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MEASUREMENTS OF FLAT-PLATE MILK COOLERS

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Abstract

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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 volume was measured with calibrated graduated cylinder. 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 several times and the final values were calculated using arithmetic average. To calculate the temperature coefficient and the amount of brought-in and let-out heat, the volume measured in litres was converted to weight unit. 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. The operating measurement was carried out on the basis of the results of laboratory measurements. The objective was to determine to what extent the use of flat-plate coolers under specific conditions results in cost reduction and improved milk cooling process. The measurement was performed in several cycles. The first measurement took place in the existing system without the use of the flat-plate cooler. The volume of drawn milk was monitored throughout the milking process along with its temperature, temperature in the tank and electricity consumption of the cooling system. At the second stage, the flat-plate cooler was introduced into the cooling process, which was followed by monitoring the milk and cooling water volume, their temperature, temperature in the tank and electricity consumption of the cooling system. The measured data indicate considerable power cost reduction if upstream flat-plate coolers are applied.

Keywords: 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 (Anděl, 2010). To maintain its quality, milk is quickly cooled after drawing, from approximately 36 °C down to 5 °C (Forsbäck, 2011; Wilson, 2012). This process consumes a lot of energy due to the high difference in temperatures and the milk volume (Mascheroni, 2012). 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 degree of hygiene (Pešek, 1999). Furthermore, the application of the flat-plate coolers offers the desirable extended service life of the cooling system thanks to the slower degradation as the average age of cooling systems used in livestock production is 8.9 years and the age degradation rate is 111.2% (Gálik *et al.*, 2006). In this way, producers could yield higher profits and enhanced competitiveness (Frančák *et al.*, 2012). 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 are becoming increasingly important (Eicker, 2009).

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. At the same time, 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 volume were measured. Flow-rate was regulated by the throttle valve both on the side of the cooling fluid (Tabs. III, IV, Fig. 4) and on the side of the cooled liquid (Tabs. I, II, Fig. 3).

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 × 230/400 V, Operating temperature: –20–60 °C.

Electromagnetic valve – MP116, 230V AC, directly controlled.

Two volumetric vessels – volume of 25 l with a calibrated scale.

The measurements were repeated five times for the respective regulated flow-rates; data shown in tables are calculated as arithmetic averages from the measured values. Volume measured in litres was converted to weight unit in order to calculate the amount of brought-in and let-out heat Q and temperature coefficient K.

Heat amount

$$Q = m \times c \times (t_2 - t_1)\ [\mathrm{J}], \tag{1}$$

m... weight of substance [kg],
c..... specific heat capacity [Jkg^{-1}K^{-1}],
t_2.... final temperature [K],
t_1.... initial temperature [K].

Heat exchange coefficient

$$K = A \frac{Q}{\dfrac{(t_{A_i} - t_{B_e}) - (t_{A_e} - t_{B_i})}{\ln \dfrac{((t_{A_i} - t_{B_e}))}{(t_{A_e} - t_{B_i})}}}\ [\mathrm{W.m^{-2}.K^{-1}}], \tag{2}$$

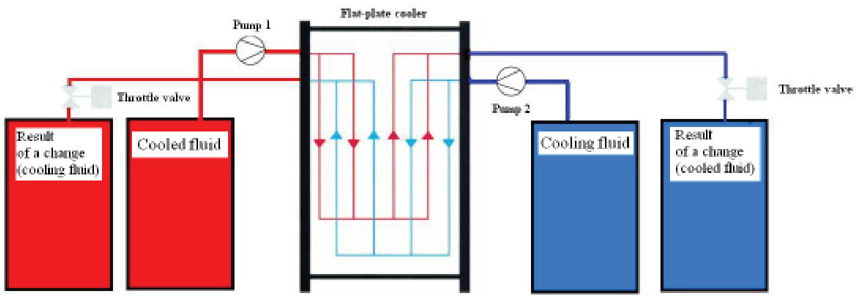
Q ... heat amount [J],
A ... area [m^2],
t_{A_i}... input temperature of cooled fluid [K],
t_{A_e}.. output temperature of cooled fluid [K],
t_{B_e}... input temperature of cooling fluid [K],
t_{B_i}... output temperature of cooling fluid [K].

