DOI: 10.4025/actascitechnol.v32i2.8273

Heat and mass transfer during the warming of a bottle of beer

Cláudio Vinicius Barbosa Monteiro, Aderson Roberto Righetto, Leonardo César de Sousa, Paulo Roberto Paraíso and Luiz Mario de Matos Jorge*

*Departamento de Engenharia Química, Universidade Estadual de Maringá, Av. Colombo, 5790, 87020-900, Maringá, Paraná, Brazil. *Author for correspondence. E-mail: lmmj@deq.uem.br*

ABSTRACT. The warming of a bottle of beer during a Friday evening happy hour directly involves transport phenomena, such as mass transfer due to condensation of air humidity on the bottle surface and heat transfer from the ambient to the bottle, which occurs by free convection and water condensation. Both processes happen simultaneously and are directly associated with the heat and mass transfer coefficients involved, which are affected by the ambient humidity and temperature. Several runs were made in several ambient conditions by exposing a cold bottle of beer to varied temperature and humidity and measuring the temperature of beer and the mass of water condensed on the bottle surface over time. From these measures, a theoretical and experimental methodology was developed and applied for the evaluation of the heat and mass transfer coefficients that govern this process. Both the relative humidity and ambient temperature exert a significant influence on the convective heat transfer coefficient. However, the mass transfer coefficient is affected only by the temperature.

Key words: heat and mass transfer coefficients, condensation, natural convection, beer.

RESUMO. Transferência de calor e massa durante o aquecimento de uma garrafa de cerveja. O aquecimento de uma garrafa de cerveja num “happy-hour” de sexta a tarde envolve diretamente os fenômenos de transferência de massa, devido à condensação da umidade do ar na superfície da garrafa, e de transferência de calor do meio para a garrafa, que ocorre por convecção natural e por condensação de vapor de água. Ambos os processos ocorrem simultaneamente e estão diretamente associados aos coeficientes de transferência de calor e massa envolvidos na dinâmica destes fenômenos e sofrem influência direta da umidade e temperatura ambientes. Neste contexto, efetuaram-se ensaios em diversas condições de temperatura e umidade ambientes, expondo-se uma garrafa de cerveja gelada ao ambiente e medindo-se a temperatura da cerveja e a massa de água condensada ao longo do tempo. A partir destas medidas, desenvolveu-se uma metodologia teórico-experimental que proporcionou a determinação dos coeficientes de transferência de calor e massa que regem este processo. Constatou-se que tanto a umidade relativa quanto a temperatura ambiente exercem influência significativa sobre o coeficiente de transferência de calor por convecção. Entretanto, o coeficiente de transferência de massa sofre influência apreciável apenas da temperatura.

Palavras-chave: coeficientes de transferência de calor e massa, condensação, convecção natural, cerveja.

Introduction

Brazil is one of the largest consumers of beer in the world. Therefore, pleasing the final consumer is a task that requires knowledge of the market and technical knowledge of how the product behaves in different ambient conditions.

The warming of beer is a known undesirable effect for the consumer. Knowing its mechanisms and identifying its main causes are key to appropriately tackling this problem.

The warming of a bottle of beer is thought to be due mainly to two heat transfer processes, natural convection and condensation, which are influenced mainly by the air temperature and relative humidity.

Natural convection heat transfer always occurs from a body immersed in a stagnant fluid whose temperature is different from that of the body, such as a bottle of beer in the ambient. Due to the different temperatures of the air and the bottle surface, the density of the air near the bottle changes, resulting in a descending movement of the colder and heavier air near the bottle surface.

The determination of the heat exchange rate requires knowing the natural convection heat transfer coefficient. For practical applications, we can use Newton’s Law of Cooling (KREITH, 2003), Equation 1.

The heat and mass transfer phenomena are frequently associated and may occur in common daily situations, such as the warming of a bottle of beer, in which both phenomena are simultaneous until the system reaches thermodynamic equilibrium.

$$q_{conv} = h_{conv} A_0 (T_S - T_\infty) \quad (1)$$

Condensation occurs when air with a certain amount of humidity makes contact with the cold surface of the bottle of beer. From this point on, a liquid film forms and flows continuously on the surface (INCROPERA; DAVID, 2003).

