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SIMULATION OF HEAT TRANSPORT DURING THE PROCESS OF COOLING A SUGAR SOLUTION IN A RECUPERATION EXCHANGER

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Abstract. The paper describes a mathematical model of the cooling process of a highly concentrated sugar solution in an exchanger with a specifically shaped heat exchanging surface of the cooling panels. An analysis of the individual parts of the stum cooling line is made, dealing with the cooling performance of the cooling panels located in the stum tanks, whose volume is 3230 litres or 1430 litres. One of the monitored parameters is the cooling performance of the JN30 aggregate. The article also deals with the appropriateness of the aggregate for cooling the stum with a total volume 78.21 m^3, from the real operation temperature to 0 °C during 48 hours.

Keywords: concentrated solution; cooling; numeric simulation..

1. Introduction

The cooling performance of cooling units working on the principle of coolant compression and expansion depends on the operating temperature of the evaporator. The heat transport from the aggregate to the appliance is done via heat transferring medium, which is usually an anti-freeze fluid. The appliance used for cooling of various solutions (such as stums) is a heat exchanger (cooling panel). The heat in the primary circuit is transferred by force convection; the heat in the secondary circuit is led away by free convection. In order to determine the dependence of solution temperature on time during the cooling, it is necessary to know the cooling performance of the heat transfer surface. The performance is dependent on the geometric shape, the physical properties of the heat transfer material, the material characteristics of the panel, the physical characteristics of the solution from which the heat flow is led away, and on the temperature gradient between the panel and the solution. By increasing the temperature gradient, the performance of the cooling panel increases, but the performance demand of the cooling device decreases. The derivation of the mathematical dependencies describing the balanced thermodynamic state of this process is the basic presupposition allowing us to design devices of this kind.

When determining the cooling performance of the panel, criteria equations are used from which we can calculate the HTC (Heat Transfer Coefficient) between the external heat exchanging surface and the cooled solution. However, there is a problem with defining the average panel temperature, as the temperature arrangement on the heat exchanging panel may be significantly uneven. For this reason, it is better to execute the calculation using a numerical method, for example using the ANSYS CFX program.

The final mathematical model has been used to verify the thermal performance of a particular device intended to cool the stum. The cooling aggregate performance of the JN30 type is 27.5 kW at a cooling mixture temperature of 13 °C. The aggregate works at a pressure of 2.5 bar and at a cooling mixture flow of 120 l min^{-1}. The volume of the cooling mixture tank is 330 litres. The device cools down 22 tanks with a volume of 3230 litres (T1400 tank type) and 5 tanks with a volume of 1430 litres (T930 type), which equals 78210 litres of stum in total.

The mathematical model requires a knowledge of the functional dependence of the cooling performance (P_{ch}) on the cooling mixture temperature at the entrance to the cooling panel (t_{v1}). Using the data from the technical documentation of the JN30 device, a regression equation in the following form was derived:

$$P_{\mathrm{ch}} = a t_{\mathrm{v1}} + b = 938.98 t_{\mathrm{v1}} + 15380. \qquad (1)$$

At a temperature of approximately 0 °C, the cooling performance of the installed device falls to approximately 15 kW. Cooling the stum cooling to the temperature of approximately 0 °C in 2 days requires an increase in the cooling aggregate performance. That is why the calculation is focused on the heat transfer in the cooling panels, as well as on obtaining the cooling curve for 100 % of the volume of the cooled stum, and on the minimum cooling performance necessary to meet the requirement of the stum cooling.

