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INFLUENCE OF THE HEAT TRANSFER CHARACTERISTICS OF A HELICAL COIL ON THE WATER CONSUMPTION AND COOLING TIME OF HOME-BREWED WORT

Rogério Gomes de Oliveira
Patrick Nikson Rubbo
Federal University of Santa Catarina; Sustainability and Energy Department; Science, Technology and Health Centre; Araranguá, SC, Brazil, 88905-120
rogerio.oliveira@ufsc.br, patrickrubbo@hotmail.com

Abstract. *The cooling process of home-brewed wort by a helical coil heat exchanger was mathematically modeled and simulated to identify the influence of the coil configuration on the water consumption and cooling time. The model assumed that tap water flowed inside the helical coil, which was immersed in a cylindrical vessel containing wort. The cooling process was simulated considering wort stirred or still, and coils with different diameter, tube length and tube diameter. The results indicated that shorter cooling time does not always led to smaller water consumption, as not only the heat transfer characteristics were affected by the heat exchanger configuration, but also the water flow rate, due to changes in the head loss. For similar helical coil configuration, wort agitation reduced the cooling time and water consumption in between 25 % and 63 %. The minimum cooling time and water consumption were obtained with coils that has 20 cm diameter and tube 12 m long. The coil which the tube had nominal diameter of 5/8" produced the smallest cooling time, whereas the smallest water consumption, with the wort stirred was obtained with coil which nominal diameters was 1/2". Considering intermittent wort agitation during 1 minute for every 5 minutes without agitation, 25 L of wort can be chilled from 100 ºC to 26 ºC in about 30 minutes, using tap water at 25ºC and a 20 cm diameter helical coil with tube 12 m long and nominal diameter of 1/2".*

Keywords: *Beer, Heat Exchanger, Helical Coil, Wort.*

1. INTRODUCTION

Home-brewing has been practiced for more than 2000 years, and greatly increased in England and USA, from the 1970´s due to the beer consumers campaigns and changes in legislation, which legalized this activity (Bates, 1993). In Brazil, several regional associations, called ACERVAS, join home brewers to exchange information. The popularity of this subject can be seem by the intense exchange of information in internet based forums like http://www.homebrewtalk.com.br/forum.php. In this regard, scientific research can also help improving the brewing technology and provide information for such a public. Scientific journals like the Journal of the Institute of Brewing, the Journal of the ASBC, and the Journal of Brewing and Distilling publish research related to beer production, but mainly focusing in the beer chemistry and microbiology. Relative less research have focused on the beer process, which are usually scattered in food engineering, chemical engineering and applied heat transfer journals, as the pasteurization studies of Augusto *et al.* (2010) and Bhuvaneswari and Anandharamakrishnan (2014) or the heat integration studies of Tokos *et al.* (2010) and Sturm *et al.* (2013). Hence, as a contribution to the brewing process technology, this work presents a numerical study about the influence of helical coil heat exchanger configuration on the water consumption and cooling time of the home-brewed wort.

2. MATERIAL AND METHOD

The cooling process of wort around an helical coil heat exchanger was modeled and simulated in the software Matlab®. The simulation procedures and mathematical model are presented in the following subsections.

2.1 Simulation procedures

Initially, 18 different helical coils were simulated and analyzed with the wort still and 12 different helical coils were simulated and analyzed with the wort stirred. In all these situations, the initial and final wort temperatures were, respectively, 100 ºC and 30 ºC. The characteristics of the helical heat coil that varied were the coil diameter (D_{HC}), the tube outer diameter (d_{Out}), and tube length (L). The dimensions for these variables are shown in Tab. 1. The values of tube outer diameter correspond to those of commercial cooper tubes with nominal diameters of 3/8”, 1/2” and 5/8”. Regardless the tube outer diameter, the wall thickness was constant and equal to 0.79 mm.

Table 1. Helical coil dimensions.