Power plate cooler

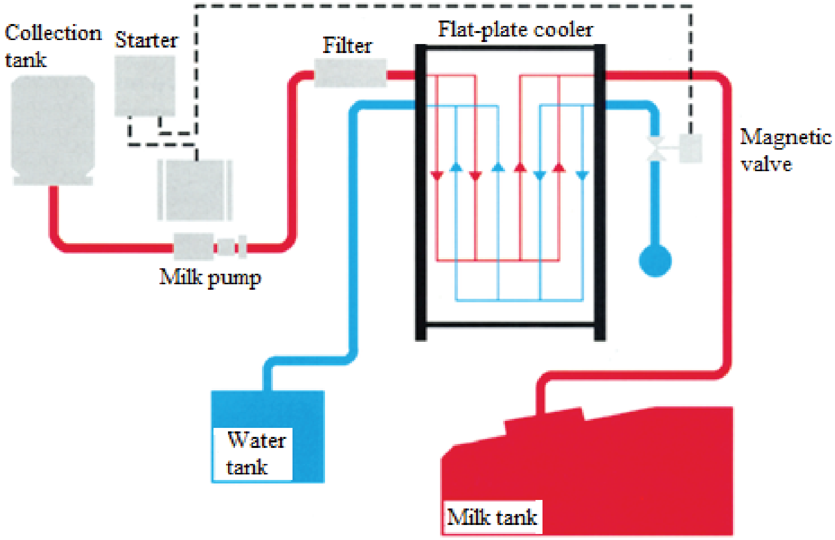
$$P = \frac{Q}{t}\ [\mathrm{W}], \tag{3}$$

Q ... heat amount [J],
t ..... time [s^{-1}].

The operating measurement was carried out in Hospodářské obchodní družstvo Jabloňov-Ruda. This agricultural facility operates a tandem milking parlour, 2 × 3. The drawn milk is cooled by means



1: *Diagram of laboratory measurements*
[source: author]



2: *Flat-plate cooler connection to the cooling process – diagram*
[source: author]

of the compressor system MCZC136MTA02E manufactured by Danfoss with an expansion valve (Ullrich, 2000), which provides for ice storage (cold storage) in the cooling tank wall in a period between milking. During milking, the ice melts and once melted away, the milk cooling only depends on the instantaneous output of the cooling unit. The first measurement took place in the existing system (without the use of the flat-plate cooler). The cooling unit was connected to an electrometer which monitored the total system consumption. Once the milking started, the milk pump actuation time was recorded along with the volume and temperature of the pumped milk and the continuous temperature in the cooling tank. The next day, the milk cooling process was extended by the flat-plate cooler (Fig. 2). Once the milk pump was switched on, the magnetic valve got automatically opened and freshly drawn milk was pre-cooled in the flat-plate cooler by water coming from a water main. During the measurement, we recorded the temperature and volume of milk and water, the total consumption of el. power of the system and continuous temperature in the cooling tank.

The volume was measured in litres and then converted to a weight unit so as to calculate the volume of let-out, fed-in heat Q, temperature coefficient K and the flat-plate cooler output.

RESULTS AND DISCUSSION

Comparing the resulting values with parameters provided by the manufacturer, we can conclude that the values were achieved during the measurements.