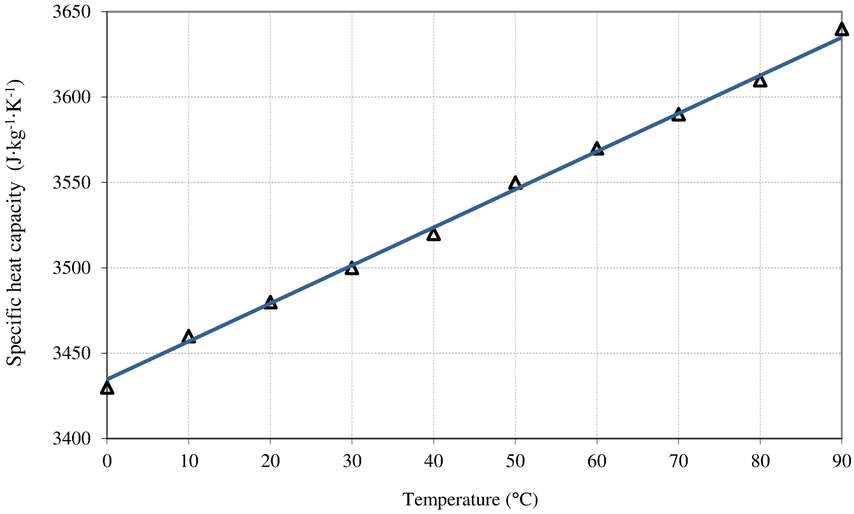

FIGURE 1. Dependence of the specific thermal capacity of the 30 % sugar solution on the temperature.

Entered values					
Δt_N	(°C)	−4	−8	−15	−20
S	(m^2)	1.1627			
t_{v1}	(°C)	−4			
Q_m	($kg\ s^{-1}$)	0.0773			
Calculated values					
t	(°C)	0	4	1	16
c_{str}	($J\,kg^{-1}\,K^{-1}$)	3699	3702	3704.7	3707.4
t_{v2}	(°C)	−3.053	−1.892	0.586	2.704
$t_{str\text{-}panel}$	(°C)	−1.491	1.413	7.198	11.812
α_{panel}	($W\,m^{-2}\,K^{-1}$)	159.4	205.4	305.5	406.7
$P_{ch,panel}$	(W)	270.8	603.2	1313.3	1921.2
P_{ch}	(W)	6634	14779	32176	47071

TABLE 1. Entered and calculated values.

2. Heat transfer in the cooling panels

In order to construct the heat exchanger thermal balance equation, it is necessary to know the dependence of the cooling performance of the panel on the temperature difference (Δt_N) between the cooling mixture (t_{v1}) and the stum temperature (t). In order to achieve this, numerical calculations for four temperature states have been made (at the temperature differences of $\Delta t_N = -4, -8, -15, -20$ °C) and for the nominal flow of the cooling mixture through one panel of $7.407 \cdot 10^{-5}\,m^3\,s^{-1}$ (corresponding to the total flow of $120\,l\,min^{-1}$ through 27 cooling panels). In order to ensure the temperature gradient between the coolant and the stum, the cooling mixture temperature must be constantly lower than the stum temperature. The higher the absolute value of the temperature difference, the higher the panel cooling performance. Table 1 shows the values of the input data and the values of the relevant parameters calculated by analytic procedure or by numerical simulation.

In Table 1, S is the real total heat exchanging surface of the cooling panel (m^2), t_{v2} is the temperature of the cooling mixture on the cooling panel output (°C), $t_{str\text{-}panel}$ is the average temperature of the rustless panel surface (°C), c_{str} is the thermal capacity of the coolant at its average temperature ($J\,kg^{-1}\,K^{-1}$), Q_m is the mass flow of the coolant ($kg\,s^{-1}$), α_{panel} is the heat transfer coefficient on the panel surface ($W\,m^{-2}\,K^{-1}$), $P_{ch,panel}$ is the cooling performance of one panel (W).

The heat transfer coefficient from the stum to the cooling panel surface was determined from the criteria (2) and (3) for a free convection at the vertical panel [1]:

$$Nu = \left(0.825 + 0.387(Ra\, f(Pr))^{1/6}\right)^2, \tag{2}$$

$$f(Pr) = \left(1 + (0.492/Pr)^{9/16}\right)^{-16/9}. \tag{3}$$

In order to calculate the Prandtl (Pr) and Rayleigh (Ra) similarity criteria, it is necessary to know the material characteristics of the stum, which consists, ideally, of a mixture of water and sugar with an amount of 400 g of sugar per 1 litre of the solution [2]. The volume concentration c, which is calculated as the

