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Analysis of the Heat Transfer at Final Cooling Process of Sweet Biscuits

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Abstract- The conceptual solution for the final cooling of the chocolate dressing of biscuit in one confectionary factory in Serbia was presented in this paper. The proposed concept solution was derived from the desired technological process of final cooling of biscuit and the required process parameters that were to be achieved, and which were an integral part of the project task. The desired process parameters for achieving proper hardening and coating formation are: the exchanged amount of heat in the time unit between the two media (air and chocolate dressing), speed of air inside the tunnel cooler and the surface of all biscuits in contact with the air. These parameters were calculated in the paper. The final cooling of chocolate dressing on biscuits could be optimized by changing process parameters and dimensions of the tunnel cooler, and looking for the appropriate values for them.

The accurate temperature predictions and fluid flow analysis could be conducted by using heat balance and flow balance equations having in mind theory of similarity. Furthermore, some parameters were adopted from previous technology process, such as: inlet temperature of biscuits and input air temperature. A thermal calculation was carried out and it was demonstrated that the percentage error between the contact surface of the air and the chocolate biscuit topping, which is obtained from the heat balance and geometrically through the proposed conceptual solution, does not exceed 0.67%, which is very good agreement. This enabled quality of the cooling process of chocolate dressing applied on biscuit and hardness of its coating.

***Keywords*:** chocolate dressing, hot air, cooling, heat balance.

1. Introduction

Company JAFFA” at Crvenka, in Serbia, produces biscuits called: Jaffa, overflowing with jelly with the taste of orange and chocolate. It was necessary to install a device for final cooling of the base of Jaffa. The main purpose of this device and the entire cooling tunnel is to perform the final cooling and hardening of the chocolate mass based on Jaffa biscuits with jelly. It is envisaged that the device is made of high-quality metal sheets, which is thermally insulated, in order to prevent unnecessary wastage and cold air losses. A complete device with a tunnel, precision mechanical circuits and drive electronics should be represented reliable device for carrying out a technological operation of cooling biscuits.

The design of all parts should fully meet the ergonomic conditions and allow workers to work properly during production. All circuits and sub-assemblies must be readily available to all workers who are in charge of approaching and monitoring its work, for the purpose of preventive and concrete maintenance [1].

2. Description of the Device for Cooling of the Jaffa Biscuits

Figure 1 shows the tunnel cooler as one of the possible solutions for final cooling of biscuit in A.D.„Jaffa” – Crvenka, Serbia..

Fig.1: The tunnel cooler (the mid part of the tunnel)

On the Figure 2. It's shown the conceptual solution of the complete device for final cooling of Jaffa biscuit.

