Optimizing operating parameters for flat-plate milk coolers

VLASTIMIL NEJTEK, JIRI FRYC, JOSEF LOS, RADOVAN KUKLA
Department of Agricultural, Food and Environmental Engineering
Mendel University in Brno
Zemedelska 1, 613 00 Brno
CZECH REPUBLIC

vlastimil.nejtek@mendelu.cz

Abstrakt: Measuring in laboratory conditions was performed with the aim to collect a sufficient quantity of measured data for the qualified application of flat-plate coolers in measuring under real operating conditions. The cooling water tank was filled with tap water; the second tank was filled with water at a temperature equivalent to freshly milked milk. At the same time, pumps were activated that delivered the liquids into the flat-plate cooler where heat energy was exchanged between the two media. Two containers for receiving the run-out liquid were placed on the outputs from the cooler; here, temperature was measured with electronic thermometer and weight was measured with calibrated scales. Flow rate was regulated both on the side of the cooling fluid and on the side of the cooled liquid by means of a throttle valve. The measurements of regulated flow-rates were repeated five times and the final values were calculated using arithmetic mean and optimum flow ratio calculated by program MATLAB. The measured values show that the volume of exchanged heat per weight unit increases with the decreasing flow-rate. With the increasing flow-rate on the throttled side, the flow-rate increases on the side without the throttle valve. This phenomenon is caused by pressure increase during throttling and by the consequent increase of the diameter of channels in the cooler at the expense of the opposite channels of the non-throttled part of the circuit. If the pressure is reduced, there is a pressure decrease on the external walls of opposite channels and the flow-rate increases again. This feature could be utilised in practice: a pressure regulator on one side could regulate the flow-rate on the other side.

Key-Words: plate cooler, milk cooling

Introduction

Milk is a valuable agricultural product and, after its finalisation, an irreplaceable component of human nutrition. Milk contains a balanced score of proteins, fat, milk sugar, minerals, 14 trace elements, and numerous vitamins [1]. To maintain its quality, milk is quickly cooled after drawing, from approximately 36°C down to 5°C [2, 3]. This process consumes a lot of energy due to the high difference in temperatures and the milk volume [4]. If it were possible to reduce the cost of cooling, e.g. by using preliminary flat-plate flow coolers, the saving would reflect in the overall costs per unit of milk. Another advantage is faster achievement of the required temperature than by standard means, and therefore higher level of hygiene will be reached [5]. Furthermore, the application of the flat-plate coolers offers the desirable extended lifespan of the cooling system thanks to the slower degradation as the average age of cooling systems used in livestock production is 8.9 years [6]. In this way, producers could yield higher profits and enhanced competitiveness [7]. The environmental perspective is important as well. With the ever-growing global population and increasing quality of people's lives a higher need for energy is expected, therefore energy-saving measures become increasingly important [8].

Material and methods

Diagram of the flat-plate cooler connection for the purpose of measuring is presented in Fig. 1. The cooling fluid tank was filled with 13 °C tap water; the second tank, which simulated freshly drawn milk, was filled with water at a temperature of 35 °C. Before the measurement, tanks were filled. The pumps were simultaneously activated, the pumps were activated for 30 seconds. Fluids entered the flat-plate cooler where heat energy was exchanged between the two media. Two containers for receiving the run-out liquid were installed on the output pipes where temperature and weight were measured. Flow-rate was regulated by the throttle valve both on the side of the cooling fluid and on the side of the cooled liquid.

