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DESCRIPTION OF ENERGY BALANCE FOR SELECTED REFRIGERATION FURNITURE

Summary

Food is a product that breaks down quickly and easily. Therefore, it require storage at a low and controlled temperature. Maintaining a constant temperature inside the refrigeration furniture requires removal of the heat which enters the interior of the furniture and the heat produced by stored products. The paper presents methods of heat transfer implementation, such as: heat conduction (including fluid stratification case), natural and forced convection and radiation. Heat balance have been presented for selected refrigeration furniture including the characteristics of its individual parameters. A method for determining the components of a heat balance is also presented.
***Keywords**: heat balance, refrigeration furniture, stratification*

WYZNACZENIE BILANSU ENERGII DLA WYBRANYCH MEBLI CHŁODNICZYCH

Streszczenie

Żywność jest produktem, który szybko i łatwo się psuje, dlatego wymaga przechowywania w kontrolowanej temperaturze. Zachowanie niezmiennej temperatury wewnątrz mebla chłodniczego wymaga odprowadzenia ciepła, które dopływa do wnętrza mebla z otoczenia i ciepła wytwarzanego przez przechowywany produkt. Omówiono sposoby realizacji procesu przepływu ciepła takie jak: przewodzenie ciepła (w tym stratyfikacja), konwekcja naturalna i sztuczna oraz promieniowanie. Przedstawiono bilans cieplny dla wybranych mebli chłodniczych wraz z charakterystyką jego poszczególnych parametrów. Zaprezentowano również sposób pozwalający wyznaczyć składowe bilansu ciepła.
***Słowa kluczowe**: bilans cieplny, meble chłodnicze, stratyfikacja*

1. Introduction

A lifestyle observed in recent years has changed by increased interest in eating meals away from home. There is an intense development of various types of catering outlets. In each of these points there are different furniture used to display and store ready-made food products, e.g. refrigerated counters, bain maries, etc. In order to properly select the cooling system for the counter and the sites, it is necessary to draw up a thermal balance of refrigeration furniture. Therefore, it is important to understand the processes responsible for the transport of heat in these furniture. This issue will be devoted to this article.

2. Presentation of heat transfer processes
2.1. Heat conduction

As heat conduction one should understand the possibility of energy transfer in solid materials and static fluids under the influence of temperature difference [1, 2], according to following equation (1).

$$q_{ed} = -k \cdot \frac{\partial T}{\partial x} \qquad (1)$$

where:
q_{cd} – density of the heat conduction flux [W/m^2],
k – thermal conductivity [W/mK],
T – temperature [K].

The graphical representation of the phenomenon is presented in Fig. 1. In solid bodies, thermal energy is transmitted through the free movement of electrons and vibrations of atoms in the crystal lattice, while in the gases or fluids the kinetic energy of molecules and atoms is transmitted. The conduction of heat transfer takes place in case liquids and gases when there is no flow.

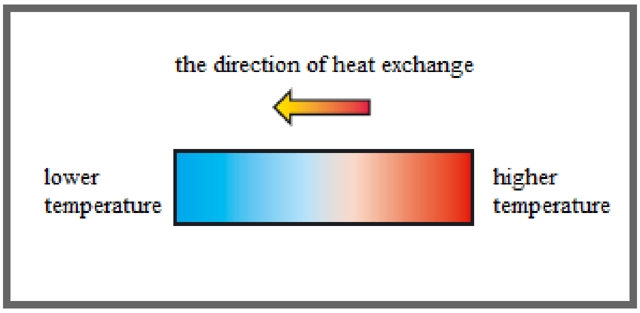


Fig. 1. Graphic example of heat conduction *[3]*
Rys. 1. Graficzny przykład przewodzenia ciepła [3]

2.2. Heat convection

In the case of fluids, in most cases heat transport is due to convection. Particular gas or liquid particles transfer energy due to changing their position as a result of mixing. For convection, it is necessary to occur the movement of particles in a given medium [2, 4]. The movement of particles may occur naturally due to the temperature difference. In this case the free convection occur. The fluid movement may also occur artificially, e.g. when the particles are moved by the use of a fan or pump, and heat transfer takes place as a forced convection. In the case, the pressure difference caused by the flow system (fan, pump, etc.) forcing the fluid movement. Forced convection is determined by the velocity of the fluid flow and surface geometry. Heat flux in case convective case can be describe by the equation (2).

$$q_{cv} = \alpha \cdot \Delta T \quad (2)$$

where:

q_{cv} – density of the heat convection flux [W/m^2],

α – heat transfer coefficient [W/m^{2}K],

ΔT – difference of temperature [K].