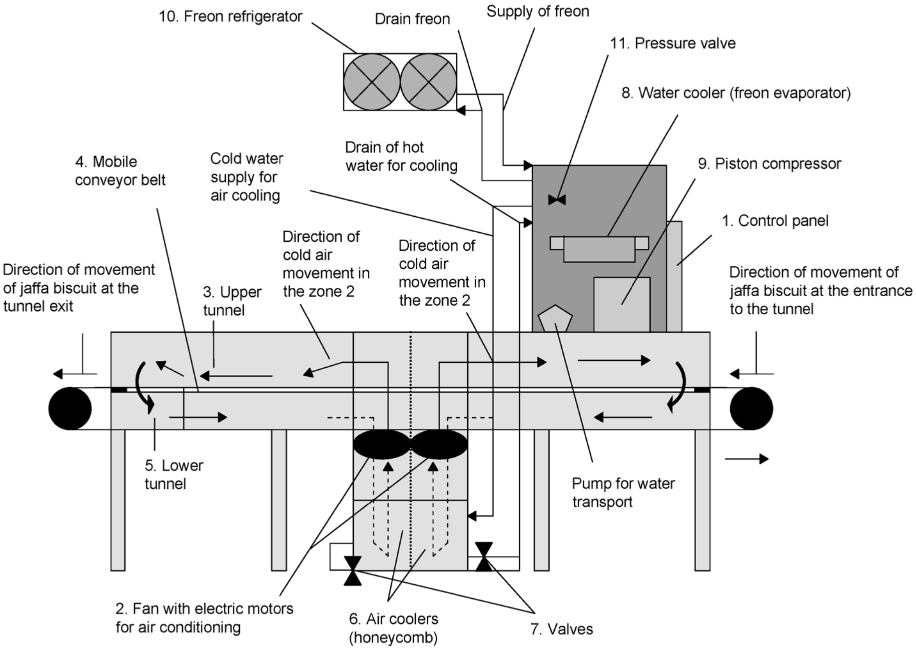

Fig. 2. Complete device for cooling of Jaffa biscuit

2.1 Elements of the Final Cooling Device for Jaffa biscuit

1. Control panel
2. Fan with electric motors for air conditioning
3. Upper tunnel
4. Mobile conveyor belt
5. Lower tunnel
6. Air coolers (honeycomb)
7. Valves
8. Water cooler (freon evaporator)
9. Piston compressor
10. Freon refrigerator
11. Pressure valve

3. Description of the Jaffa Biscuit Final Cooling Technology Process

By the endless conveyor belt of the upper tunnel (Figure 2), from the right to the left, warm and complete Jaffa biscuits, which in zone 1 are cooled in contact with the cold air, which flows from the right (first) fan to zone 1. The air along the upper tunnel flows in the opposite direction from the movement of Jaffa biscuit. The air gently receives the heat from the biscuit, heats it, then goes through the return (bottom) tunnel, passes through the filter and transfers heat to the water, which is then heated. The air is again sucked by the same fan, and goes to the new cycle. There is therefore an intense heat exchange between the Jaffa biscuit and the air that cools them, and the air that cools the water that is heated.

After passing the Jaffa biscuit through zone 1, it further goes through zone 2 in which cold air, driven by a fan (first to zone 2), flows now in the same direction as the biscuit. The air returns through the return (bottom) tunnel and is sucked in the middle of the tunnel (from the side), from the fan (as in Zone 1), passes through the filter and transfers heat to the water, as in the previous case. It is envisaged that the fans are separated by the bulkheads as well as the middle of the upper tunnel from where the air flows to the right (zone 1) and to the left (zone 2), so as not to mix the current. Biscuit, after passing through the tunnel cooler, goes to packaging and storage. The tape returns back to the new biscuit reception. Possible measurements of mass of biscuits on conveyor belt was expressed in literature [2].

In Figure 3, a functional display of the final cooling system of the Jaffa biscuit is given.