The liquid film is formed due to the mass transfer from the water in the air to the surface of the bottle. This process is called convective mass transfer and is described by an equation similar to Newton's Law of Cooling, (CREMASCO, 2002), Equation 2.

$$N_A = K_m (C_{AP} - C_{A\infty}) \quad (2)$$

Mass transfer by natural convection occurs due to the difference in water concentration between the bottle surface and the surrounding gas. In turn, the concentration of water on the bottle surface can be evaluated using saturation pressures obtained by Antoine's equation (SMITH et al., 2000) and the appropriate coefficients.

Parallel to the mass transfer, heat is transferred by condensation, as is described by Equation 3. The heat transfer rate on the surface can also be evaluated using Equation 4, if the water condensation rate (m_{cond}) is known.

$$q_{cond} = h_{cond} A_0 (T_s - T_\infty) \quad (3)$$

$$q_{cond} = m_{cond} \Delta H_{cond} \quad (4)$$

According to Fortes et al. (2006), in most processes the condensation heat transfer has a greater magnitude than the convective heat transfer.

A theoretical-experimental methodology has been developed to evaluate the heat and mass transfer coefficients in the initial instants of the warming of a bottle of beer, in which the condensation heat transfer prevails, and to verify the influence of ambient temperature and humidity on the heat and mass transfer coefficients.

Material and methods

Experimental apparatus

In this work, the experimental module illustrated in Figure 1 was used, which is constituted of a bottle of beer and a plastic tray placed under the bottle of beer, which served as a condensate collector. A Gehaka analytical balance (1 ± 0.01 g), a graduated mercury thermometer (-10 to 60°C) set on a rubber stopper, and a stopwatch were also used.

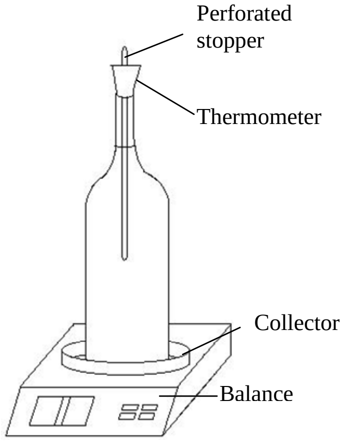

Figure 1. Scheme of the experimental module.

Experimental procedure

A full bottle of beer with the thermometer-stopper was placed in a refrigerator and kept there until it reached the temperature of -2°C.

The full bottle with the thermometer was taken to the balance room and the bottle surface was wiped dry. The bottle was placed in the condensate-collecting tray in the balance plate and the balance and the stopwatch were reset.

From this point on, the temperature and accumulated condensate mass were measured in regular intervals of time corresponding to 0.5°C until the system reached room temperature.

The ambient temperature, relative humidity, and pressure were measured simultaneously.

Several assays were performed to estimate the influence of the ambient temperature and humidity on the process in a wide range of ambient temperature and relative humidity conditions (Table 2).

Determination of K_m and h_{cond}

The mass of condensed water was correlated by fitting a polynomial of appropriate order as a function of time, M(t).

The condensate flow rate (m_{cond}) can thus be evaluated by deriving M(t) in relation to time, as shown in Equation 5.

$$m_{cond} = \frac{d(M(t))}{dt} \quad (5)$$

The condensation heat transfer coefficient (h_{cond}) can be determined from the condensate mass flow rate (m_{cond}) by equaling Equations 3 and 4, and Equation 6.

$$h_{cond} = \frac{m_{cond}\,\Delta H_{cond}}{A_0(T_\infty - T_S(t))} \quad (6)$$

In turn, the molar rate of condensation of water on the bottle surface (m_{cond}/PM_{H2O}) is equal to the mass transfer rate from the air to the surface, ($N_A A_0$), which gives Equation 7.