Coil diameter (cm)	Length (m)	Tube outer diameter (mm)
20	4	9.52 (3/8”)
30	8	12.7 (1/2”)
-	12	15.87 (5/8”)

When the wort was still, external heat transfer occurred by natural convection, whereas when the wort was stirred, we assumed the presence of a 6 blades turbine with diameter (d_T) equal to 40 % of the vessel diameter and rotating (n) at 45 rpm. This rotation condition is similar to that encountered when the wort is manually rotated by a mash paddle. The cooling process of the stirred wort with helical coil that had nominal tube diameter of 3/8” was not simulated due to restrictions of the Nusselt correlation chosen for the heat transfer coefficient on the coil external surface.

The simulations of the different cooling processes aimed to identify which dimensions for the helical coil resulted in the smallest cooling period and the smallest water consumption.

Once these dimensions were identified, we conducted other two types of simulations: in the first one, we compared the cooling time and water consumption using helical coils with similar prices but different tube length and diameter, whereas in the second one, we compared the cooling time and water consumption when the wort was either still, or continuously stirred or intermittently stirred.

2.2 Mathematical model for heat transfer and flow rate

The heat transfer mathematical model was build upon heat transfer correlations available in the literature, whereas the flow model was based on the extended Bernoulli equation with the friction factors for the head loss obtained from the literature. Both models were combined in a single code and solved with the following assumptions:

- a helical coil heat exchanger was placed inside a cylindrical vessel containing the wort;
- the wort volume at 20 ºC was 25 L;
- the inner diameter of the vessel was 0,36 m and the height of the wort inside the vessel depended on the volume occupied of the helical coil, which was a function on the helical tube external diameter and length;
- the height of the helical tube and the height of the wort at 20 ºC were the same;
- the wort physical properties like specific mass (ρ), specific heat (Cp), thermal conductivity (λ), viscosity (μ) and Prandlt (Pr) were assumed equal to those of a sucrose solution 12 ºBx, and they were obtained from the literature (Darros-Barbosa *et al.* 2003; Werner *et al.* 2007; Chenlo *et al.* 2004)
- tap water flowed inside the helical pipe and came from a water tank above the helical coil;
- the inlet temperature of the tap water into the helical coil was 25 ºC;
- tap water flow rate was a function of an elevation head of 3.5 m and head loss that varied depending on the helical coil configuration;
- the head loss up to the helical coil heat exchanger entrance was calculated considering that the sum of the minor loss coefficients was 2.7 and that the frictional loss occurred due a flow within within a 7 m long smooth plastic tube with internal diameter of 25 mm;

The friction factor (f) for the plastic tube was calculated with Eq. (1) (Von Bernuth and Wilson, 1989), whereas for the helical coil, it was calculated with Eq. (2) when the Reynolds number (Re) was smaller than the critical Reynolds number (Re_C) and with Eq. (3) (Ito, 1959) when Re was higher than Re_C.

$$f = \frac{0.345}{\mathrm{Re}^{0.25}} \qquad (1)$$

$$f = \frac{64}{\left(1 - \left\{1 - \left[\frac{11.6}{\mathrm{Re} \times \left(\frac{d_{In}}{D_{HC}}\right)^{0.5}}\right]^{0.45}\right\}^{2.22}\right) \times \mathrm{Re}} \tag{2}$$

$$f = 4\left[\frac{0.076}{\mathrm{Re}^{0.25}} + 0.00725\left(\frac{d_{In}}{D_{HC}}\right)^{0.5}\right] \tag{3}$$

Where d_{In} is the internal diameter of the coil tube, D_{HC} is the coil diameter, and Re_C was calculated with Eq. (4) (Ito, 1959).

$$\mathrm{Re}_C = 20000\left(\frac{d_{In}}{D_{HC}}\right)^{0.32} \tag{4}$$

When the wort was still, natural convection occurred at the external coil surface, and the heat transfer coefficient (h_o) was calculated from the Nusselt correlation presented by Prabhanjan *et al.* 2004 and shown in Eq. (5).

$$Nu_o = 2.0487 \times Ra^{0,1768} \tag{5}$$

Where Ra is the Rayleigh number. The characteristic length for Nu_o and Ra was calculated with the normalized diameter. The normalized diameter was obtained by assuming the coil as a cylinder, and then, dividing the outer surface area of this cylinder by the tube length.