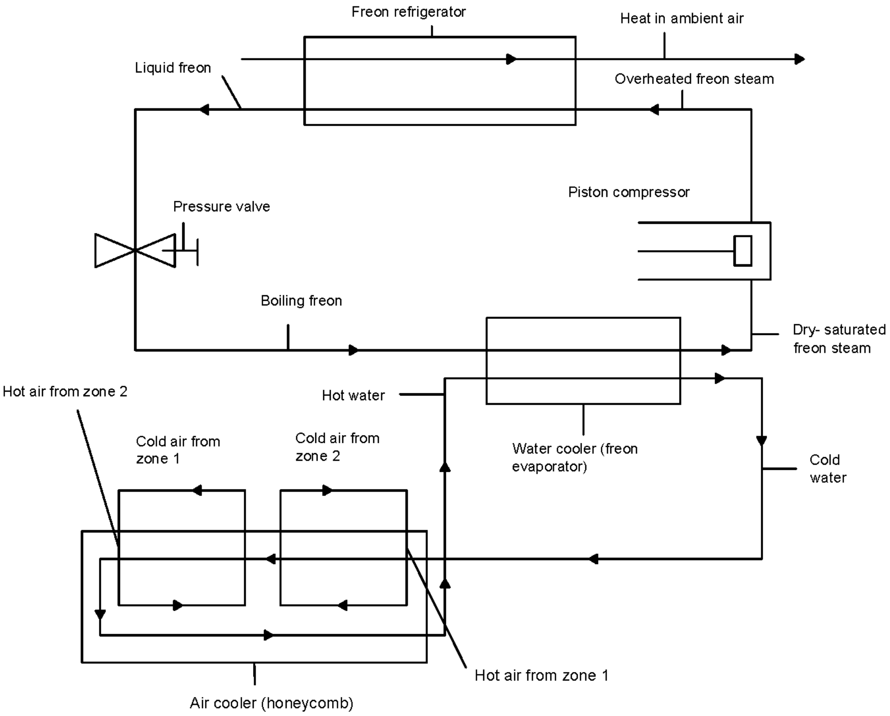

Fig. 3: Functional display of the final cooling system of the Jaffa biscuit

The water that received heat from the air during its cooling is taken from one and the other swapper of a common pipeline into the water cooler (freon evaporator) through the valve, which is leaking in exact quantities. The water cooler is located above the tunnel where freon is used as a working fluid. Freon, which receives heat from it during cooling of cooling water, evaporates. Therefore, the process of evaporation of freons should be timed in a way that all the heat generated from water during cooling is used to convert the boiling fluid (lower limit curve) to the state of the dry-saturated vapor of freon (upper limit curve) [3]. Evaporation of the freon takes place at constant pressure. The heat that freon received during the evaporation must pass on some medium. That medium is air outside the factory hall. The problem is that freon evaporates according to the tables at -12ºC to -7ºC [4], and the budgetary temperature of the environment for the second climate zone is -5ºC [5], up to the expected maximum 40ºC, depending on the season. It is necessary to raise the temperature of the dry-saturated freon to a temperature higher than the ambient temperature, in order for it to be able to release the heat received during evaporation. The dry-saturated steam of freon receives a piston compressor, which compresses at a higher pressure and at a higher temperature. On that occasion, the dry-saturated steam goes into the condition of overheated steam.

The overheated freon steam would be taken to the freon refrigerator located outside the hall 1. It would be performed as a multi-stage heat exchanger, where the heated freon steam flow through the tube, while from the outside of the tube ambient air flows by two fans. In the freon refrigerant, the freon cools to the state of the co-steam, so it condenses to the state of boiling liquids, and then cools the liquid phase further. This gives all the heat received to the environment. The entire cooling process of freons is carried out at approximately constant pressure.

In the end, since freon has given heat to the environment, it is necessary to return it to the initial lower pressure. To achieve this, the liquid freon, which returns to the inlet pipe, needs to be passed through the throttle valve, by which its pressure drops to the initial value and it reaches the state of the humid steam or at a lower pressure. On that occasion, the temperature drops further, also to the initial value. Freon is then brought back to the water cooler (freon evaporator), and then it is prepared for a new cycle of hot water cooling and re-evaporation

Therefore, in order for the final cooling of the Jaffa biscuit to proceed continuously, it is necessary to have a separate air-cooling system, in this case water, which constantly receives heat from the air and heats up.

Water cooling is designed with a special Freon apparatus that works on the left-handed Rankin-Claudius circular cycle.

4.Thermal Calculation of Cooling Process of Jaffa Biscuits

In this chapter, the required physical quantities for Zone 1 will be calculated, characterized by the process of heat exchange between the warm overflow of Jaffa biscuit and the cooler air, which receives the heat from the chocolate overflow. The heat exchange takes place in the tunnel shown in Figure 4. The requested sizes to be calculated are:

A^* (m^2) =?	- the surface of all Jaffa biscuits in contact with the air
w_2 (m/s) =?	- speed of air
$\dot{Q}$ (W) = ?	- the exchanged amount of heat in the time unit between the two media