I: *Change of cooling water parameters on passing through the cooler (cooled water throttling regime)*

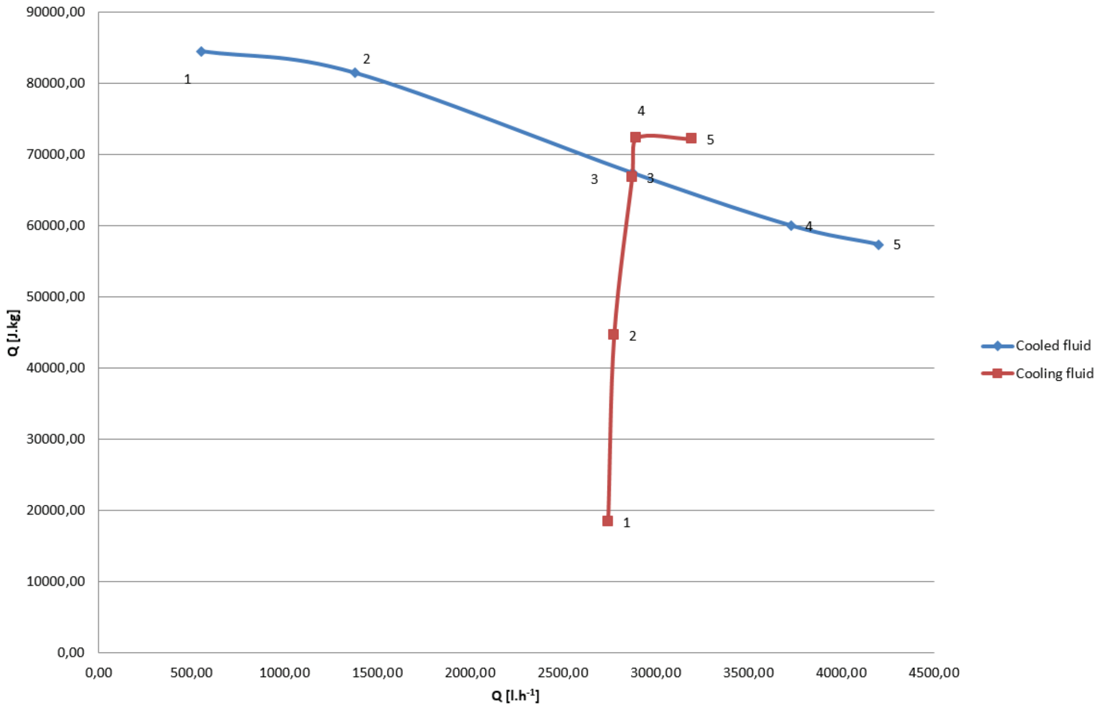
T_1 [°C]	T_2 [°C]	m [kg]	Q [J]	P [W]	i [J.kg^{-1}]	K [W.m^{-2}.K^{-1}]
13.0	17.4	22.88	420884	14029	18392	969
13.0	23.6	23.15	1032664	34422	44600	2805
13.0	28.9	23.95	1598906	53296	66754	4265
13.0	30.3	24.15	1746498	58216	72314	4584
13.0	30.2	26.65	1923580	64119	72188	4818

[source: author]

II: *Change of cooled water parameters on passing through the cooler (cooled water throttling regime)*

T_1 [°C]	T_2 [°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

[source: author]



3: *Graph of dependence of enthalpy change between the cooling and cooled fluid on the flow*
[source: author]

III: *Change of cooled water parameters on passing through the cooler (cooling water throttling regime)*

T_1 [°C]	T_2 [°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

[source: author]

IV: *Change of cooling water parameters on passing through the cooler (cooling water throttling regime)*