For the simulations considering stirred wort, the external heat transfer coefficient (h_o) was calculated with the Nusselt correlation proposed by Havas *et al.* (1987) and shown in Eq. (6).

$$Nu_o = 0.187 \times \mathrm{Re}_O^{0.688} \times \mathrm{Pr}^{0.36} \times \left(\frac{\mu}{\mu_w}\right)^{0.11} \times \left(\frac{d_{Out}}{D_{HC}}\right)^{0.62} \tag{6}$$

Where Re_O is the modified Reynolds number, as shown in Eq. (7), the subscript w is related to the properties at wall temperature.

$$\mathrm{Re}_o = \frac{d_{Out} d_T n}{\nu} \tag{7}$$

The internal heat transfer coefficient (h_i) was calculated with Eq. (8) (Mori and Narayama, 1967) if Re was larger than Re_C and with Eq. (9) (Xin and Ebadian, 1997) if Re was smaller than Re_C.

$$Nu_i = \left[\frac{\mathrm{Re}^{5/6}}{41} \times \left(\frac{d_{In}}{D_{HC}}\right)^{1/12}\right]\left\{1 + \frac{0.061}{\left[\mathrm{Re} \times \left(\frac{d_{In}}{D_{HC}}\right)^{2.5}\right]^{5/6}}\right\}\mathrm{Pr}^{0.4} \tag{8}$$

$$Nu_i = \left[2.153 + 0.318 \times \left(\mathrm{Re} \sqrt{\frac{d_{In}}{D_{HC}}} \right)^{0.643} \right] \mathrm{Pr}^{0.177} \tag{9}$$

The wort temperature was calculated with Eq. (10), which was obtained in this work, with the assumption that the wort temperature varied uniformly and exchange heat only with the fluid that flowed inside the helical coil.

$$T_{W,t+\Delta t} = \left(T_{W,t} - T_{In} \right) e^{\left\{ \frac{\Delta t \left[1 - \exp\left(\frac{1}{R \dot{m} Cp} \right) \right] \frac{\dot{m} Cp}{m_W CP_W}}{\exp\left(\frac{1}{R \dot{m} Cp} \right)} \right\}} + T_{In} \tag{10}$$

Where, $T_{W,t}$ is the wort temperature at an instant t, $T_{W,t+\Delta t}$ is the wort temperature at an instant $t+\Delta t$, Δt is the time interval between two wort temperatures, R is the helical coil thermal resistance which depends on the internal (h_i) and external (h_o) heat transfer coefficients, as shown in Eq. (11), $\dot{m}$ is the water mass flow inside the helical coil, Cp is the water specific heat, m_W is the mass of wort inside the vessel and Cp_W is the wort specific heat.

$$R = \frac{1}{A_o h_o} + \frac{1}{A_i h_i} + \frac{\ln\left(\frac{d_{Out}}{d_{In}} \right)}{2 \pi L \lambda_{Cooper}} \tag{11}$$

Where A_o and A_i are, respectively, the external and internal helical coil area and λ_{Cooper} is the cooper thermal conductivity.

Every time that the wort temperature was calculated, all temperature dependent parameters of Eq. (10) were recalculated, and they were used to obtain the next wort temperature.

3. RESULTS

The cooling times for the difference cooling processes are shown in Fig. 1, whereas the water consumptions are shown in Fig. 2.

