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An experimental investigation into heat transfer in milk cooling vessels

U. Durmaz*, **M. Ozdemir, and H. Pehlivan**

Department of Mechanical Engineering, Sakarya University, Sakarya, Turkey.

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Heat transfer coefficient;
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Power intensity;
Horizontal and vertical vessels.

Abstract. The raw milk is an important basic material for many food products. Fresh milk must be cooled immediately after milking to keep high quality and processability. In this work, the overall heat transfer coefficients of the milk cooling vessels used for this purpose have been studied experimentally. This study is aimed at determining the overall heat transfer coefficients of cooling vessels, which have different types and capacities without freezing and churning to avoid separation of milk's fat. Vessels are used ranged as follows: 300-500-1000-1500-1850-2000 liters for verticals and 2000-2500-3000-4000-5000-6000 liters for horizontals. It is found that the theoretical calculations are in satisfactory agreement with the experimental data. As a result of investigation, the overall heat transfer coefficient can be written in relation to power intensity for horizontal vessels. It is a certain constant value for vertical ones.

1. Introduction

Nowadays, there are different types of mechanically agitated milk cooling vessels used in dairy industry. Agitated milk cooling vessels with different capacities can be classified into two main groups. One of them is horizontal cylindrical vessels and the other group is vertical vessels.

The cows are milked twice a day and the milk is collected in the vessels to be picked up by the milk processing plant every day. The temperature of the fresh milk is approximately 35°C and it is desired to cool the fresh milk to 4°C by using mechanical stirrer cooling vessels as soon as possible. Milk processing factories obtain the raw materials they need through third party producers or their own milk producing factories. While factories that need large capacities of raw materials must obtain their milk from farms that specialize in high-capacity production, low-capacity milk processing plants are able to obtain their milk immediately from the surroundings.

Initially, when an animal is milked, the milk contains no microorganisms. Microorganisms found on the nipples of the animal, the milking tools and equipment, and the milking environment can be transferred to the milk. Due to the rich content and temperature (approximately 35°C) of the milk, microorganisms in the milk multiply rapidly. These microorganisms cause degradation of sensory, physical, and chemical quality of the raw milk. If the microorganisms are pathogenic, consumption of the milk and the milk products can cause a variety of serious diseases. Steps to be carried out prior to the delivery of milk to the factory will increase the quality of the final product. Milk is cooled immediately after milking and filtration. The cooling process is performed through buckets, plate heat exchangers, or milk cooling vessels. Microorganisms in cooled milk slowdown in terms of life activities and, therefore, multiply at a slower rate. It can be seen that

*. *Corresponding author. Tel.: +90 264 295 58 88*
E-mail address: udurmaz@sakarya.edu.tr (U. Durmaz)

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milk with 4000 unit/mL microorganisms can increase up to 1100000 unit/mL at a temperature of 30°C within 24 hours. It is also seen that this amount can be decreased to 8000 unit/mL at 4°C within 24 hours. Simply, the amount of microorganisms in milk at 30°C is equal to 275 times the amount of microorganisms in milk at 4°C. Therefore, the milk must be cooled immediately after milking. Thus, spoilage of milk, increase in acidity, and change in taste are delayed, leading to increase in quality, economic value, and processability of milk.

There are 3 important factors that determine the rate of heat transfer in agitated milk cooling vessels, namely, surface area of the condenser, power of the compressor, and heat transfer area of the evaporator, which is called roll bond area.

2. Technical devices of milk cooling vessels

Milk cooling vessels are manufactured in vertical and horizontal structures. Vertical and horizontal tank models are shown in Figure 1. In vertical vessels, the cooling surface consists of the entire base, while in horizontal vessels, the cooling surface is half the base. Both vessel models are made by AISI 304 stainless steel and are designed to be suitable for discharging and cleaning. The vessel's thickness is 2.5 mm in both models. Agitating is necessary for the milk cooling vessels. Therefore, 40-watt agitating power is used per ton in all types of vessels.

The vessel refrigeration system is operated using R404A gas. According to the Montreal Protocol [1], chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) refrigerants have been replaced by hydro fluorocarbons (HFCs) refrigerants, which are entirely harmless to ozone layer, considered free of greenhouse gases and the Ozone Depletion Potential (ODP) under the Kyoto Protocol [2].

3. Theory

The milk temperature is affected not only by the rate of heat transfer through the vessel's wall, but also by other energy terms, such as heat losses and mechanical energy input. The vessels are isolated with polyurethane material. As it is commonly done in heat transfer applications in diary product industry, mechanical energy imparted by the agitator and the heat losses can be neglected in comparison with the cooling energy terms. In experiments, water is used as working fluid instead of milk. Thus, according to the standard, water is used in the formal test of the milk cooling vessels. Taking the aforementioned conditions into account, the energy balance equation can be written as follows:

$$q_p = q_r + q_l, \tag{1}$$

where q_p is the rate of heat transfer from the product to refrigerant through the vessel's wall, q_r is the rate of energy from the refrigerant to the environment, and q_l is the rate of heat loss to the surroundings.