2.3. Radiation

Radiation is a phenomenon involving the transfer of heat by means of electromagnetic wave. A characteristic feature of this type of heat transfer is the lack of the need to contact surfaces of two bodies. Heat energy emitted by surface through an optically transparent medium [2] [5], is describe by equation (3).

$$q_r = \varepsilon \cdot \sigma \cdot T_s^4 \quad (3)$$

where:

q_r – density of heat radiation flux [W/m^2]

ε – emissivity of surface [-]

σ – constant of radiation [W/m^{2}K^4],

T_s – surface temperature [K].

2.4. Determination of the type of heat transfer in the selected refrigeration furniture

The thermal analysis of typical geometry of refrigeration bathtub leads to conclusion that dispoit that bathtub of refrigeration furniture fulfil by fluid, because of specific field of surface temperature the so call temperature stratification occure [4]. That means that in refrigeration bathtub instead internal free convection the conduction in cooling fluid occure. This effect was numerical simulated by use the convection and conduction equation (4).

$$\nabla(-\lambda \cdot \nabla T + \rho \cdot c_p \cdot T \cdot u) = 0 \quad (4)$$

where:

λ – thermal conductivity [W/mK],

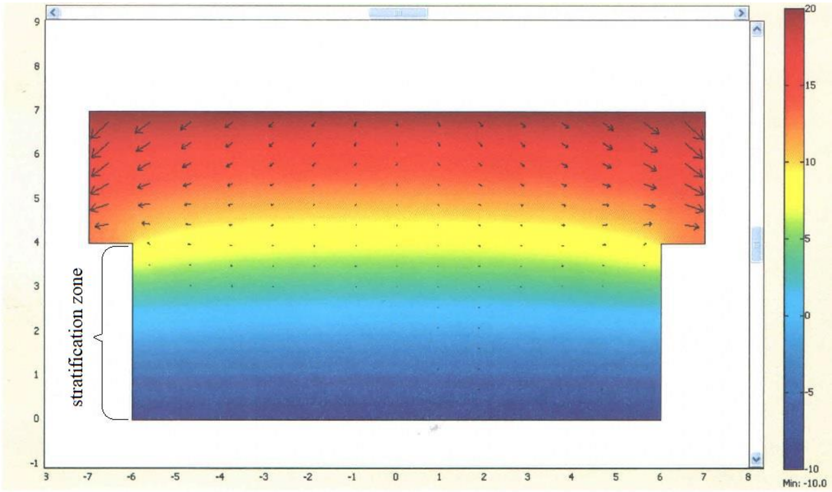
T – temperature [K],

ρ – density [kg/m^3],

c_p – thermal capacity [J/K],

u – velocity [m/s].

For the thermal stratification case the velocity u is equal 0 so conduction occure only. The dependence of fluid temperature on cooling surface is visible in Fig. 2 and 3.



Source: own study / Źródło: opracowanie własne

Fig. 2. Simulation of heat transfer in a refrigeration bathtub at the same bottom temperature over the entire width

Rys. 2. Symulacja przewodzenia ciepła w wannie chłodniczej przy jednakowej temperaturze dna na całej szerokości