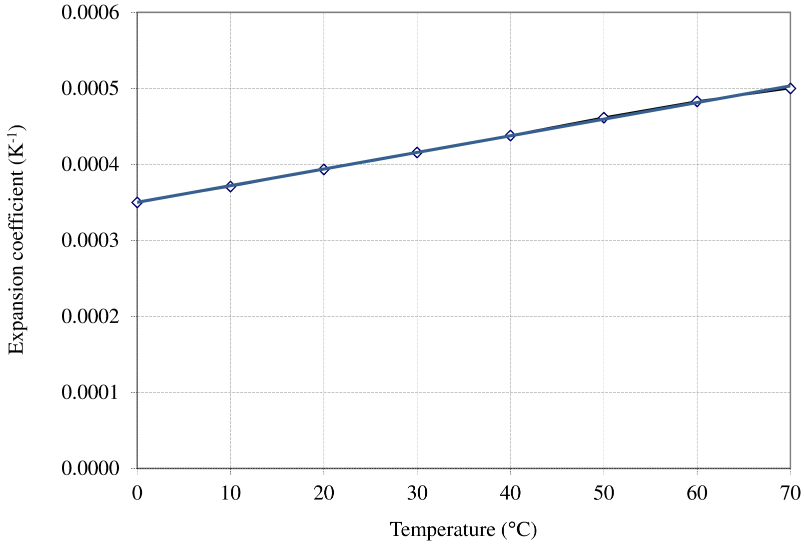

FIGURE 2. Dependence of the volume expansion coefficient of the 30 % sugar solution on temperature.

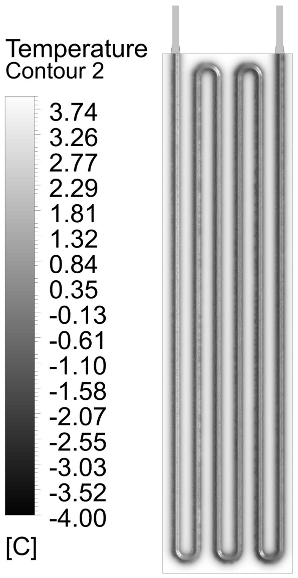

FIGURE 3. Temperature field at $\Delta t_{\mathrm{N}} = -8\,°\mathrm{C}$.

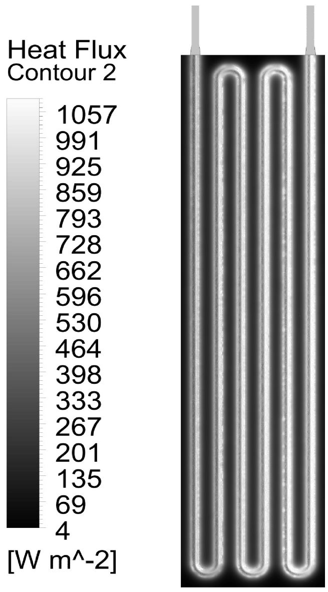

FIGURE 4. Heat flux at $\Delta t_{\mathrm{N}} = -8\,°\mathrm{C}$.

ratio of the sugar weight to the total solution weight, is about 30 %. The dynamic viscosity of this solution has the value of $3.188 \cdot 10^{-3}$ Pa s at the temperature of 20 °C and $2.5 \cdot 10^{-3}$ Pa s at the temperature of 30 °C. The temperature dependence of the dynamic viscosity of liquids may be described [2] by exponential dependence

$$\eta = A\mathrm{e}^{B/T}. \qquad (4)$$

The value of the following constants, $A = 2 \cdot 10^{-6}$ Pa s and B = 2160.4 K, has been obtained thanks to a logarithmic calculation of (4), and by solving a set of two linear equations.

The thermal conductivity of the solution is linearly dependent on the concentration c (kg/kg) [3]:

$$\lambda = Dc + E. \qquad (5)$$

The variables D and E are functionally dependent on the temperature of the solution, in accordance with

$$D = 5.466 \cdot 10^{-8}t^2 - 1.176 \cdot 10^{-5}t - 3.024 \cdot 10^{-3}, \qquad (6)$$

$$E = -7.847 \cdot 10^{-6}t^2 + 1.976 \cdot 10^{-3}t + 0.563. \qquad (7)$$

The thermal capacity of the solution in the range of 0 to 90 °C is shown in Figure 1 [4].

The volume expansion of the sugar solution may be defined from the known density dependence on temperature. It is determined by solving the following equation numerically:

$$\beta = -\frac{1}{\varrho}\left(\frac{\partial \varrho}{\partial T}\right)_p. \qquad (8)$$

The dependence of the coefficient β of the used solution on temperature in the range from 0 to 70 °C is plotted in Figure 2.