Material used in the measurements:

Cooled and cooling water pumps: Manufacturer: AL-KO, Type: DRAIN 8001, Power input: 550 W, Performance: 10 000 l/h

Flat-plate flow cooler (counter-flows): Manufacturer: SAC Nederland B. V., Finish: Stainless steel, Type: 42, Heat-exchange area: 2.1 m^2
Electronic thermometer: TESTO 922, Resolution: 0.1 °C, Temperature range: -50 to +1000°C,
Stop watch: Manufacturer: JVD, Type: VST31, Accuracy: 1/1000 sec.
Electrometer - HT-353M mechanical, voltage: 3 x 230 / 400 V, Operating temperature: -20 ~ 60°C
Electromagnetic valve - MP116, 230V AC, directly controlled
Hanging calibrated weights OCS-20A/50
The measurements were repeated five times for each regulated flow-rate setup; data shown in tables are calculated as arithmetic means from the measured values. Flow-rate were calculated from the measured values according to equation (1) The 3D graph has three axis, of which two are independent variables (the horizontal axes) and one is a dependent variable (the vertical axis). The measured data were plotted in the space using the points and the grid between them was calculated using the 'griddata' feature.
Feature griddata: ZI = griddata (x,y,z,XI,YI) fits a surface of the form z = f(x,y) to the data in the (usually) nonuniformly spaced vectors (x,y,z). Griddata interpolates this surface at the points specified by (XI,YI) to produce ZI. The surface always passes through the data points. XI and YI usually form a uniform grid (as produced by meshgrid). XI can be a row vector, in which case it specifies a matrix with constant columns. Similarly, YI can be a column vector, and it specifies a matrix with constant rows.
[XI,YI,ZI] = griddata(x,y,z,xi,yi) returns the interpolated matrix ZI as above, and also returns the matrices XI and YI formed from row vector xi and column vector yi. These latter are the same as the matrices returned by meshgrid.

[...] = griddata(...,method) uses the specified interpolation method:

'linear'	Triangle-based linear interpolation (default)
'cubic'	Triangle-based cubic interpolation
'nearest'	Nearest neighbor interpolation
'v4'	MATLAB 4 griddata method

The method defines the type of surface fit to the data. The 'cubic' and 'v4' methods produce smooth surfaces while 'linear' and 'nearest' have discontinuities in the first and zero'th derivatives, respectively. All the methods except 'v4' are based on a Delaunay triangulation of the data.

Heat amount

$$Q = m.c.(t_e - t_i) \quad [J] \quad (1)$$

m – weight of substance [kg]
c – specific heat capacity [$Jkg^{-1}K^{-1}$]
t_e - final temperature [°C]
t_i – initial temperature [°C]

Heat exchange coefficient

$$K = A\frac{\frac{Q}{(t_{Ai}-t_{Be})-(t_{Ae}-t_{Bi})}}{ln\frac{(t_{Ai}-t_{Be})}{(t_{Ae}-t_{Bi})}} \quad [W.m^{-2}.K^{-1}] \quad (2)$$

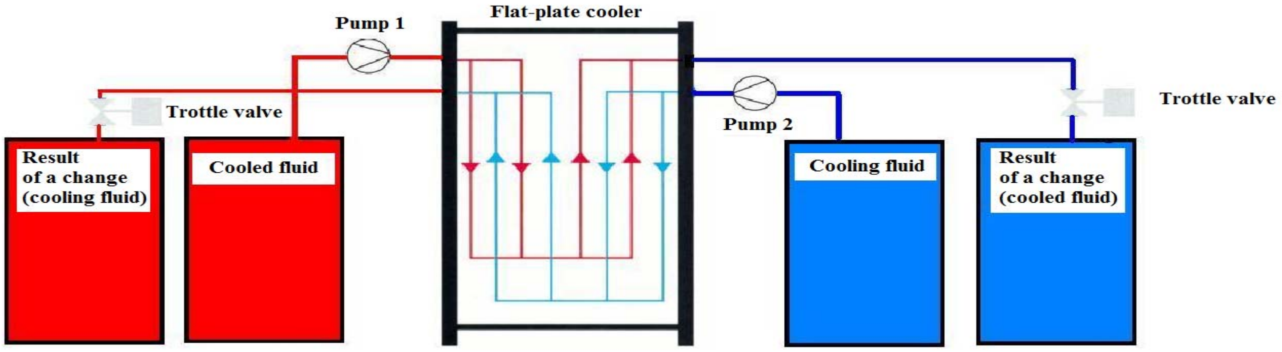
Q – heat amount [J]
A - area [m^2]
t_{Ai} – input temperature of cooled fluid [K]
t_{Ae} – output temperature of cooled fluid [K]
t_{Be} - input temperature of cooling fluid [K]
t_{Bi} - output temperature of cooling fluid [K]