Taking 4°C temperature of the inner surface of the vessel in contact with the product and 20°C temperature of the outer surface of the vessel in contact with the ambient air into account, q_l is calculated 32 W/m^2. In other words, taking perfect heat convection into account, calculated heat loss is small enough to be neglected.

Rate of heat transfer from the product in the agitated vessel to the refrigerant R404A in the jacket is given by Eq. (2).

$$\frac{dq_p}{dt} = U.(T_p - T_r), \tag{2}$$

where, U is the overall heat transfer coefficient, which depends on the product and the refrigerant properties as well as impeller speed and vessel geometry; $(T_p - T_r)$ is the difference between the average product temperature in the vessel and temperature of the refrigerant in the jacket.

The overall heat transfer coefficient, U, can be theoretically estimated as follows:

$$\frac{1}{U} = \frac{1}{h_p} + \frac{\delta}{k_{ss}} + \frac{1}{h_r}, \tag{3}$$

where U is the overall heat transfer coefficient, h_p

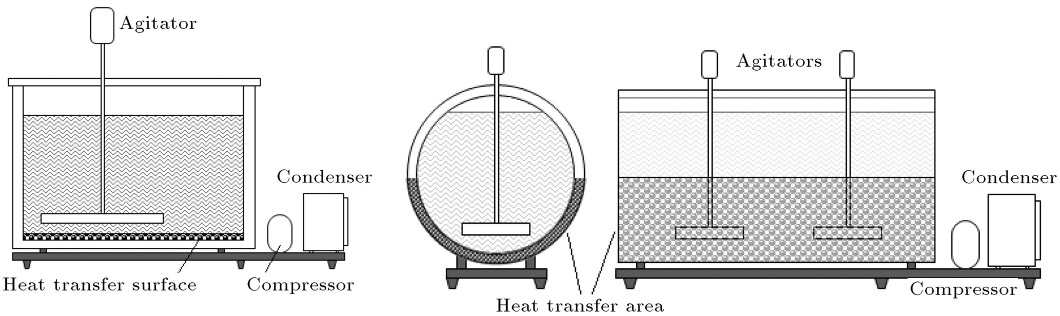

Figure 1. Vertical and horizontal vessel models.

is the heat transfer coefficient inside the vessel, h_r is the heat transfer coefficient outside the vessel or in the jacket, δ is the vessel wall thickness, and k_{ss} is thermal conductivity of the stainless steel at the average temperature. k_{ss} for AISI 304 is accepted to be 15.9 W/mK at 300 K [3].

The heat transfer coefficient for the agitated Newtonian liquid inside the vessel to the jacket walls of the vessel is estimated from the following correlation [4].

$$\frac{h_p D_t}{k_p} = 0.36 \left(\frac{D_a^2 N \rho}{\mu}\right)^{2/3} \left(\frac{c_p \mu}{k_w}\right)^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.21}, \quad (4)$$

where h_p is heat transfer coefficient inside the vessel, D_t is the inside diameter of the vessel, k_p is thermal conductivity of the product, D_a is the diameter of the agitator in (m), N is the impeller rotational speed in revolutions per sec, ρ is density of the product, μ is viscosity of the product, and μ_{wt} is viscosity of the product at the wall temperature. k_p is accepted to be 0.610 W/mK at 300 K [3].

Eq. (4) for the refrigerant R404A can be used to estimate heat transfer coefficient outside or inside the jacket [5].

$$h_r = \max\{h_{nb}, h_{cb}\}, \quad (5)$$

$$h_{nb} = (0.6683\mathrm{Co}^{-0.2} f\mathrm{Fr} + 1058\mathrm{Bo}^{0.7} F_{fl})(1-x)^{0.8} h_{lq}, \quad (6)$$

$$h_{cb} = (1.136\mathrm{Co}^{-0.9} f\mathrm{Fr} + 667.2\mathrm{Bo}^{0.7} F_{fl})(1-x)^{0.8} h_{lq}, \quad (7)$$

$$h_{lq} = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4}(k/D). \quad (8)$$