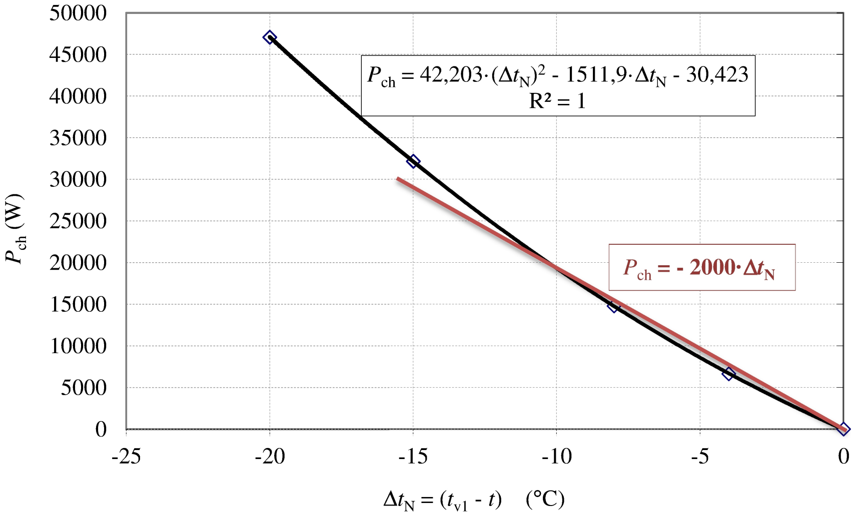

Figure 5. Dependence of the cooling performance on the temperatures of the cooling mixture and of the stum.

In the T1400 and T930 tanks, cooling panels with similar channel arrangements are used for the cooling mixture transport, but the panel of the T930 tank has half the total dimension and channel length compared to the T1400 tank panel. Taking these facts into account, the total cooling performance of 24.5 cooling panels is considered (22 panels of the T1400 type + 0.5 × 5 panels of the T930 type). The temperature field of the cooling panel in the axis section is seen in Figure 3 at $\Delta t_N = -8$°C. The distribution of heat flux on the surface of the panel at above specified boundary conditions is shown in Figure 4.

The course of another investigated dependence of the cooling performance of all the panels on the temperature difference of the cooling mixture and the stum is shown in Figure 5.

The regression line describing the cooling performance must cross zero because if the mixture and the stum have the same temperature, the cooling performance is zero. The regression dependence equation for a performance ranging from 0 to 30 kW is in the form of

$$P_{ch} = d\Delta t_N = -2000\Delta t_N. \tag{9}$$

This equation shows that in order to achieve a cooling performance of 27.5 kW, it is necessary to bring the cooling mixture to a temperature which is lower by 13.75 °C than the temperature of the stum (at the stum temperature of 0 °C, the cooling mixture will have the temperature of -13.75 °C).

3. JN30 device cooling capacity calculation

The cooling device takes off the thermal output (P_{ch}) from the tank, including the heat exchange with the environment (P_{ok}), and at the same time the heat taken from the tank material and from the stum (P_{ak}) – Figure 6.

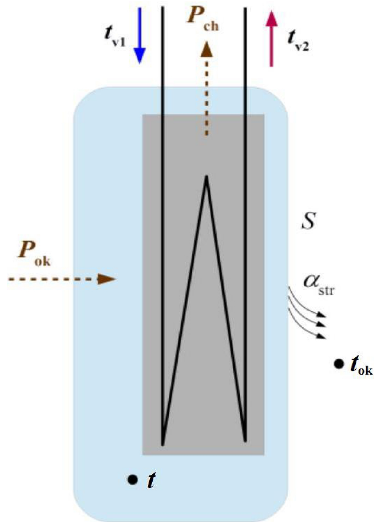

Figure 6. Stum tank scheme with thermal flows.

The thermal balance of this system may be written in a time unit as the following equation:

$$P_{ok} - P_{ch} = P_{ak} \tag{10}$$

The thermal flow coming from the environment into the tank is given by the Newtonian relationship and the accumulated performance is described by a calorimetric equation concerning the elementary time change [5–7]:

$$n\alpha_{str}S(t_{ok} - t) - P_{ch} = \sum(mc)\frac{dt}{d\tau}. \tag{11}$$

where α_{str} is the average value of the transfer coefficient at the surrounding temperature of 8 °C and in the interval of the tank surface temperatures of 0 to 22 °C (W m^{-2} K^{-1}); S is the external heat exchanging surface of the tank (m^2); t_{ok} is the environment temperature (°C); t – stum temperature in time τ (°C); n – number of cooling panels (1); P_{ch} – device cooling performance (W); m – cooled material weight (kg);