$$N_A = \frac{m_{cond}}{PM_{H2O}A_0} \quad (7)$$

The substitution of Equation 7 in Equation 2 gives Equation 8 and the value of K_m.

$$K_m = \frac{m_{cond}}{A_0 PM_{H2O}\left[C_{AP}(t) - C_{A\infty}\right]} \quad (8)$$

Both $C_{A\infty}$ and $C_{AP}(t)$ were obtained with Equations 9 and 10, while the water saturation pressures were estimated with Antoine's equation (Equation 11).

$$C_{A\infty} = UR\frac{P_{Asat}}{RT_\infty} \quad (9)$$

$$C_{AP}(t) = \frac{P_{Asat}}{RT(t)} \quad (10)$$

$$\log(P_{Asat}) = A - \frac{B}{T + C} \quad (11)$$

Contribution of q_{cond} to q_{total}

The heat transferred to the bottle by convection was calculated using the empiric Equation 12, as proposed by Fortes et al. (2006).

$$q_{conv} = 0.0002624\ \frac{T_s^{\,2}}{2} - T_s T_\infty \quad (12)$$

Considering that the total heat received by the bottle of beer (q_{total}) is the sum of q_{conv} and q_{cond}, the total percentage of heat received by the bottle by convection (q_{cond}) in relation to the total heat (q_{total}) can be estimated using Equation 13.

$$q_{cond}(\%) = \frac{q_{cond}}{q_{conv} + q_{cond}}100 \quad (13)$$

Results and discussion

As previously mentioned, the condensation heat (q_{cond}) may contribute to the heat received by the bottle of beer to a larger extent than the heat received by convection (q_{conv}).

To determine these parameters, Table 1 was constructed using Equations 4, 12, and 13. The percent contribution of the condensation heat in relation to the total heat involved in the bottle warming process over time was thus estimated.

Table 1. Heat rates involved in the warming of the bottle of beer.

Time (min.)	q_{cond} (J s^{-1})	q_{total} (J s^{-1})	q_{cond} (%) (J s^{-1})
0	3.356	3.363	99.78
0.5	3.311	3.318	99.80
1	3.266	3.272	99.82
1.5	3.222	3.227	99.83
2	3.177	3.182	99.85
2.5	3.132	3.136	99.87
3	3.087	3.091	99.89
3.5	3.043	3.045	99.91
4	2.998	3.000	99.93
4.5	2.953	2.955	99.95
5	2.864	2.865	99.97
6	2.774	2.774	99.99
7	2.684	2.686	99.96
8	2.595	2.597	99.92
9	2.505	2.508	99.89
10	2.416	2.420	99.85
11	2.326	2.331	99.81
12	2.237	2.242	99.77
13	2.147	2.153	99.73
14	2.058	2.064	99.70
15	1.968	1.975	99.66

Table 1 shows that the behavior of q_{cond} and $q_{total} = q_{cond} + q_{conv}$ during the initial 15 min. of warming of the bottle of beer. These data correspond to assay 2, Table 2.

Table 2. Assay ambient conditions.

Assay	RH	$T_{amb}=T_{\infty}$ (°C)
1	0.32	24
2	0.68	19
3	0.85	19
4	0.35	28
5	0.48	25

The interval of time of study was established so that the contribution of the condensation heat transfer rate was greater than 99.66% of the rate of total heat received by the bottle of beer in any given instant. In this way, the complete analysis was carried out in the initial 15 min., as shown in Table 1.

In this period of time, both the mass of condensed water and the temperature of the beer increased and could be correlated by fitting a 2nd order polynomial, as shown in Figure 2, and with Equations 14 and 15, whose coefficients of correlation were over 0.98.

$$M = -3.95\mathrm{x}10^{-7}t^2 + 1.58\mathrm{x}10^{-3}t - 3.89\mathrm{x}10^{-4} \tag{14}$$

$$T_s = -1.66\,\mathrm{x}10^{-6}t^2 + 4.68\,\mathrm{x}10^{-3}t - 1.452 \tag{15}$$