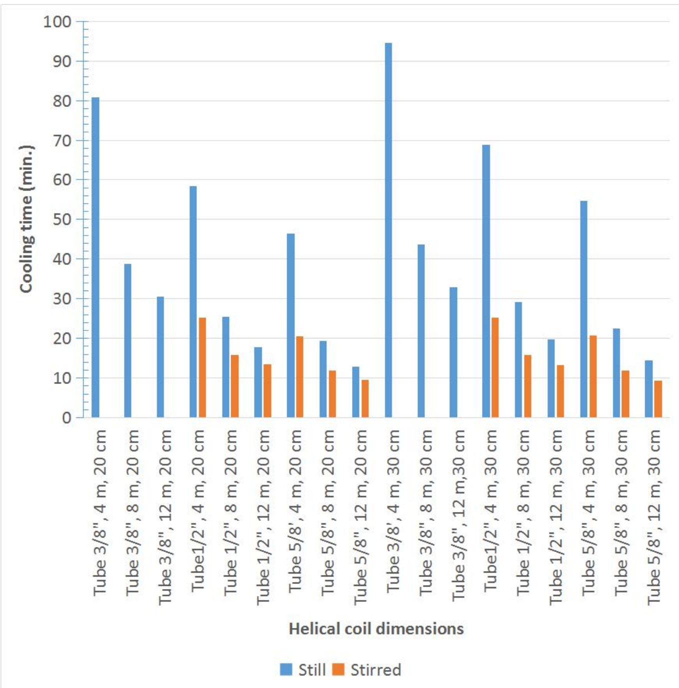

Figure 1. Cooling time for different cooling process and coil configuration.

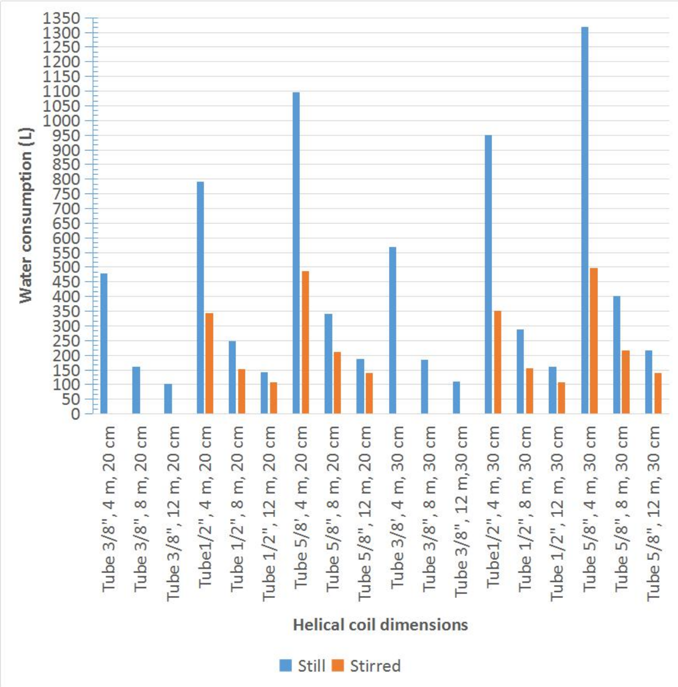

Figure 2. Water consumption for different cooling process and coil configuration.

Obviously, stirring the wort reduced cooling time and water consumption. For similar helical coil configuration, agitation reduced the cooling time and water consumption in between 25 % and 63 %.

The helical heat exchanger that caused the highest cooling time had 30 cm diameter, tube 1/2" and was 4 m long. The smallest cooling time when the wort was stirred and still, was, respectively, 9 minutes and 13 minutes. They both occurred with the coil that had 20 cm diameter, was 12 m long, and tube 5/8". The water consumptions at these conditions were, respectively, 138 L and 187 L. Moreover, the smallest cooling time with the wort still was 14 % of the highest value, whereas with the stirred wort, the smallest cooling time was 37 % of the highest time.

Regarding the water consumption without agitation, the smallest value was 102 L and occurred with the coil that had 20 cm diameter, was 12 m long with tube 3/8", in a cooling process that lasted 31 minutes. We do not have results for the stirred wort and tube 3/8" due to restrictions applied to the utilization of the chosen Nusselt correlation. Hence, with stirred wort, the smallest water consumption was 106 L and also occurred with the coil 12 m long that had 20 cm diameter, but the tube had nominal diameter of 1/2". This cooling process lasted 13 minutes.

The highest water consumption occurred, regardless the wort condition, occurred with helical tube that had 30 cm diameter, tube 5/8"and was 4 m long.

The highest water consumption was 13 times the smallest water consumption when the wort was still, whereas with the stirred wort, the highest value was 5 times the smallest value.