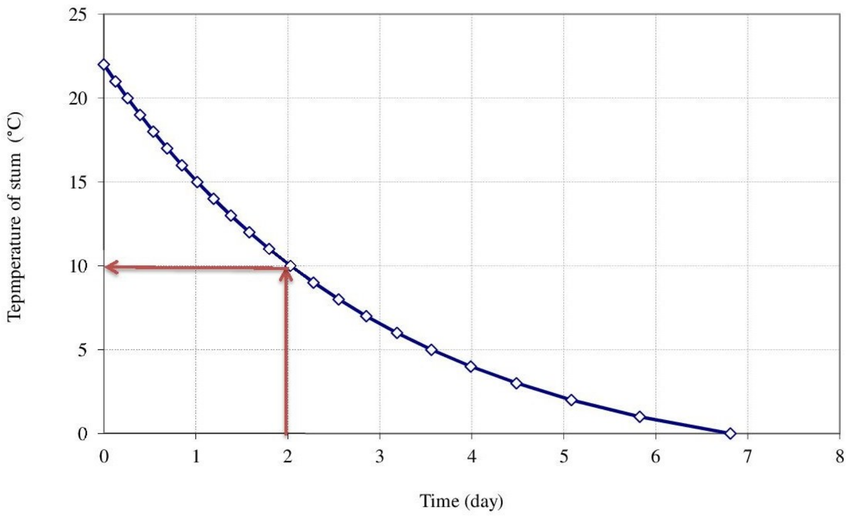

FIGURE 7. Course of the stum temperature, depending on time.

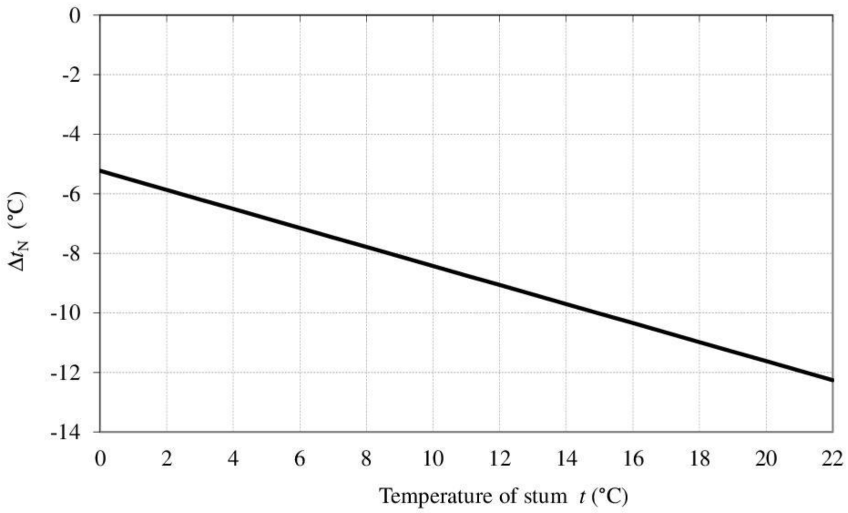

FIGURE 8. Dependence of excessive cooling of the cooling mixture on the stum temperature.

c – specific thermal capacity of the cooled material ($\mathrm{J\,kg^{-1}\,K^{-1}}$). The item of $\sum(mc)$ in relationship (11) represents the total capacity of the stum, the stainless tank and the cooling panel material.

If the equation $t_{v1} = \Delta t_N + t$ applies, the differential equation which describes the stum temperature dependence on time, can be obtained by combining (1) and (11)

As there is the following equation: $t_{v1} = \Delta t_N + t$, this is the connection of relationships (1) and (11), a differential equation describing the stum temperature dependence on time, which may be constructed in the following form:

$$\mathrm{d}\tau = \frac{\sum(mc)}{n\alpha_{\mathrm{str}}St_{\mathrm{ok}} - n\alpha_{\mathrm{str}}St - at - a\,\Delta t_N - b}\mathrm{d}t. \quad (12)$$