Here, F_{fl} is the fluid-dependent parameter and its value varies over a range from 0.5 to 5.0 [5]. The value of F_{fl} for the refrigerant R404A is taken as 1.3 [6]. Assuming that heat loss is neglected, Eq. (1) can be written as follows for transient heat transfer:

$$U.A.(T_p - T_r) = m.c.\frac{dT_p}{dt}, \quad (9)$$

where m is the product mass in the vessel and c is the average specific heat capacity of the product. Integration of both sides yields:

$$\frac{U.A}{m.c}.t = \ln\left[\frac{T_o - T_r}{T_p - T_r}\right]. \quad (10)$$

Hence, the temperature of the product can be obtained as follows:

$$T_p = T_r + (T_i - T_r).e^{-\left[\frac{U.A}{m.c}.t\right]}, \quad (11)$$

so that a correlation is obtained with the overall heat transfer coefficient, the area of the vessel wall in contact with the product, product mass in the vessel, the average specific heat capacity of the product, initial temperature of the product, temperature of the refrigerant, and cooling period. Thus, the temperature of the product at the end of any period of time can be calculated by Eq. (11). Considering the desired temperature of the milk equal to 4°C, the cooling period is a specified value that depends on performance classifications for milk cooling vessels. To reach the desired temperature by transferring heat from the smallest possible surface area in a minimum time period, it is necessary to produce a vessel with a minimum cost based on engineering approach. Therefore, the value of the overall heat transfer coefficient is also important.

The temperature of cooling refrigerant at the evaporator inlet varies between 7°C and -2°C during the cooling period. It is necessary that the temperature of the refrigerant should not be less than -2°C while the temperature of the milk is 4°C, otherwise the milk in contact with the cooling surface starts to freeze. The time-dependent temperature range of the refrigerant is the same for all types and capacities of the vessels. It means that the chosen compressors and condensers are proper for the cooling conditions.

Kline and McClintock [7] suggested an accurate method called uncertainty analysis. According to Holman [8], if R is given function of the independent variables $x_1, x_2, x_3, \cdots, x_n$, $R = R(x_1, x_2, x_3, \cdots, x_n)$, and $W_1, W_2, W_3, \cdots, W_n$ are the uncertainties in these independent variables, the uncertainty of R can be evaluated by:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1}W_1\right)^2 + \left(\frac{\partial R}{\partial x_2}W_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}W_n\right)^2\right]^{(1/2)}. \quad (12)$$

In the experiments, the maximum errors are expressed in this way. W is the absolute error of the parameters.

The thermocouples are calibrated for every cycle of experiment. They have an accuracy of ±0, 1°C. The relative and absolute errors are calculated by considering the maximum of 35°C and the minimum of 4°C for temperature on the product side and the maximum of 7°C and the minimum of -2°C on the refrigerant side. The experimental uncertainty of the temperature difference between the product and the refrigerant is ±5% or ±1.4°C.

The vessels are insulated with a 50-55 mm layer of polyurethane material. Heat loss to the environment is calculated 32 W. Material properties (μ, ρ, c_p) related to temperature are taken from corresponding tables [3,9].

4. Results and discussion

The capacities of compressors and condensers, which are used in cooling vessels, are determined according to the amount of milk and cooling duration. For this, the transferred heat from evaporation surface, which is in contact with milk, must be known. The time-dependent milk temperatures as cooling curves are used to calculate the overall heat transfer coefficient.

In this study, the cooling vessels, which have different types and capacities, are investigated and the cooling characteristics are experimentally obtained as time (t) (s) versus temperature (T) (°C). Eq. (11) is verified with experimental t-T diagrams. Figures 2 and 3 show experimental and theoretical cooling curves for vertical and horizontal vessels, respectively.

As mentioned in Eq. (3), the overall heat transfer coefficient is dependent on the product and the