Power plate cooler

$$P = \frac{Q}{t} \quad [W] \quad (3)$$

Q – heat amount [J]
t - time [s^{-1}]

Fig. 1 Diagram of laboratory measurements, Brno, CR, 2014



Results and discussion

Table 1 Change of cooling water parameters on passing through the cooler (cooled water throttling regime)

T_{Bi} [°C]	T_{Be} [°C]	m [kg]	Q [J]	P [W]	i [J.kg^{-1}]	K [W.m^{-2}.K^{-1}]
13.0	17.4	22.88	420884	14029	18392	969
13.0	23.6	23.15	1032664	34422	44600	2805
13.0	28.9	23.95	1598906	53296	66754	4265
13.0	30.3	24.15	1746498	58216	72314	4584
13.0	30.2	26.65	1923580	64119	72188	4818

Table 2 Change of cooled water parameters on passing through the cooler (cooled water throttling regime)

T_{Ai} [°C]	T_{Ae} [°C]	m [kg]	Q [J]	P [W]	i [J.kg^{-1}]	K [W.m^{-2}.K^{-1}]
35.0	14.7	4.59	388204	12940	84561	894
35.0	15.5	11.51	937927	31264	81510	2547
35.0	18.8	23.98	1616941	53898	67423	4313
35.0	20.6	31.07	1866131	62204	60066	4898
35.0	21.2	35.03	2010409	67013	57391	5036

Table 3 Change of cooled water parameters on passing through the cooler (cooling water throttling regime)

T_{Ai} [°C]	T_{Ae} [°C]	m [kg]	Q [J]	P [W]	i [J.kg^{-1}]	K [W.m^{-2}.K^{-1}]
35.0	30.0	24.75	513826	17127	20760	1402
35.0	26.7	24.68	856247	28541	34694	2332
35.0	20.1	24.98	1548843	51628	62003	3962
35.0	18.4	24.88	1719440	57314	69109	4411
35.0	17.7	27.28	1968924	65630	72174	4964

Table 4 Change of cooling water parameters on passing through the cooler (cooling water throttling regime)

T_{Bi} [°C]	T_{Be} [°C]	m [kg]	Q [J]	P [W]	i [J.kg^{-1}]	K [W.m^{-2}.K^{-1}]
13.0	33.9	5.86	511941	17064	87362	1397
13.0	33.2	9.85	833067	27768	84575	2269
13.0	29.6	21.52	1499226	49974	69666	3835
13.0	28.0	27.67	1738764	57958	62839	4461
13.0	26.8	35.23	2037116	67903	57823	5136

Fig. 2 Graph showing the dependence of the cooled water heat content on changes cooling water flow, Brno, CR, 2014