If the thermal losses in the distributions are omitted, the thermal performance, taken by all the panels, must be equal to the performance of the JN30 cooling device. This shows the uniformity of relationships (1) and (9), on the basis of which you can define the functional dependence between Δt_N and the stum temperature t in the following form:

$$\Delta t_N = \frac{a}{d-a}t + \frac{b}{d-a}. \quad (13)$$

After inputting Δt_N from relationship (13) to (12), we get

$$\mathrm{d}\tau = \frac{\sum(mc)}{n\alpha_{\mathrm{str}}St_{\mathrm{ok}} - n\alpha_{\mathrm{str}}St - at - a\frac{a}{d-a}t + \frac{b}{d-a} - b}\mathrm{d}t. \quad (14)$$

By solving the differential equation (14), we get the resulting relationship for the calculation of the dependence of the stum temperature change on time, whose solution is in the following form:

$$\tau = \frac{1}{n\alpha_{\mathrm{str}}S + a + \frac{a^2}{d-a}}\sum(mc)$$
$$\ln\frac{\left(n\alpha_{\mathrm{str}}St_{\mathrm{ok}} - \frac{ab}{d-a} - b\right) - \left(n\alpha_{\mathrm{str}}S + a + \frac{a^2}{d-a}\right)t_1}{\left(n\alpha_{\mathrm{str}}St_{\mathrm{ok}} - \frac{ab}{d-a} - b\right) - \left(n\alpha_{\mathrm{str}}S + a + \frac{a^2}{d-a}\right)t}, \quad (15)$$

where t_1 is the stum temperature at the beginning of the cooling process (°C).

The stum cooling time according to (15) was calculated for the following parameters: number of tanks $n = 24.5\,\mathrm{pcs}$, $\alpha_{\mathrm{str}} = 2.853\,\mathrm{W\,m^{-2}\,K^{-1}}$, surface $S = 11.875\,\mathrm{m}^2$, coefficient of linear regression from (1) $a = 938.98\,\mathrm{W\,K^{-1}}$, coefficient of linear regression from (1) $b = 15380\,\mathrm{W}$, coefficient of linear regression from (9) $d = -2000\,\mathrm{W\,K^{-1}}$, stum volume in one tank $V = 3.23\,\mathrm{m}^3$, stum density $\varrho = 1400\,\mathrm{kg\,m^{-3}}$, steel weight $m_{\mathrm{oc}} = 148.9\,\mathrm{kg}$ (weight of the steel tank coating and weight of the cooling panel), specific thermal capacity of steel $c_{\mathrm{oc}} = 465\,\mathrm{J\,kg^{-1}\,K^{-1}}$, temperature of environment $t_{\mathrm{ok}} = 8°C$, stum thermal capacity $c = 3460\,\mathrm{J\,kg^{-1}\,K^{-1}}$, initial temperature of the cooled stum $t_1 = 22\,°\mathrm{C}$. The time course of the stum is shown in Figure 7.

On the basis of the described model, we may calculate the dependence of excessive cooling of the cooling mixture on the stum temperature (Figure 8).

Figure 8 shows that at a stum temperature of 0 °C, the temperature of the cooling mixture is -5.2 °C. At this temperature, frost may form on the heat exchanging surface, which significantly increases the thermal resistance of the cooling panel and lowers the stum cooling intensity. An increase of the cooling mixture temperature can be achieved for example by increasing the heat exchanging surface of the cooling panel.

4. Conclusion

The methodology for determining cooling parameters using a combination of a numeric and an analytical calculation enables us to describe the dynamic behaviour of the cooling system precisely. With the help of the described model, it is possible to determine the cooling performance, the cooling factor and the excessive cooling of the cooling medium not only in relation to the temperature of the cooled solution, but also to the changes of these parameters over time.

The executed thermal calculations show that the analysed cooling device cannot cool $78.21\,\mathrm{m}^3$ of stum in 48 hours from the initial temperature of 22 °C to 0 °C, but that it makes it possible, within the given timeframe, to cool the stum to the temperature of 10 °C (arrows in Figure 7). At the moment, the cooling aggregate is only fully sufficient for the cooling of the given amount of stum to the temperature of the managed fermentation, which is approximately 7 °C.

The requirement of cooling the stum to the temperature of approximately 0 °C in 2 days will be fulfilled if the performance of the cooling aggregate increases from the current 27.5 kW to approximately 47 kW. Due to the large temperature difference between the cooling mixture temperature and the stum temperature at the performance of 47 kW, it might be appropriate to also increase the total heat exchanging surface of the cooling panels.

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