From the above results, we decided to run a new set of simulations where we compared the cooling time and water consumption of helical coils with different tube diameter and length but with price similar to the price of the helical coil with 20 cm diameter, 12 m long and tube 5/8". The price of the tube 5/8" was assumed as 31 % higher than that of the tube 1/2", whereas the price of the tube 3/8" was assumed as 26 % lower than the price of the tube 1/2". These price assumptions were based on the mass per unit length of each tube diameter. Hence, a tube 21.3 m long with 3/8" diameter and a tube 15.7 m long with 1/2" diameter would have price similar to that of a tube 12 m long with nominal diameter of 5/8".

When the cooling process occurred without wort agitation, it took 15 minutes to chill the wort with the tube 15.7 m long and 31 minutes with the tube 21.3 m long. The water consumption with these tubes were, respectively, 106 L and 76 L. When the cooling process occurred with stirred wort, it took 13 minutes to chill the wort with the tube 15.7 m long and the water consumption was 89 L. We do not have results for the cooling process with stirred wort and tube 3/8", due to restrictions applied to the utilization of the Nusselt correlation. Hence, for all conditions simulated, the helical coil whose tube was 12 m long and had diameter of 5/8" resulted in the shortest cooling time even when compared to other helical coils with similar price. However, coils with similar price but smaller diameter resulted in less water consumption. In the condition without wort agitation, the cooling process with the coil 15.7 m long and tube 1/2" consumed 81 L less water and was only 2 minutes longer than the cooling process with the coil 12 m long and tube 5/8". In the condition with stirred wort, the cooling process with the coil 15.7 m long and tube 1/2" consumed 49 L less water and was only 4 minutes longer than the cooling process with the coil 12 m long and tube 5/8".

Regarding the condition for the smallest water consumption, the configurations of helical coil that consumed less water were also those with the smallest price. The results indicated that when coils with similar length but different diameters were compared, the reduction of the tube diameter also resulted in a reduction of the water consumption, even if the cooling period was longer.

The cooling process of small beer batches in home-brewing usually occurs with intermittent manual agitation under short periods. The wort should be cooled to the smallest possible temperature, which is slightly above the tap water temperature used in the cooling process. Hence, to conclude this work, we simulated the cooling process of the wort down to a temperature 1 ºC higher than the assumed tap water temperature considering that the wort could be either still, or continuously stirred or intermittently stirred, with agitation occurring for 1 minute after every 5 minutes that it remained still. The helical coils configuration chosen had 20 cm diameter with tube 12 m long, and tube diameter of 1/2” or 5/8”. The water consumption in these cooling process are shown in Fig. 3.

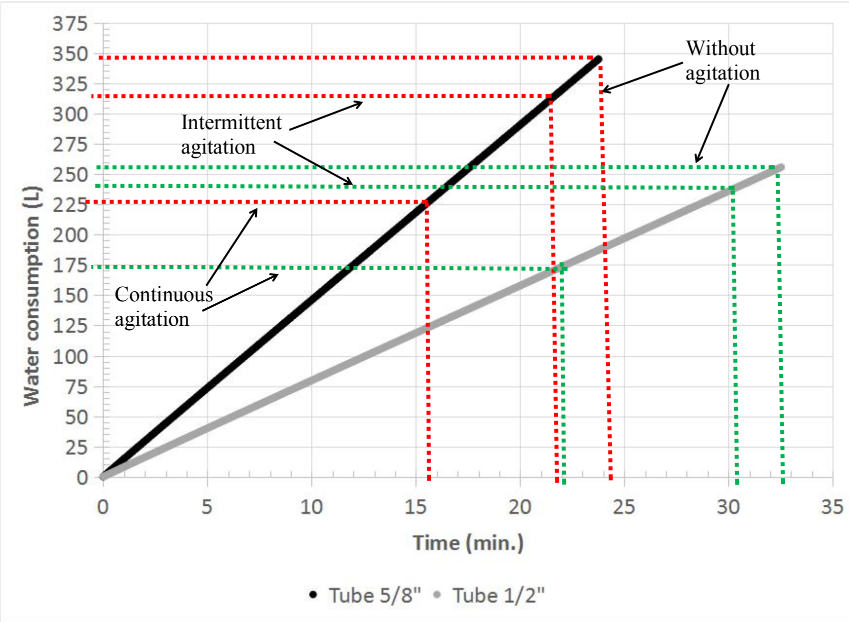

Figure 3. Water consumption for helical coil with diameter of 20 cm, 12 m long.