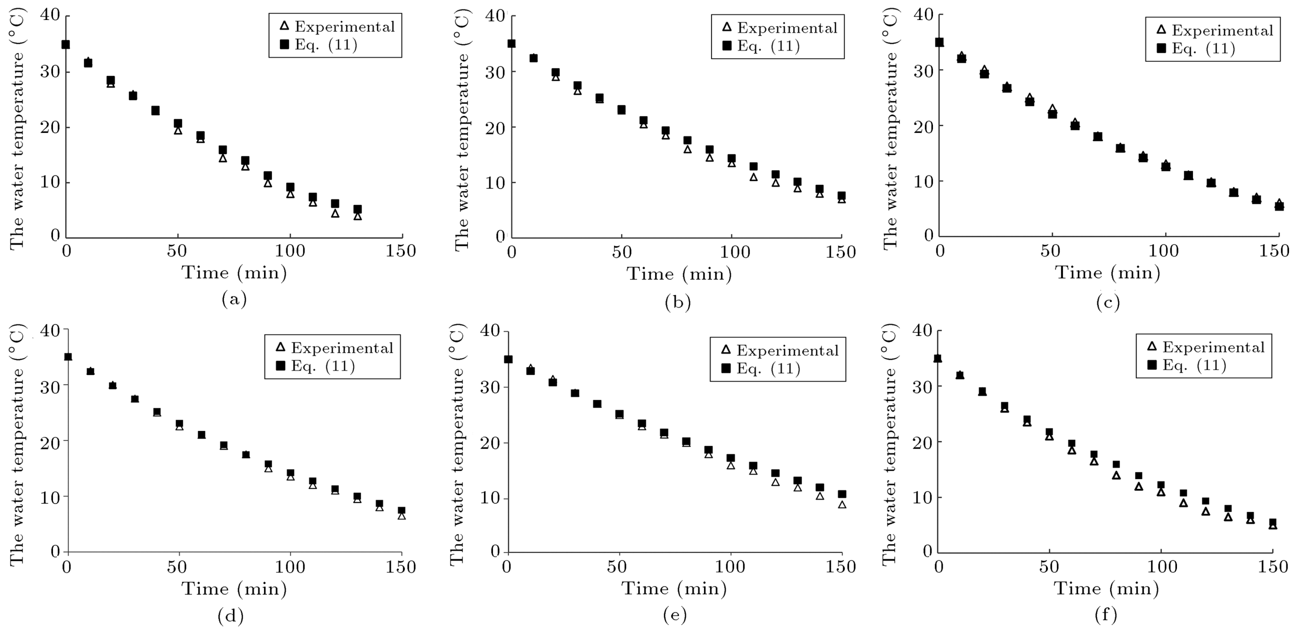

Figure 2. Experimental and theoretical cooling curves for vertical vessels: (a) 300 liter, (b) 500 liter, (c) 1000 liter, (d) 1500 liter, (e) 1850 liter, and (f) 2000 liter.

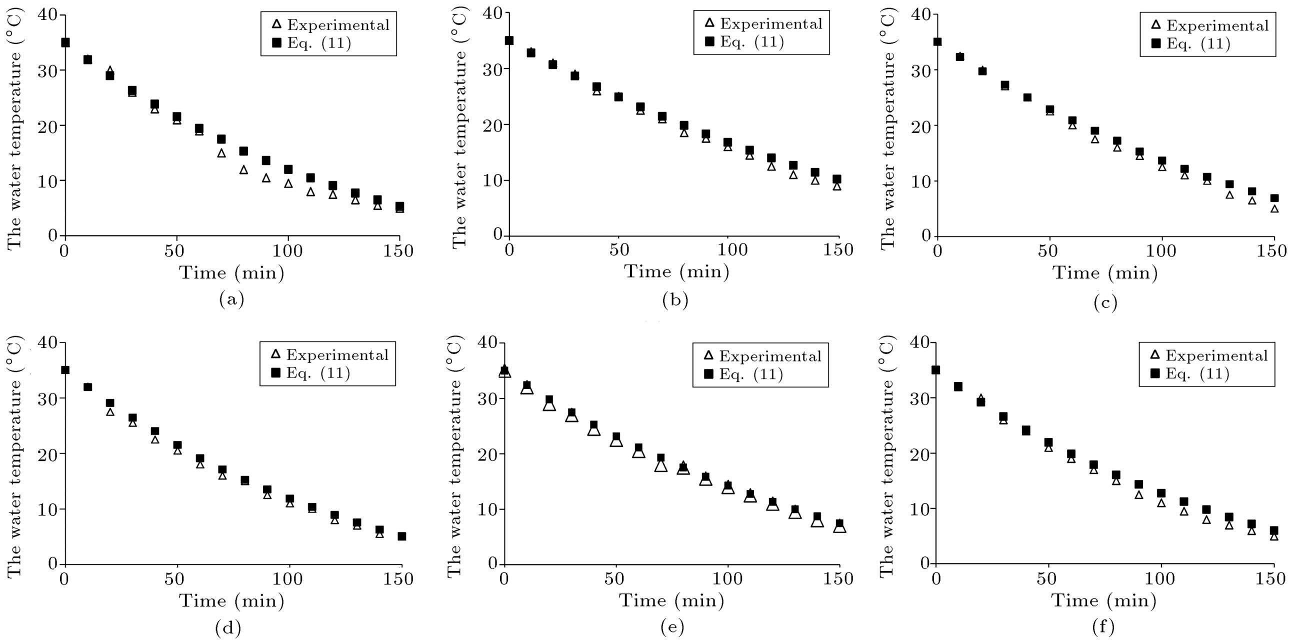

Figure 3. Experimental and theoretical cooling curves for horizontal vessels: (a) 2000 liter, (b) 2500 liter, (c) 3000 liter, (d) 4000 liter, (e) 5000 liter, and (f) 6000 liter.

refrigerant side heat transfer. The experimental data and calculated values show that the heat convection coefficient of the product side is the limiter. The overall heat transfer coefficient has a specific limit of value, which is dependent on the agitator speed, because the milk and its fat are separated from each other. The desired milk temperature and performance classifications for milk cooling vessels are standardized by EN 13732. According to the standard, the process of milk cooling from 35°C to 4°C is limited to a maximum time of 3.5 hours. Figures 4 and 5 show overall heat transfer coefficients versus time for vertical and horizontal vessels, respectively. Figures 6 and 7 show overall heat transfer coefficients versus product temperature for vertical and horizontal vessels, respectively.