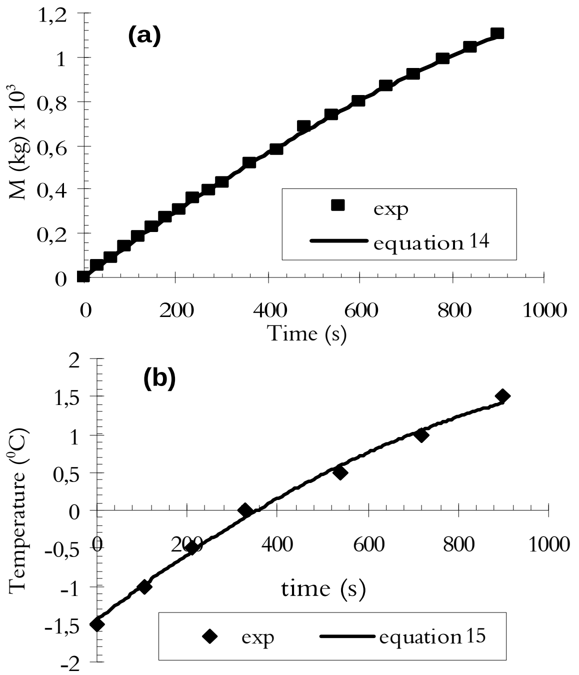

Figure 2. accumulated mass (a) and temperature (b) as a function of time.

The behavior of the heat and mass transfer coefficients as a function of the temperature and the relative humidity is shown in Figures 3 and 4. Both coefficients decreased as the temperature of the surface of the bottle of beer increased.

Figure 3a shows the influence of relative humidity on K_m. The values of K_m obtained in assays 2 and 3 were compared, Table 2, and it was concluded that the mass transfer coefficient is hardly affected by the relative humidity of the air.

Figure 3b compares assays 2 and 4. Both the relative humidity and the temperature of the ambient air varied, as shown in Table 2. It is known that the air humidity does not affect the mass transfer significantly; therefore, the different behaviors shown in Figure 3b result from the influence of the ambient temperature.

Similarly, Figure 4a, which shows the influence of the relative humidity on the heat transfer coefficient, compares the behavior of h_{cond} obtained in assays 2 and 3 for the same ambient temperature. It can be observed that the higher the relative humidity is, the larger the value of K_m is. It is also observed that h_{cond} is influenced by the relative humidity of the air.

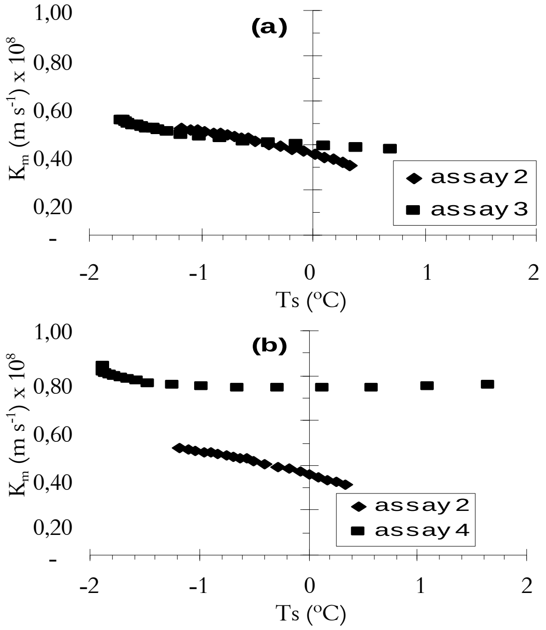

Figure 3. Influence of relative humidity (a) and the ambient temperature (b) on the mass transfer coefficient.

Figure 4b shows the influence of temperature on the heat transfer coefficients in assays 2 and 4 in different T_{amb} and RH conditions. As RH affects h_{cond}, it can be inferred that the effect of RH opposes that of the ambient temperature. Thus, while RH increase leads to an increase in h_{cond}, the increase in the ambient temperature results in a decrease of the heat transfer coefficient.