Considering that even without agitation, the cooling process with the helical coil that had tube with 1/2” was less than 35 minutes, it is advised to use coil with this diameter, to consume the smallest possible water quantity.

4. CONCLUSIONS

Continuous wort agitation reduced the cooling time and water consumption in between 25 % and 63 %, for similar helical coil configuration. The cooling process with the helical coil that had 20 cm diameter with tube 12 m long and nominal diameter of 5/8” resulted in the shortest cooling time to reduce the wort temperature. However, the smaller water consumption was obtained with similar coils that had smaller tube diameter.

Considering that even without wort agitation, the cooling process with the helical coil that had tube with 1/2” was close to 30 minutes, it is advised to use coil with this diameter to ensure a cooling process within a reasonable period, and with little water consumption.

5. REFERENCES

Augusto, P.E.D., Pinheiro, T.F., Cristianini, M., 2010. “Utilização de fluidodinâmica computacional (CFD) na avaliação da pasteurização de cervejas: efeito da orientação da lata”. *Ciência e Tecnologia de Alimentos*, Vol. 30, p. 980-986.

Bates, R.P., 1993. “Home beer making”, in: Gump, B.H., Pruett, D.J. (Eds.), *Beer and Wine Production: Analysis, Characterization and Technological Advances.* American Chemical Society, Washington.

Bhuvaneswari, E., Anandharamakrishnan, C., 2014. “Heat transfer analysis of pasteurization of bottled beer in a tunnel pasteurizer using computational fluid dynamics”. *Innovative Food Science and Emerging Technologies*, Vol. 23, p. 156-163.

Chenlo, F., Moreira, R., Pereira, G., 2004. "Kinematic viscosity of aqueous solutions of several sugars with sodium chloride: correlation with concentration and temperature". *The Ibero-American Journal of Rheology*, Vol. 4, p. 1-6.

Darros-Barbosa, R., Balaban, M.O., Teixeira, A.A., 2003. "Temperature and concentration dependence of density of model liquid foods". *International Journal of Food Properties*, Vol. 6, p. 1-20.

Ito, H., 1959. "Friction factors for turbulent flow in curved pipes". *Transactions of the American Society of Mechanical Engineers,* Vol. 81, p. 123-132.

Prabhanjan, D.G., Rennie, T.J., Raghavan, G.S.V., 2004. "Natural convection heat transfer from helical coiled tubes". *International Journal of Thermal Sciences*, Vol. 43, p. 359–365.

Sturm, B., Hugenschmidt, S., Joyce, S., Hofacker, W., Roskilly, A.P., 2013. "Opportunities and barriers for efficient energy use in a medium-sized brewery". Applied Thermal Engineering, Vol. 53, p. 397-404.

Tokos, H., Pintarič, Z.N., Glavič, P., 2010. "Energy saving opportunities in heat integrated beverage plant retrofit". Applied Thermal Engineering, Vol. 30, p. 36-44.

Von Bernuth, R.D., Wilson, T., 1989. "Friction factors for small diameter plastic pipes". *Journal of Hydraulics Engineering*, Vol. 115, p.183-192.

Werner, M., Baars, A., Werner, F., Eder, C., Delgado, A., 2007. "Thermal conductivity of aqueous sugar solutions under high pressure". *International Journal of Thermophysics*, Vol. 28, p. 1161–1180.

White, C.M., 1929. "Streamline flow through curved pipes". *Proceedings of the Royal Society of London. Series A*, Vol. 123, p. 645-663.

Xin, R.C., Ebadian, M.A., 1997. "The effects of Prandtl numbers on local and average convective heat transfer characteristic in helical pipes". *Journal of Heat Transfer*, Vol. 119, p. 467-473.

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