A certain approximate value of 0.3 kW/m^{2}K for overall heat transfer coefficient is experimentally obtained for vertical vessels. It is seen that the value of overall heat transfer coefficient changes in horizontal

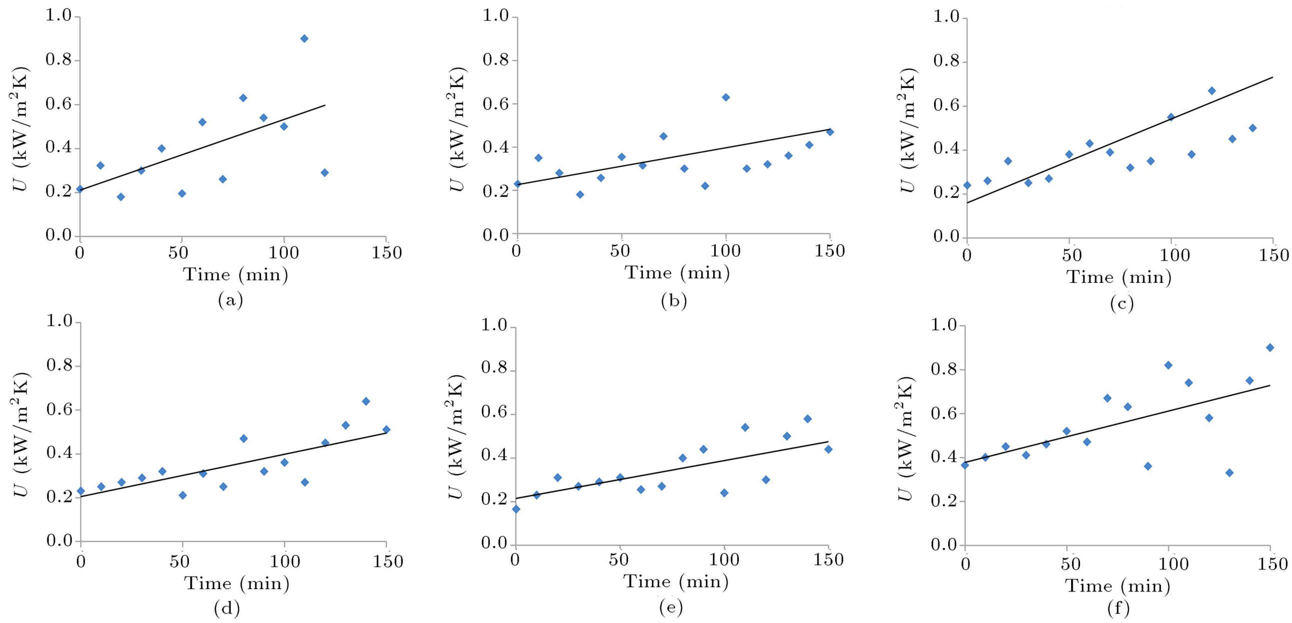

Figure 4. Overall heat transfer coefficients versus time for vertical vessels: (a) 300 liter, (b) 500 liter, (c) 1000 liter, (d) 1500 liter, (e) 1850 liter, and (f) 2000 liter.