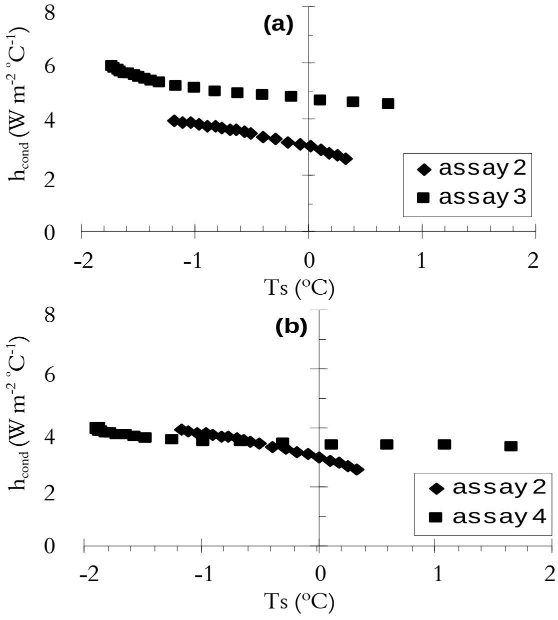

Figure 4. Influence of relative humidity (a) and ambient temperature (b) on the heat transfer coefficient.

Nomenclature

A	Antoine equation constant (dimensionless)
A_o	External area of the bottle (m^2)
B, C	Antoine equation constants (K)
C_{AP}	Concentration of water vapor on the bottle surface ($mol\ m^{-3}$)
$C_{A\infty}$	Concentration of water vapor in the ambient ($mol\ m^{-3}$)
h_{conv}	Natural convection heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_{cond}	Condensation heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
K_m	Mass transfer coefficient ($m\ s^{-1}$)
M	Mass of condensed water (kg)
m_{cond}	Condensate mass flow rate ($kg\ s^{-1}$)
N_A	Water molar flux ($mol\ s^{-1}\ m^{-2}$)
P_{Asat}	Water saturation pressure ($N\ m^{-2}$)
PM_{H2O}	Water molecular weight ($kg\ mol^{-1}$)
q_{total}	Total heat transfer rate ($J\ s^{-1}$)
q_{cond}	Condensation heat transfer rate ($J\ s^{-1}$)
q_{conv}	Natural convection heat transfer rate ($J\ s^{-1}$)
R	Ideal gas constant ($J\ mol^{-1}\ K^{-1}$)
RH	Relative air humidity (dimensionless)
T_s	Bottle surface temperature (°C).
T_∞	Ambient temperature (°C).
ΔH_{cond}	Condensation enthalpy ($J\ kg^{-1}$)

Conclusion

Heat transfer by condensation determines the rate of warming of the bottle in the initial 15 min.

In this period of time, the temperature and the accumulated condensed mass vary quadratically with time.

In contrast to the relative humidity, ambient temperature affects K_m significantly in the range of experimental conditions that was investigated.

Both the relative humidity and the ambient temperature influence h_{cond} significantly; however, the results suggest that the increase in the relative humidity of the air is associated with an increase in h_{cond}, while an increase in the ambient temperature results in a decrease of h_{cond}.

References

CREMASCO, M. A. **Fundamentos de transferência de calor e massa**. 2. ed. Campinas: Unicamp, 2002.

FORTES, M.; FERREIRA, D. A.; FERREIRA, W. R.; SOUZA, A. C. Modelagem de um condicionador de ar de alta precisão para uso em processamento agrícola. **Engenharia Agrícola**, v. 26, n. 2, p. 578-589, 2006.

INCROPERA, F. P.; DAVID, P. D. **Fundamentos de transferência de calor e de massa**. 5. ed. Rio de Janeiro: LTC, 2003.

KREITH, F. **Princípios de transferência de calor**. São Paulo: Pioneira Thomson Learning, 2003.

SMITH, J. M.; VAN HESS, H. C.; ABBOTT, M. M. **Introdução à termodinâmica da engenharia química**. 5. ed. Rio de Janeiro: LTC, 2000.

Received on September 14, 2009.
Accepted on March 19, 2010.