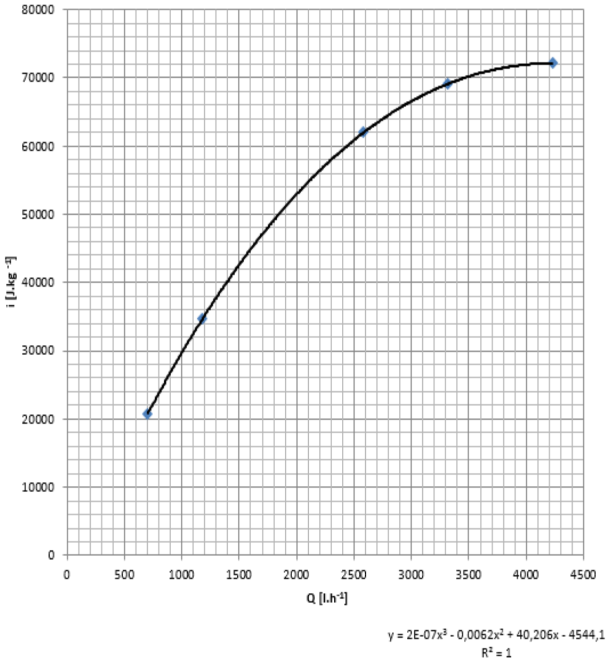


Fig. 3 Graph showing the dependence of cooled water temperature reduction on cooling water flow, Brno, CR, 2014Fig. 2 shows the dependence of the cooled water heat content change on the flow-rate of cooling water – over the flow-rate 3000 $l.h^{-1}$ the rate of increasing is lower. Fig. 3 clearly indicates that the cooled water temperature reduction is minimal at flow rates above 3,000 $l.h^{-1}$. Therefore, the value of 3,000 $l.h^{-1}$ of cooling water was set as optimal.

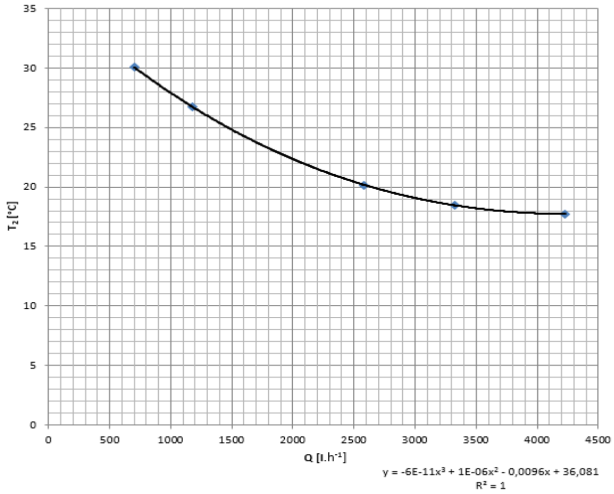
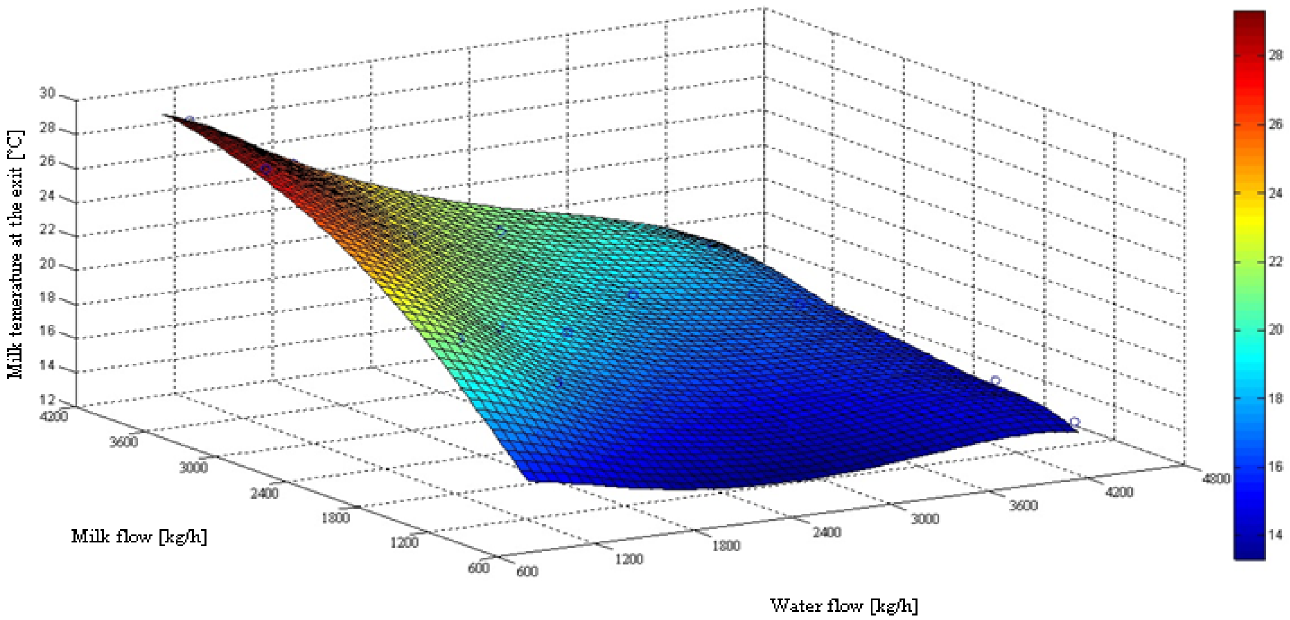


