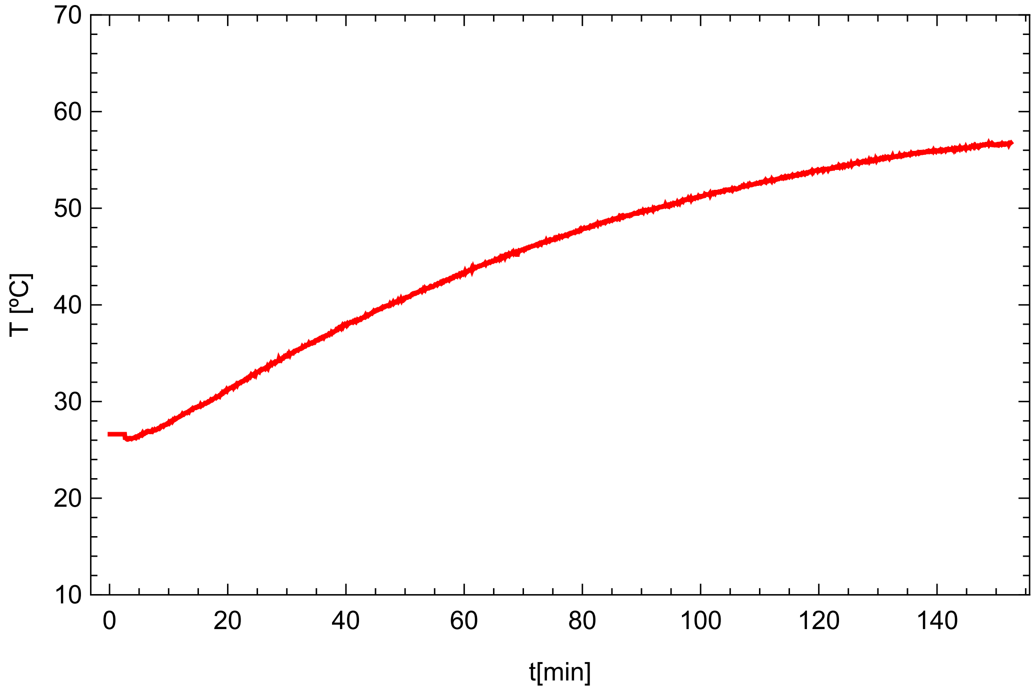

Figure 7. Experimental outlet temperature as function of mashing duration.

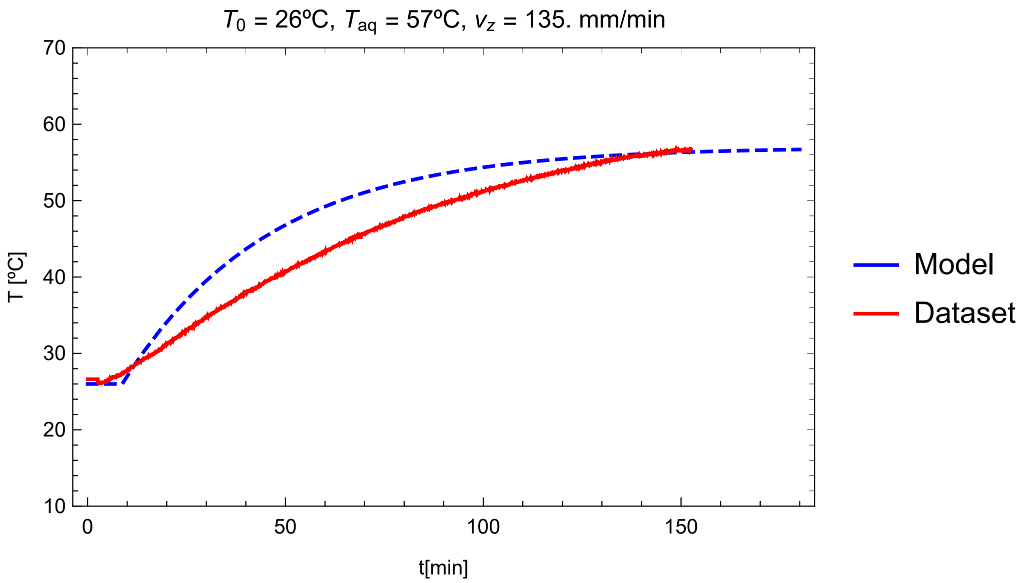

Figure 8. Comparison between model and measured outlet temperature.

in a recirculation system built with all the operational and control characteristics according to the project, including the use of raw material, in this case Pilsner barley malt. A reasonable agreement between the mathematical model and the simulation could be noticed in this first stage, however it is still necessary to carry out a greater number of tests, with a longer duration and different operational parameters, such as machinery sizing and pump flow. These results aim to understand the minutiae of the mashing process in recirculation systems and aid in the design and improvement of such equipment.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support provided by CAPES, CNPq, FAPERJ and PMN.

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