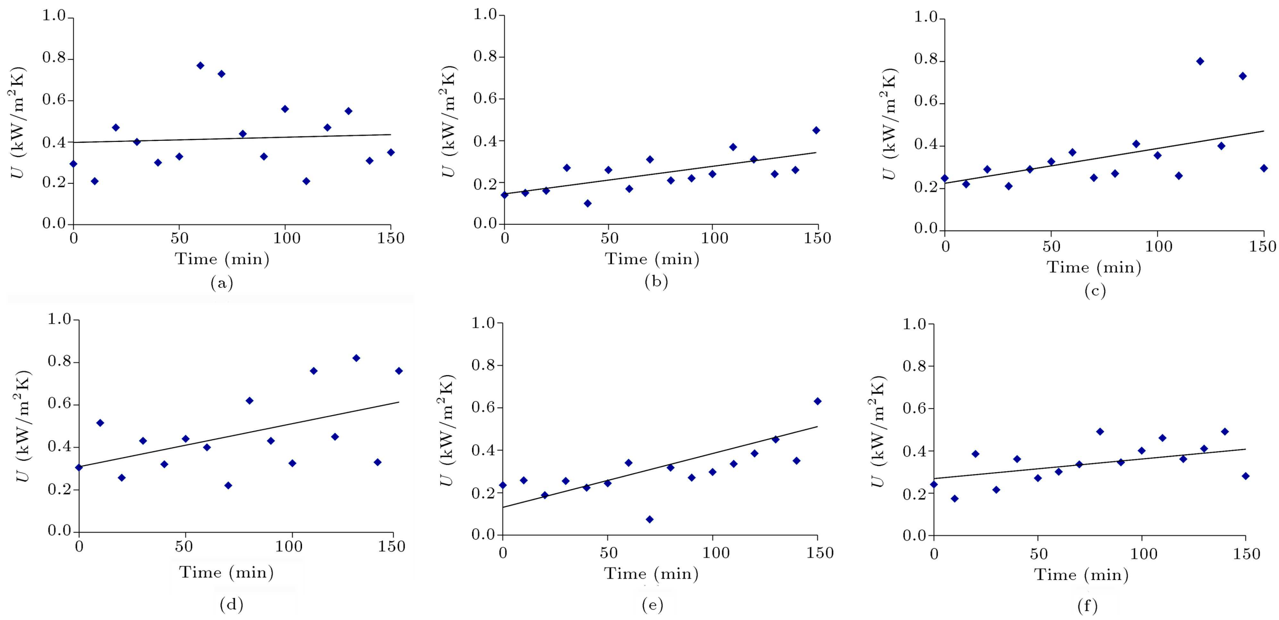

Figure 5. Overall heat transfer coefficients versus time for horizontal vessels: (a) 2000 liter, (b) 2500 liter, (c) 3000 liter, (d) 4000 liter, (e) 5000 liter, and (f) 6000 liter.

vessels in the range of 0.2 to 0.4 kW/m^{2}K depending on capacity. This can be seen in Figures 8 and 9. Figure 4, and figure 5 show overall heat transfer coefficients versus time for vertical and horizontal vessels, respectively. Figure 6, and figure 7 show overall heat transfer coefficients versus product temperature for vertical and horizontal vessels, respectively.

Compressor power/heat transfer area or, in other words, power intensity must be more than 4000 W/m^2 to cool down the milk in less than 3.5 hours and to prevent the freezing of the milk. On the other side, it must be less than 8000 W/m^2 to avoid butter separation. This situation can be controlled in the agitator speed range of 30-60 rpm.

We can see volume versus power intensity for both horizontal and vertical vessels in Figure 10.

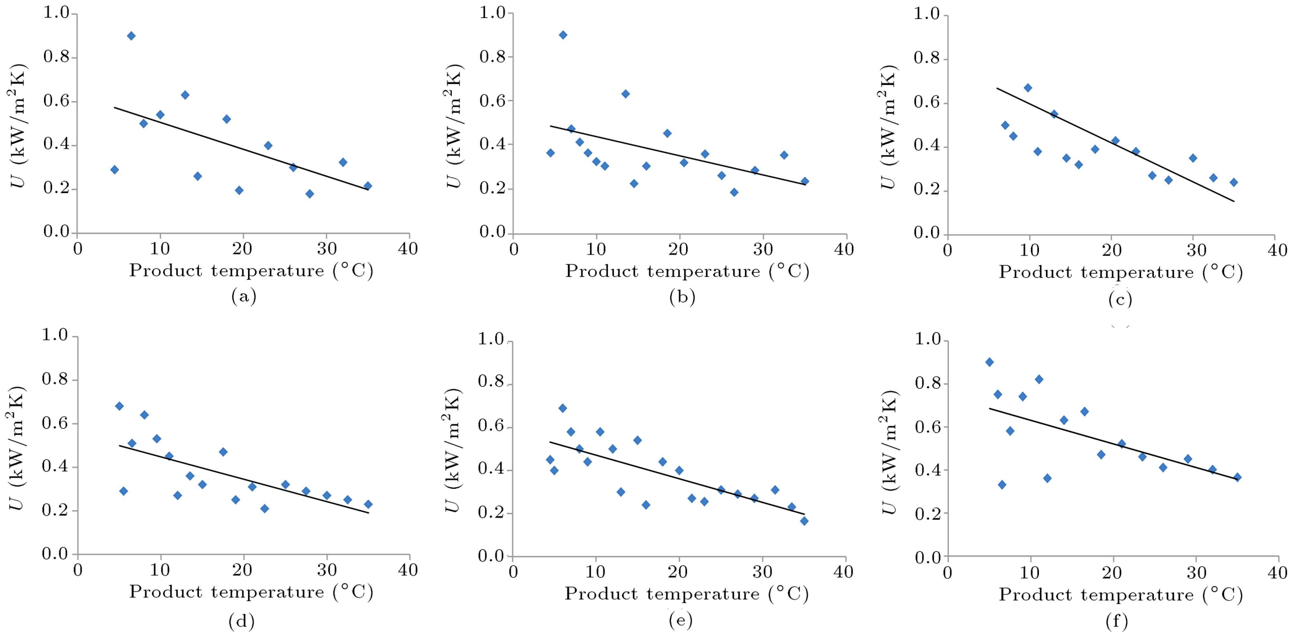

Figure 6. Overall heat transfer coefficients versus product temperature for vertical vessels: (a) 300 liter, (b) 500 liter, (c) 1000 liter, (d) 1500 liter, (e) 1850 liter, and (f) 2000 liter.