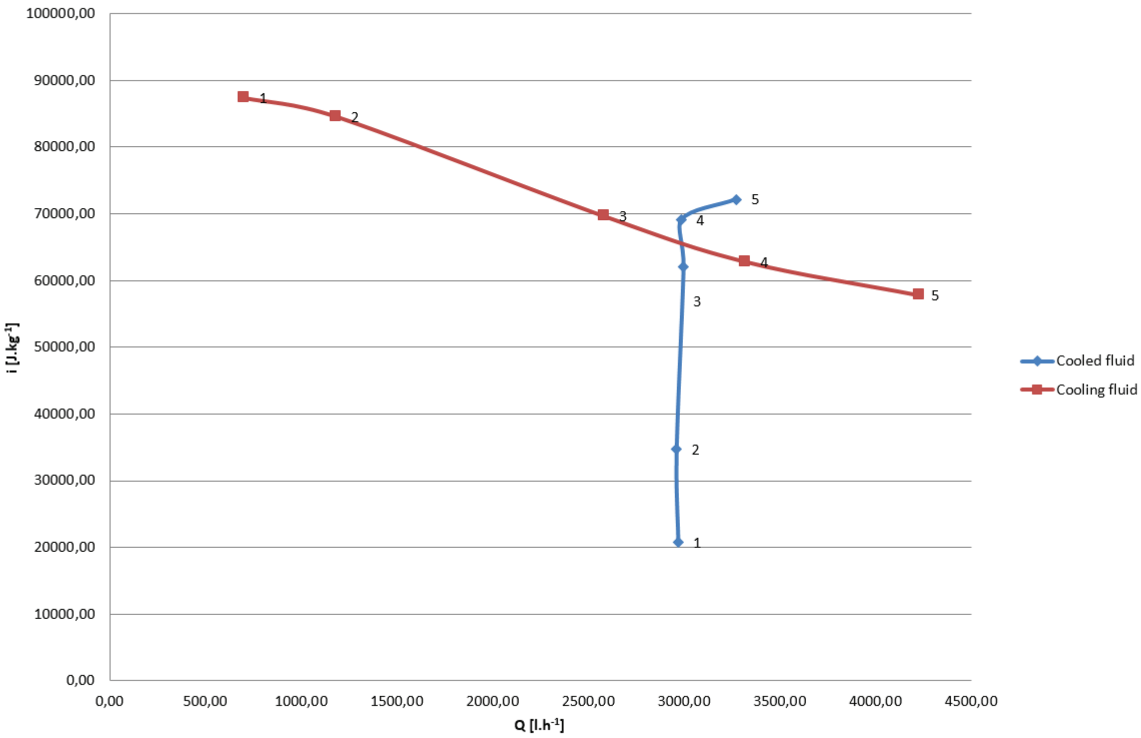
T_1 [°C]	T_2 [°C]	m [kg]	Q [J]	P [W]	i [J.kg⁻¹]	K [W.m⁻².K⁻¹]
13.0	33.9	5.86	511941	17064	87362	1397
13.0	33.2	9.85	833067	27768	84575	2269
13.0	29.6	21.52	1499226	49974	69666	3835
13.0	28.0	27.67	1738764	57958	62839	4461
13.0	26.8	35.23	2037116	67903	57823	5136

[source: author]

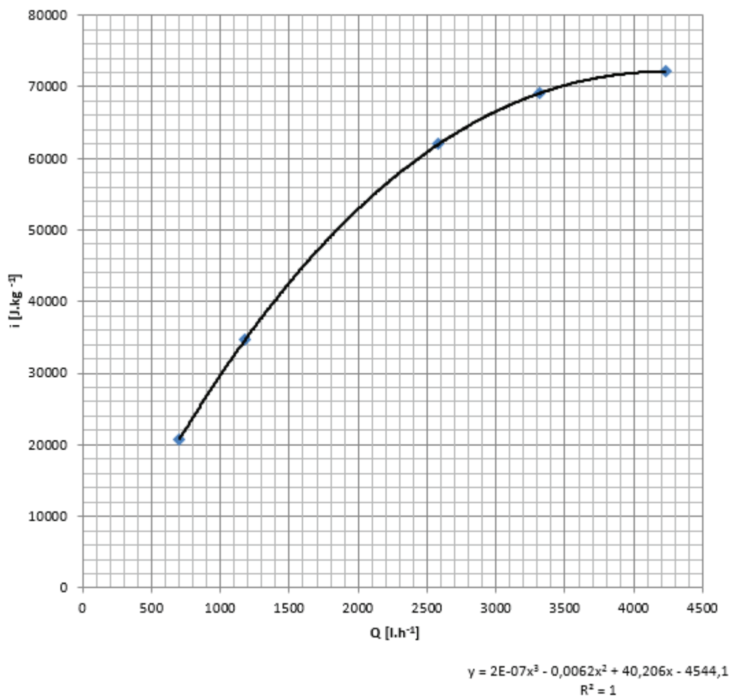
For the type of the used flat-plate cooler (Type 42) the manufacturer claims milk temperature of milk on the output by 2–4 °C higher than the temperature of cooling water on the input at a flow-rate of 4,000 litres of milk per hour. In our case, this temperature difference ranged near the upper limit provided by the manufacturer.