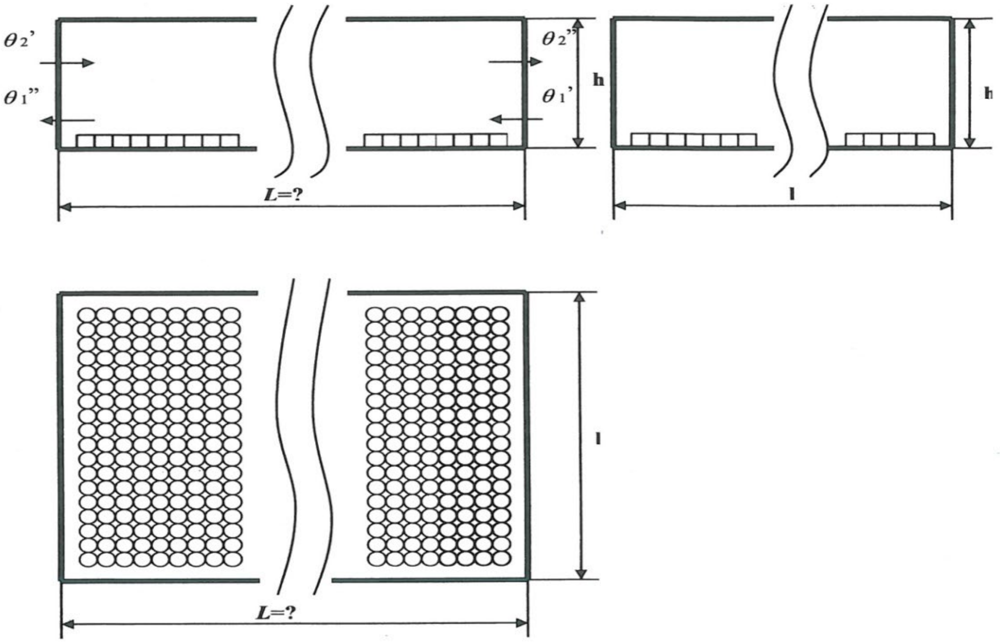

Fig. 4: Appearance of the tunnel for the final cooling of the Jaffa biscuit

The average air temperature in the chamber is (Figure 4):

$$\theta_{2sr} = \frac{\theta'_2 + \theta''_2}{2} \tag{1}$$

It was assumed that there was no significant pressure change along the cooling tunnel, so nominal atmospheric pressure and mean air temperature in the chamber were adopted for budget values from $p_{2sr} = 10^5 (Pa)$ and $\theta_{2sr} = 18(°\mathrm{C})$. From the corresponding tables [4], the data for the physical air velocities were adopted.

The average temperature of Jaffa biscuit is (Figure 4):

$$\theta_{1sr} = \frac{\theta'_1 + \theta''_1}{2} \tag{2}$$

For this temperature,

$Pr_z = 0.701$ - Prandtl's number in the border layer of air with the Jaffa biscuit topping

The cross-sectional area of the Jaffa biscuit is:

$$\mathrm{A}_1 = \mathrm{n} \cdot D \cdot H \tag{3}$$

The cross-sectional area of the tunnel through which the air flows is:

$$\mathrm{A}_2 = l \cdot \mathrm{h} - \mathrm{A}_1 \tag{4}$$

The mass flow of Jaffa biscuit will be:

$$\dot{m}_1 = \rho_1 \cdot w_1 \cdot \mathrm{A}_1 \tag{5}$$

The heat capacity of Jaffa biscuit is:

$$\dot{W}_1 = \dot{m}_1 \cdot C_1 \tag{6}$$

The Jaffa biscuit part of the heat flux is surrendered by cooling the cooling air, and the part by conveying the conveyor belt, so that the heat flux is fed to the air in the upper tunnel is:

$$\dot{Q} = \dot{W}_1 \cdot \left(\theta'_1 - \theta"_1\right) - \frac{\lambda}{\delta} \cdot \Delta\theta \cdot L \cdot l \tag{7}$$

The heat capacity of the air is now:

$$\dot{W}_2 = \frac{\dot{Q}}{\theta''_2 - \theta'_2} \tag{8}$$

Mass flow of air will be:

$$\dot{m}_2 = \frac{\dot{W}_2}{C_{p2}} \tag{9}$$

The air velocity is:

$$w_2 = \frac{\dot{m}_2}{\rho_2 \cdot \mathrm{A}_2} \tag{10}$$

Reynolds number is:

$$Re_2 = \frac{w_2 \cdot L}{v_2} > 500\,000 \quad - \text{the flow is turbulent} \tag{11}$$

Nusselt's number is [6]:

$$Nu_2 = 0{,}037 \cdot {Re_2}^{0{,}8} \cdot {Pr_2}^{0{,}43} \cdot \left(\frac{Pr_2}{Pr_z}\right)^{0{,}25} \tag{12}$$

The coefficient of heat transfer is:

$$\alpha_{t2} = \frac{Nu_2 \cdot \lambda_{t2}}{L} \tag{13}$$

The mean logarithmic temperature difference will be:

$$\Delta\theta_m = \frac{(\theta'_1-\theta''_2)-(\theta''_1-\theta'_2)}{\ln\frac{\theta'_1-\theta''_2}{\theta''_1-\theta'_2}} \tag{14}$$