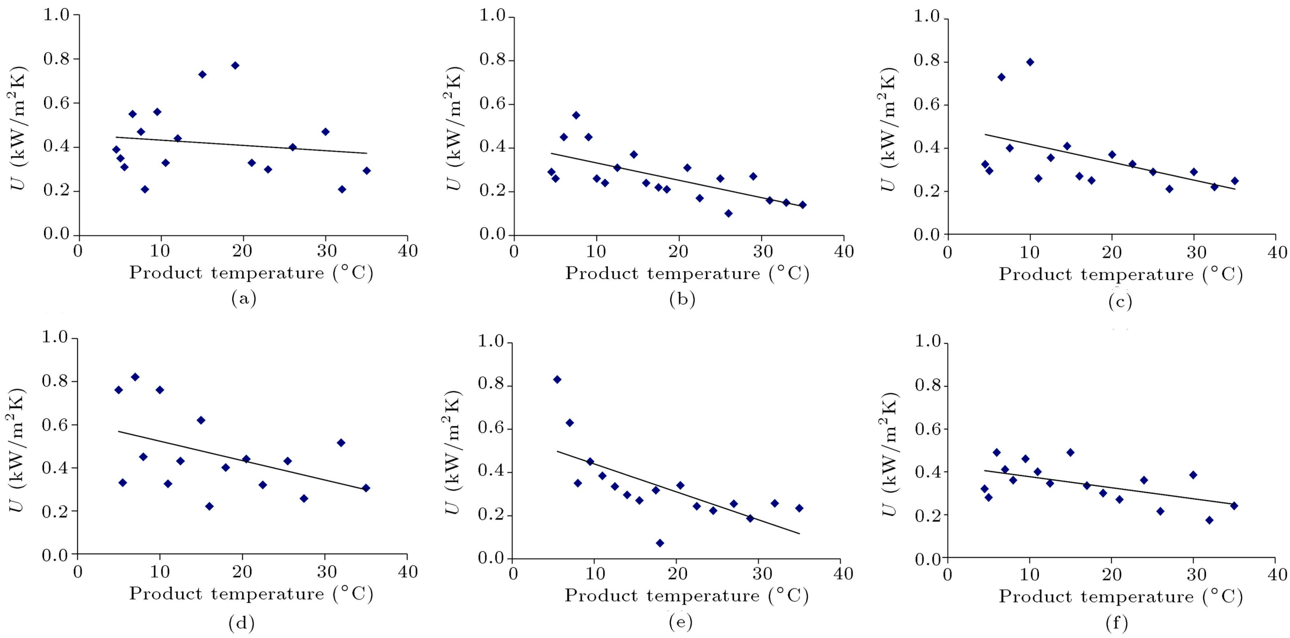

Figure 7. Overall heat transfer coefficients versus product temperature for horizontal vessels: (a) 2000 liter, (b) 2500 liter, (c) 3000 liter, (d) 4000 liter, (e) 5000 liter, and (f) 6000 liter.

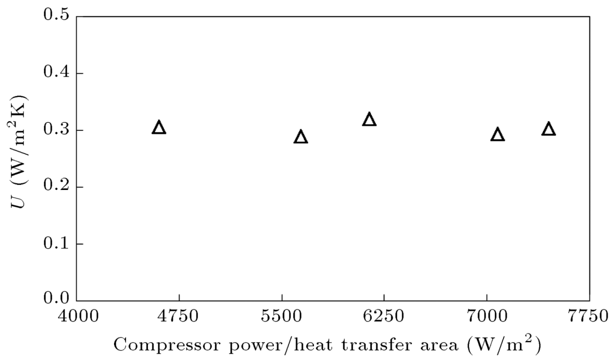

Figure 8. Overall heat transfer coefficients versus compressor power/heat transfer area for vertical vessels.

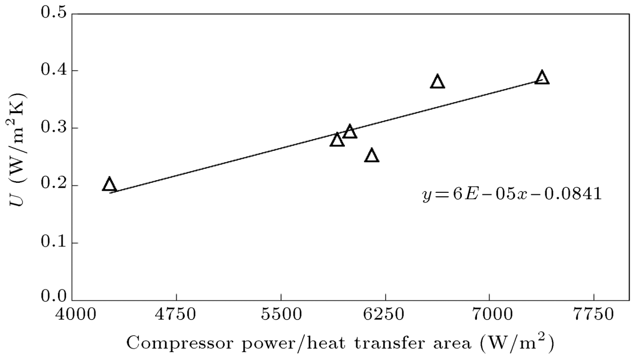

Figure 9. Overall heat transfer coefficients versus compressor power/heat transfer area for horizontal vessels.