Fig. 5 shows the dependence of the cooled water heat content change on the volume of cooling water – the increase is negligible starting from a flow rate of 3,000 $l.h^{-1}$. Fig. 6 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 of cooling water was set as optimal.

During the measurement in the existing system (without the use of the flat-plate cooler) (Fig. 7), the temperature of milk flowing into the cooling tank ranged between 35–38 °C. At the end of milking, the temperature in the tank was 24.1 °C. During the period defined by the standard as 150 min, the milk temperature in the tank was 5.2 °C, and therefore the system was not capable of reaching the temperature of 5 °C in the required time. El. power consumption for cooling reached

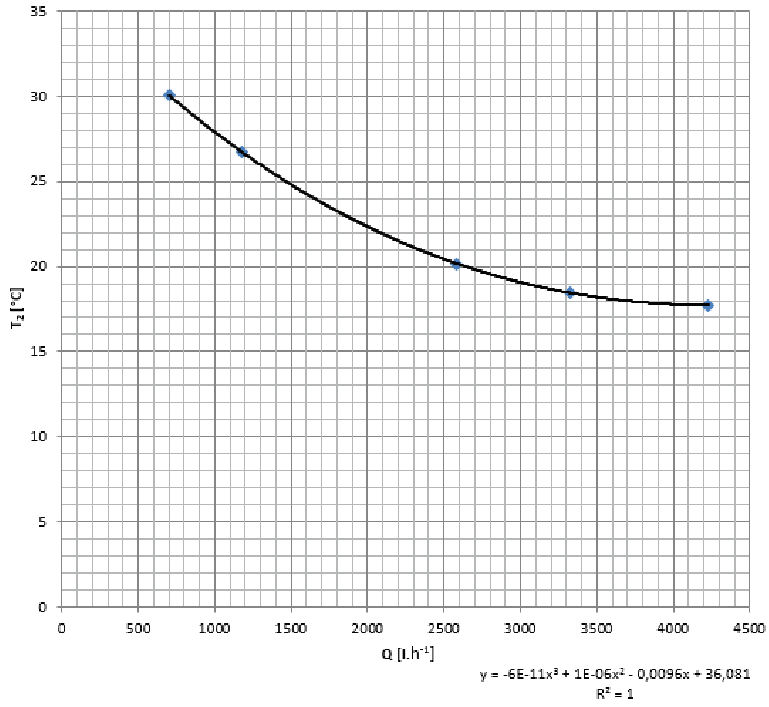


4: *Graph of dependence of enthalpy change between the cooling and cooled fluid on the flow*
[source: author]