The contact surface of the two media (air-chocolate dressing) is now:

$$\mathrm{A}^* = \frac{\dot{Q}}{\alpha_{t2}\cdot\Delta\theta_m} \tag{15}$$

From the geometric point of view, considering the proposed conceptual solution, the contact surface of the two media (air-chocolate dressing) would be:

$$\mathrm{A}^{*'} = N \cdot \mathrm{A} \tag{16}$$

The results of all calculated values from equations (1) ÷ (16) are given in Table 1:

Table 1: Calculated parameters from equations (1) ÷ (16)

No. of equation	Calculated values	Amount	Unit
1	θ_{2sr}	18	^{0}C
2	θ_{1sr}	27.5	^{0}C
3	A_1	0.021450	m^2
4	A_2	0.257550	m^2
5	$\dot{m}_1$	0.872	kg/s
6	$\dot{W}_1$	959.8446	W/K
7	$\dot{Q}$	1983.27	W
8	$\dot{W}_2$	495.82	W/K
9	$\dot{m}_2$	0.493	kg/s
10	w_2	1.59	m/s
11	Re_2	1944866	-
12	Nu_2	3418	-
13	α_{t2}	4.80	W/ (m^2K)
14	$\Delta\theta_m$	9.49	℃
15	A^*	43.538593	m^2
16	$\mathrm{A}^{*'}$	43.250376	m^2

The matching of the results is quite acceptable, as the percentage error is 0.67%, between equations (15) and (16). Figure 5 shows the temperature of air and biscuit along the tunnel.

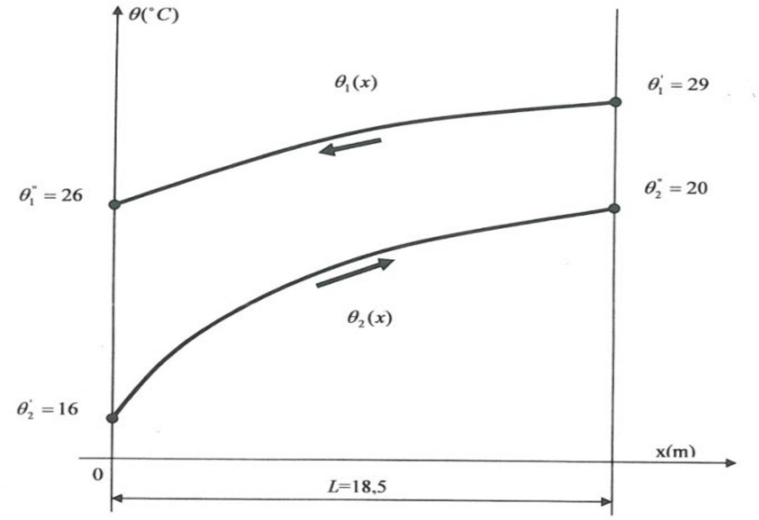

Fig. 5: Graphs of air temperature and chocolate overflow at the entrance and exit from the tunnel

5. Conclusion

Having all above in mind, it can be concluded that the constructively predicted half-length of the 18.5m cooling tunnel fully meets the required parameters necessary for the technological process of cooling the Jaffa biscuit. The thermal calculation showed a good agreement on the values obtained for the contact surface of two media (air-chocolate overlays), calculated in two different ways: through the heat balance and taking into account the geometric characteristics of the proposed conceptual solution. The desired temperature from the chocolate top at the exit from zone 1 of 26ºC corresponds to the continuation of the cooling process in zone 2, so that the final desired overflow temperature at the zone 2 exit is 23,5ºC. It is still necessary to carry out the techno-economic analysis and choose the optimal solution from the cooling devices present on the market. Certainly, when choosing an optimal solution, it is necessary to take into account the values of the quantities determined by the thermal budget, and especially when choosing a tunnel cooler with good insulating properties.

Nomenclature (additional)

n - number of biscuits
D - diameter of biscuit
H - height of biscuit
l - required bandwidth
h - proposed tunnel height
ρ_1 - density of biscuit
w_1- velocity of movement of biscuit
C_1 – specific thermal capacity of biscuit
λ - thermal conductivity of the conveyor belt
δ - predicted thickness of the conveyor belt
L - required strip length
ρ_2- density of air
C_{p2}- specific thermal capacity of air at constant pressure
λ_{t2}- thermal conductivity of air
ν_2- kinematic viscosity of air

Acknowledgments

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