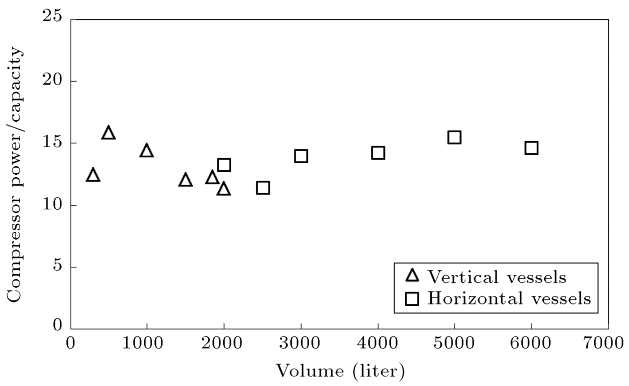

Figure 10. Volume versus compressor power/heat transfer area for vertical and horizontal vessels.

5. Conclusions

This study was aimed to determine overall heat transfer coefficients of the milk cooling vessels, which had different types and capacities. The overall heat transfer coefficient of the horizontal cylindrical vessels was a function of power intensity or, in other words, compressor power/heat transfer surface area. Also, the heat transfer was affected by geometrical shape of small-capacity horizontal vessels. Therefore, it was difficult to design a cooling vessel without any knowledge about overall heat transfer coefficients.

For the vertical vessels, cooling was performed only from the bottom flat surface. Based on the results obtained, it was observed that the value of overall heat transfer coefficient did not change with capacity of the vertical vessels.

It was necessary to keep the milk unfrozen. In other words, it had a small value of power/area ratio. More heat transfer area had to be used on horizontal cylindrical vessels, because they had lower values of overall heat transfer coefficient. That means cost increments and place problem depended on the height of the vessel. Nevertheless, although the vertical vessels were more efficient than the horizontal ones with regards to power intensity, the horizontal vessels were more preferable because of the contamination and place problems.

It was seen that the cooling performance of vertical models was higher than that of horizontal models for a given volume of milk. In other words, heat transfer rate was more efficient in vertical milk cooling vessels. As a result of this investigation, overall heat transfer coefficient of vertical vessels, which was approximately 0.3 kW/m^{2}K, could be used independently of the vessel capacity. It varied between 0.2 to 0.4 kW/m^{2}K depending on capacity of horizontal vessels.

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Nomenclature

A	Heat transfer surface area (m^2)
Bo	Boiling number (-)
c	Specific heat at constant pressure (kJ/kgK)
Co	Convection number (-)
D	Diameter (m)
F_{fl}	Fluid-dependent parameter (-)
Fr	Froude number (-)
$\dot{m}$	Mass flux (kg/m^{2}s)
h	Convective heat transfer coefficient (W/m^{2}K)
k	Thermal conductivity (W/mK)
Nu	Nusselt number (-)
Pr	Prandtl number ($= c_p\mu/k$) (-)
$\dot{q}$	Heat flux (W/m^2)

$\dot{Q}$	Heat transfer rate (kW)
Q	Heat (kJ)
Re	Reynolds number (-)
T	Temperature (°C)
t	Time (s)
U	Overall heat transfer coefficient (W/m^2K)

Greek symbols

μ	Dynamic viscosity (Pa.s) (kg/m.s)
ρ	Density (kg/m^3)
δ	Wall thickness of the vessel

Subscripts

a	Agitated
cb	Convective boiling
i	Initial
l	Loss
l_q	Liquid
nb	Nucleate boiling
p	Product
r	Refrigerant
ss	Stainless steel
t	Inside
w	Water
wt	Wall temperature

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Biographies

Ufuk Durmaz is an Assistant Professor in Mechanical Engineering Department of Sakarya University, Turkey. He graduated from Electrical and Electronics Engineering Department and Mechanical Engineering Department of Sakarya University in 2002 and 2003, respectively, with a BSME degree. He received MSc degree in 2007 and PhD degree in 2013 from Mechanical Engineering Department at Sakarya University. His PhD dissertation was entitled "Investigation of agitation effects on heat transfer in boiling vessels of sugar syrup". His main research areas are pool or flow boiling, computational fluid dynamics, heat transfer, food processing machineries, and renewable energy. He made all the arrangements and writing of the paper.

Mustafa Ozdemir is an Associate Professor in Mechanical Engineering Department of Sakarya University, Turkey. He graduated from Mechanical Engineering Department of Karadeniz Technical University in 1980 with a BSME degree. He received MSc degree in 1993 and PhD degree in 1998 from Process Engineering Department at Technische Universitat Clausthal, Germany. His PhD dissertation was entitled "Experimental studies on the combustion reactivity of coal in a fixed bed reactor". His main research areas are energy technology, thermodynamics, heat transfer, food processing machineries, and renewable energy. He arranged the experimental setup for this study.

Huseyin Pehlivan is an Associate Professor of Mechanical Engineering at Sakarya University, Turkey. He graduated from University of Sakarya in 1999 with a BSME degree. He received MSc in 2002 and PhD in 2008 in Mechanical Engineering from Sakarya University. His PhD was concerned with experimental and theoretical analysis of falling film evaporation under vacuum conditions. His main research areas are fluid flow, heat exchangers, food processing machineries, heat transfer, and energy applications. He performed the experiments for this study.