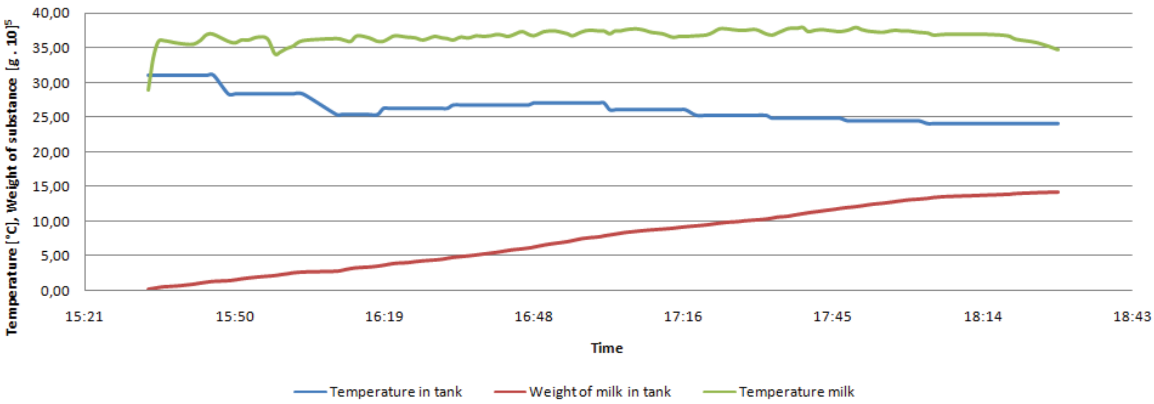


5: *Graph showing the dependence of cooling water air flow on changes in the cooled water heat content*
[source: author]

51 kWh. Fig. 8 shows the dependence of the milk volume, milk output temperature, cooling water output temperature, temperature in the tank when using the flat-plate cooler and the temperature in the tank without the flat-plate cooler. When using the flat-plate cooler (Abdallah, Basiouny,



6: *Graph showing the dependence of cooling water air flow on cooled water temperature reduction*
[source: author]

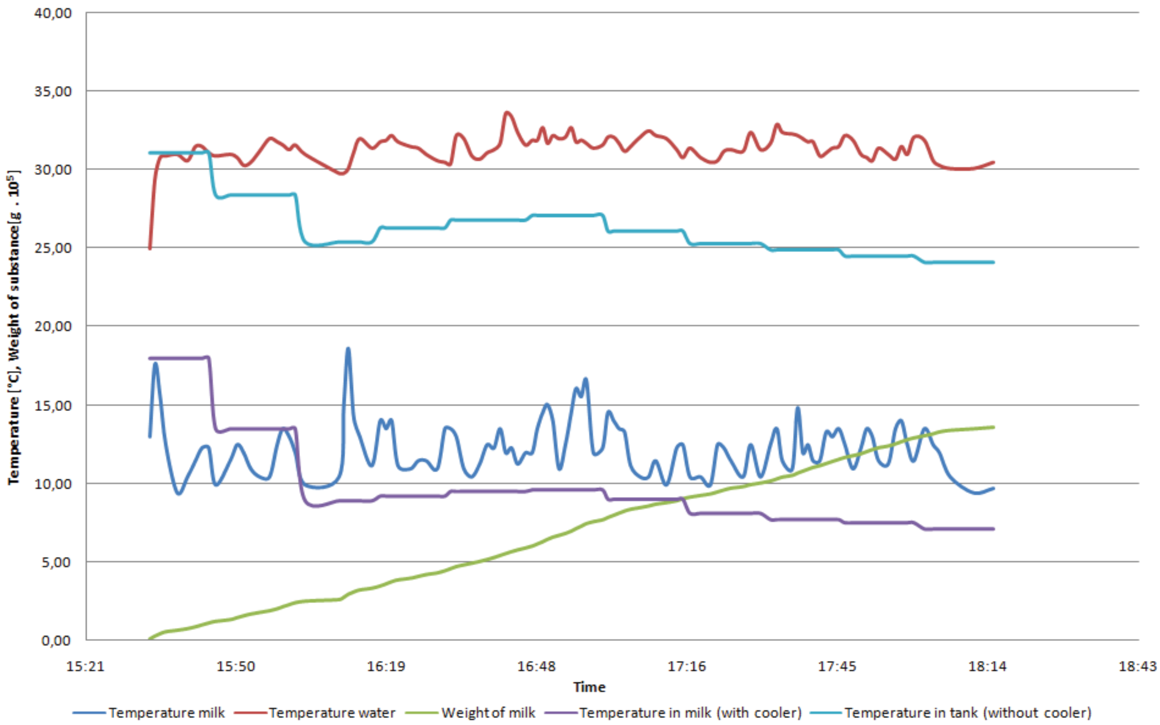


7: *Graph showing the measured values at measuring without a cooler*
[source: author]