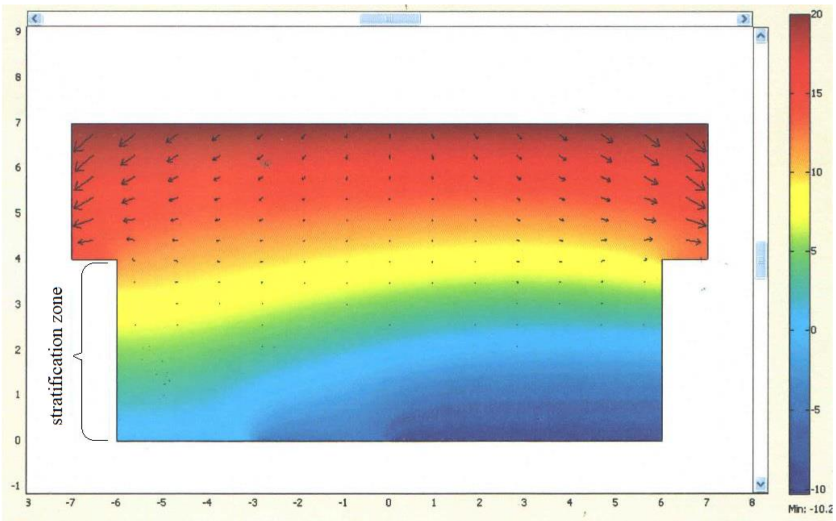


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Fig. 3. Simulation of heat transfer in a refrigeration bathtub at variable bottom temperature over the entire width

Rys. 3. Symulacja przewodzenia ciepła w wannie chłodniczej przy zróżnicowanej temperaturze dna na całej szerokości

3. Energy balance
3.1. Total heat flux

The amount of heat to be removed from the refrigeration furniture is determined by equation (5), used for selection of chillers for stationary refrigeration chambers [6].

$$\dot{Q} = C \cdot (\dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 + \dot{Q}_4 + \dot{Q}_5) \quad (5)$$

where:
$\dot{Q}$ – total heat flux delivered by the furniture cooling system [W],
C – coefficient describing the construction of refrigeration furniture,
$\dot{Q}_1$ – heat delivered from the environment [W],
$\dot{Q}_2$ – heat delivered by the product (when the temperature of the product being loaded is higher than the storage temperature) [W],
$\dot{Q}_3$ – heat of breathing of storage product [W],
$\dot{Q}_4$ – heat introduced with packaging (if exist) [W],
$\dot{Q}_5$ – heat used to drain moisture from the product [W].

The component not included in the balance sheet C (dependent on cooling furniture construction), according to the operating experience, captures the value from the range 1,05 ÷ 1,15. The smaller values are assumed for large volume chambers, larger for smaller spaces – in the case of a refrigeration unit, the upper value should be taken [7].

The value $\dot{Q}_1$ take into account the influence of all fluxes from the surroundings. It includes heat from lighting, people, ventilation, air conditioning and the refrigeration system unit build in cooling furniture. The mentioned heat fluxes does not directly influence the total energy balance, but react indirectly by affecting the ambient temperature.

The value of heat delivered in with the cooling product $\dot{Q}_2$ and introduced with the packaging $\dot{Q}_4$ approaches zero when the difference between the temperature of the product and the temperature of the interior of the refrigeration unit tends to zero.

The data from the literature [7] and from own calculations using the KOMORA computer program [7] reveals, which single mentioned heat have the greatest impact on the total heat. When storing fresh fruits and vegetables in a standard food storage container [8], the total heat from the refrigeration furniture mainly depend on heat delivered from the environment $\dot{Q}_1$ and heat of breathing of storage product $\dot{Q}_3$.

3.2. Description of the heat flux from the environment

In order to determine the amount of heat delivered to the refrigeration bathtub, it is first necessary to estimate the heat transfer coefficient for the stratified zone in the refrigeration bathtub k_g on the basis of equation (6).

$$k_g = \frac{\lambda_g}{\mathrm{d}_g} \quad (6)$$

where:
k_g – coefficient of heat transfer through the zone stratified in the refrigeration bathtub [W/m^{2}K],
λ_g – thermal conductivity of the cooling tank load [W/mK],
d_g – thickness of the bath filling layer [m].

On the basis of the calculated k_g coefficient, it is possible to determine the amount of heat penetrating from the top of the bathtub $\dot{Q}_g$ according to the equation (7).

$$\dot{Q}_g = k_g \cdot \Delta T \cdot A_g \quad (7)$$

where:
$\dot{Q}_g$ – heat flux penetrating from the top [W],
k_g – coefficient of heat transfer through the zone stratified in the refrigeration tub [W/m^{2}K],
ΔT – temperature difference between the bottom surface of the refrigeration tub and the environment [K],
A_g – area of the bathtub upper surface [m^2].