Fig. 4 shows the outlet temperature of milk depending on the flow rate of cooling water (13 °C) and flow rate of the inlet milk (35 °C). Comparing the resulting values with parameters provided by the manufacturer, we can conclude that the values were achieved during the measurements. For the type of the used flat-plate cooler (Type 42) the manufacturer claims milk temperature of milk on the output by 2 – 4°C higher than the temperature of cooling water on the input at a flow-rate of 4,000 litres of milk per hour. In our case, this temperature difference ranged near the upper limit provided by the manufacturer. [9] Fig. 4 makes it apparent that the best level of milk cooling occurs when the flow rate of cooling water is 3,000 litres per hour, while that of milk reaches 1,200 litres per hour. This best ratio can be achieved using a frequency converter that regulates the speed of the milk pump and that of the water pump in order to achieve optimal flow rates.

Fig. 4 Determining optimum flow rates, Brno, CR, 2014



Conclusion

The measured values demonstrate that the volume of exchanged heat per weight unit increases with the decreasing flow-rate. The measured values show that with the increasing flow-rate on the throttled side the flow-rate increases on the side without the throttle valve. This phenomenon is caused by pressure increase during throttling and by consequent increase of the diameter of channels in the cooler that reduce the diameter of adjacent channels with non-throttled liquid. With the decreasing pressure, there is a pressure decrease on the external walls of the opposite channels and the flow-rate increases. This property of the cooler could be utilised in practice when a pressure regulator on one side would regulate flow-rate on the other side and vice versa. We can deduce from the measured values that using flat-plate milk coolers in practice could bring a major cost-reduction of electricity needed for the cooling aggregate. Other presumed benefits include lower cost of the cooling system maintenance and repairs due to lower load, longer service life of the entire system, positive impacts on the quality of milk in terms of rate of its cooling down to the required temperature. It is also possible to consider using heated water for watering the milking cows (this is beneficial especially in winter) as well as for washing, floor hygiene, etc.

Acknowledgements

This study was financed by the Internal Grant Agency of the Faculty of Agronomy MENDELU in Brno No. TP 8/2014.

References:

[1] Anděl M, *Mléko a mléčné výrobky ve výživě* (1. vyd.) Potravinářská komora České republiky, 2010.

[2] Forsbäck L, Effect of storage and separation of milk at udder quarter level on milk composition, proteolysis, and coagulation properties in relation to somatic cell count, *Journal of Dairy Science,* Vol. 94, No. 2, 2011, pp 11-24

[3] Eicker U, *Low Energy Cooling for Sustainable Buildings.* Chichester (1vyd.) John Wiley a Sons Ltd, 2009.

[4] Mascheroni R, *Operations in Food Refrigeration,* (1rd edition), CRC Press, 2012.

[5] Frančák J, *Technika v agrokomplexe* (1. vyd.) VES, 2012.

[6] Gálik R, Karas I, Mikuš R, Drlička R, Analýza miery vekového opotrebeni a strojov a zariadení používaných v živočíšnej výrobe. *Acta technologic a agriculturae.*, Vol. 9, No. 2, 2006, pp 40-44.

[7] Pešek M, *Ošetřování, hodnocení jakosti a zpracování mléka na farmě* (1. vyd.), Institut výchovy a vzdělávání Ministerstva zemědělství ČR, 1999

[8] Wilson P, *Super cooling* (1rd edition), In Tech, 2012.

[9] Abdallah S, Basiouny M, Evaluating the performance of a bulk-milk cooler on a dairy farm, *Agricultural Mechanization in Asia, Africa and Latin America*, Vol. 43, No. 1, 2012, pp 22-31.