2012), the pre-cooled milk temperature flowing into the tank ranged between 19–21 °C and, thanks to this, the temperature in the tank after milking was 7.1 °C and the desirable temperature of 5 °C was achieved in the system 60 min after the end of milking (Tab. V). El. power consumption totalled 28.18 kWh. When comparing the resultant values with parameters specified by the manufacturer, we can conclude that these values were achieved by the measurement. For the applied type of the flat-plate cooler (Type 42), the manufacturer specifies an output milk temperature which is by 2–4 °C higher than the cooling water temperature at the inlet at a flow rate of 4,000 litres of milk per hour. In our case, this difference in temperatures ranged between 4.7–8 °C at a flow rate of 2,200 litres of milk per hour. In total, 1357.85 kg of freshly drawn milk was cooled per measurement; the average output of the flat-plate cooler was 42 kW. The total quantity of heat transferred via the flat-plate cooler totalled 88.5 MJ, which was reflected in the cooling system el. power reduction of 22.82 kWh, generating a 44.75% reduction compared to the original consumption.

CONCLUSIONS

Graphs (Figs. 3, 4) 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



8: *Graph showing the measured values at measuring with a cooler*
[source: author]

V: *Temperature in the tank (t_1 use of flat-plate cooler, t_2 without flat-plate cooler*

Time [s]	T_1 [°C]	T_2 [°C]
15:30	18.0	30.1
15:45	13.5	28.4
16:00	8.9	25.4
16:15	9.2	26.3
16:30	9.5	26.8
16:45	9.6	27.1
17:00	9.0	26.1
17:15	8.1	25.3
17:30	7.7	24.9
17:45	7.5	24.5
18:00	7.1	24.1
18:15	6.5	23.5
18:30	6.1	23.0
18:45	5.6	22.4
19:00	5.0	21.6
19:15	4.5	21.1
19:30	4.5	20.2
19:45	4.5	19.5
20:00	4.5	18.4
20:15	4.5	17.2
20:30	4.5	15.2
20:45	4.5	14.3
21:00	4.5	13.5

[source: author]

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. Although the operating measurement did not achieve the parameters specified by the manufacturer, the measurement results confirm that the introduction of the flat-plate coolers in the process of cooling freshly drawn cow's milk reduces the costs of electricity for the cooling system by close to fifty percent. The required temperatures in the cooling tank could be achieved within an hour, which meets the standardised limit of 150 minutes with a significant reserve. The results indicate an important finding of an inadequate cooling output of the cooling system, which was translated into an excessively long cooling period needed to reach the desired temperature in the tank. This deficiency was eliminated by applying the flat-plate cooler.

SUMMARY

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 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. At the same time, 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 volume 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. Volume measured in litres was converted to weight unit in order to calculate the amount of brought-in and let-out heat Q and temperature coefficient K. The measured values show dependence of the cooled water heat content change on the volume of cooling water – the increase is negligible starting from a flow rate of 3,000 $l.h^{-1}$. Data 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 of cooling water was set as optimal. During the measurement in the existing system (without the use of the flat-plate cooler), the temperature of milk flowing into the cooling tank ranged between 35–38 °C. El. power consumption for cooling reached 51 kWh. When using the flat-plate cooler the pre-cooled milk temperature flowing into the tank ranged between 19–21 °C. El. power consumption totalled 28.18 kWh. In total, 1357.85 kg of freshly drawn milk was cooled per measurement; the average output of the flat-plate cooler was 42 kW. The total quantity of heat transferred via the flat-plate cooler totalled 88.5 MJ, which was reflected in the cooling system el. power reduction of 22.82 kWh, generating a 44.75% reduction compared to the original consumption. 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.

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