The next step is to determine the heat transfer coefficient due to conduction through the insulated side walls k_b according to equation (8).

$$k_b = \frac{\lambda_b}{\mathrm{d}_b} \quad (8)$$

where:
k_b – coefficient of heat transfer through insulated side walls [W/m^{2}K],
λ_b – thermal conductivity of insulation of the side walls [W/mK],
d_b – thickness of side walls insulation [m].

Then one can calculate the amount of heat flux entering through the side walls $\dot{Q}_b$ according to the equation (9).

$$\dot{Q}_b = \sum k_b \cdot \Delta T \cdot A_b \quad (9)$$

where:
$\dot{Q}_b$ – heat flux flowing from the sides of the bathtub [W],
k_b – coefficient of heat transfer through insulated wall [W/m^{2}K],
ΔT – temperature difference between the refrigeration bathtub and ambient temperature [K],
A_b – surface area of the bathtub walls [m^2].

Summing up above values according to equation (10) it is possible to determine the total heat flux which is transfer to the refrigeration bathtub as follow. Heat flux $\dot{Q}_g$ can take into account the heat flux due to radiation if it is necessary.

$$\dot{Q}_1 = \dot{Q}_g + \dot{Q}_b \quad (10)$$

where:
$\dot{Q}_1$ – total value of the heat flux penetrating from the environment [W],
$\dot{Q}_g$ – heat flux penetrating from the top [W],
$\dot{Q}_b$ – heat flux penetrating to the side, front and back sides [W].

3.3. Description of heat of breathing

Table 1 and 2 shows the example values of the heat of breathing of selected fruits and vegetables. Almost all of the mentioned raw materials mentioned have a relatively wide range of breathing heat values for a given temperature. This is due to significant differences in the course of metabolic processes depending on their physiological status, age and species varieties. Using the data from Tables 1 and 2 to draw up the thermal balance of cooling in refrigeration furniture, the higher value of the heat of breathing should be taken.

The intensity of respiratory processes in fruit and vegetable tissues is greatly increased as a result of mechanical damage and microbial infection. Therefore, fruits and vegetables damaged mechanically or infected with diseases are not suitable for storage.

The values given in the tables correspond to the heat of breathing per ton of product weight in 24 hours. In order to obtain the desired value in the unit [W], one can transform the selected value from the table according to the equation (11).

$$\dot{Q}_3 = \frac{m}{1000} \cdot \frac{q_{hb}}{24 \cdot 3600} \tag{11}$$

where:

$\dot{Q}_3$ – heat flux of breathing [W],

m – product weight [kg],

q_{hb} – heat of breathing [kJ/t (24 h)].

4. Conclusion

The presented equations (10), (11) enable to calculate the values of heat flux flows from the environment and stored products. In order to obtain the values necessary to carry out the energy balance, according to equation (5), the operating time of the refrigeration unit should be taken into account in the previously determined values.

The carried out analysis show that the inside furniture heat transfer occure in cooling furniture takes place mainly due to the rule of conductivity. Natural convection in the heat transfer process inside furniture does not play a significant role, because the temperature distribution of air flow around furniture occur. Therefore, it is not so important to make transparent covers for products exposed in bathtubs.

Table 1. The heat of breathing some vegetables at different temperatures *[9]*
Tab. 1. Ciepło oddychania niektórych warzyw w różnych temperaturach [9]

Type	Heat of breathing kJ/t (24 h)		
	0°C	5°C	20°C
Dry onions for storage	532-721	836-1558	—
Garlic	638-2545	1367-2241	2317-4218
Kohlrabi	2317	3800	—
Parsley	7677-10697	15349-19768	45584-59307
Celery	1672	2545	15011
Spinach summer	2698-4978	6345-7486	43019-50278

Table 2. Heat of breathing of some fruits at different temperatures *[9]*
Tab. 2. Ciepło oddychania niektórych owoców w różnych temperaturach [9]

Type	Heat of breathing kJ/t (24 h)		
	0°C	5°C	20°C
Peach (Elberta)	874	1520	14252
Black berry	532-2432	2127-3850	12047-20294
Raspberry	4104-5815	7182-8968	26601-57004
Orange (Florida)	721	1482	6992
Strawberry	2850-4104	3800-7715	23752-45527
Grape (Labrusca, Concrd)	645	1254	7600

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