Optimization of Cold Store Thermal Insulation

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***Abstract*— The paper presents a method to calculate the thermal insulation of a cold store consisting of four rooms where four temperature levels must be maintained below the ambient temperature. The calculation takes into account the intermediate values of temperatures and vapor partial pressures between the layers of thermal insulation, so that the condensation of water vapor to be avoid.**

***Keywords*— insulation, dew point temperature, vapor partial pressure, layer**

I. INTRODUCTION

This paper presents a method of calculating the thermal insulation of a refrigerated food and frozen food warehouse, which uses for cold production a refrigeration system with mechanical vapor compression, with two compression stages.

The outside temperature for which the thermal insulation of the walls is dimensioned is 30 [°C]. Air humidity is 60 [%]. The warehouse has the following characteristics: refrigeration capacity 20 [t/day], indoor temperature is –1 [°C], refrigerated storage capacity 55 [t/day], indoor temperature is 0 [°C], freezing capacity 30 [t/day], the indoor temperature is -20 [°C], the storage capacity of frozen products 80 [t/day], the indoor temperature is -18 [°C], the refrigerant used in the installation is ammonia (NH3), the intermediate agent is the CaCl2 solution, the coolant of the condenser and the sub-cooler is water, whose temperature on flow is 24 [°C] and on the return is 28 [°C].

The warehouse consists of: refrigeration room, refrigerated products room, freezing room and frozen products room

In the next phase, the surfaces of all the rooms of the cold store were determined.

II. SIZING OF THE COLD STORE ROOMS

The calculation of the surfaces of the refrigeration rooms shall be carried out according to their capacity and after loading the products on 1 [m^2] (area) or 1 [m^3] (volume). The built-up surface of the rooms shall be determined by the loading surface, taking into account the distance of the stacks from a wall and the passes between the stacks of products (1).

$$S_i = \frac{q_i \cdot 10^3}{N_i} \qquad (1)$$

q_i = load capacity

N_i (the norm of loading with products per unit surface of the floor) = 500

$S_{i1} = 36\ [m^2]\ \ q_{i1} = 18\ [t]$ (refrigeration room)

$S_{i2} = 54\ [m^2]\ \ q_{i2} = 15\ [t]$ (freezer room)

$S_{i3} = 81\ [m^2]\ \ q_{i3} = 40.5\ [t]$(room of refrigerated products)

$S_{i4} = 108\ [m^2]\ q_{i4} = 54\ [t]$ (room of frozen products)

A. *Calculation of the useful surfaces*

$$S_u = S_i \cdot \beta \qquad (2)$$

$S_{u1} = 50.4\ [m^2]$, $S_{u2} = 75.6\ [m^2]$, $S_{u3} = 105.3\ [m^2]$

$$S_{u4} = 140.4\ [m^2]$$

where β = coefficient taking into account the distances between product stacks and between stacks and walls (Table 1).

Table 1 β values

$S_{U\,i}$ [m^2]	< 6	6 – 30	30 – 80	80 – 300	> 300
β	1.8	1.5	1.4	1.3	1.2

-Verification of processing capacity q_p taking into account the specific loading norm N_i (3)

$$q_p = \frac{S_U \cdot N_i}{1000} \qquad (3)$$

$$q_{p1} = 25.2\ [t] \qquad q_{p3} = 52.6\ [t]$$

$$q_{p2} = 37.8\ [t] \qquad q_{p4} = 70.2\ [t]$$

-Calculation of throughput R for each room in the store structure (4)

$$R = r \cdot q_i \quad [t/24h] \qquad (4)$$

$$R_1 = 200\ t/24h],\ R_3 = 440\ \ [t/24h]$$

$$R_2 = 300\ [t/24h], \qquad R_4 = 640\ \ [t/24h]$$

where r = percentage of maximum storage capacity

$r_R = 4 \div 12$ [%] – for refrigeration

$r_C = 10 \div 15$ [%] – for freezing

$r_{DR} = 5 \div 10$ [%] – for storage of refrigerated products

$r_{DC} = 5 \div 10$ [%] – for storage of frozen products

-Calculation of the actual useful surface S_U^r

$$S_U^r = \frac{24\cdot R\cdot 1000}{N_i}\cdot\frac{\tau}{24} = \frac{24\cdot R\cdot 1000}{N_i}\cdot\frac{70}{24} \qquad (5)$$

$S_{U1}^r = 28\ [m^2], S_{U2}^r = 42\ [m^2], S_{U3}^r = 61.6\ [m^2]$

$$S_{U4}^r = 89.6\ [m^2]$$

-Calculation of the actual area of each surface, taking into account the distance between the stacks (6)

$$S_f = \beta_i \cdot S_U \qquad (6)$$

$S_{f1} = 42.00\ [m^2] \qquad S_{f3} = 86.24\ [m^2]$

$S_{f2} = 58.80\ [m^2] \qquad S_{f4} = 116.98\ [m^2]$

Because $S_f > S_i$, initial surface sizes are accepted.

III. THERMAL INSULATION STRUCTURE

In order to reduce cold losses, the exterior building elements of the cold store building are supplemented with a layer of heat resistant materials called insulation.

The main role of the cold store insulation is to reduce the heat transfer through the exterior walls. In this way, more uniform temperatures can be achieved in the food storage rooms. The economic function of a cold store depends, to a large extent, on the quality of the insulation.

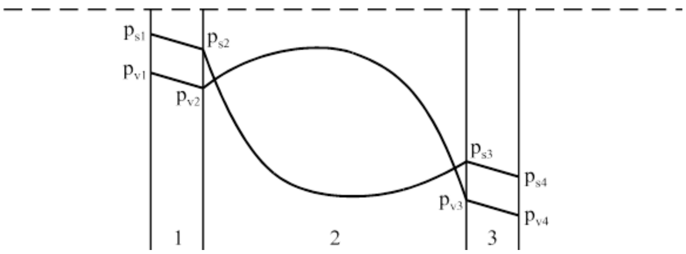

Fig. 1 Vapor partial pressure distribution

The quality of the insulation depends on the right choice of insulating material, of sufficient thickness, on the rational combination of insulation with building materials to protect against moisture. If the insulation is good, it is possible to install a lower capacity refrigerated machine.

The quality of the insulation is determined by the heat transmission coefficient K [kcal/m^2·h·grad] and it depends on the coefficient of thermal conductivity of the insulation material used [λ]. The calculation of the insulation of the cold store consists in determining the coefficient of heat transmission through the outer walls. For this purpose, the thickness of the layer of insulating material is adopted.

The heat transmission coefficient for the outside surface depends on the destination and size of the cold store, the temperatures inside and outside the rooms, and the cost of insulation and refrigeration equipment.

Insulation materials shall meet the following conditions:

-to have a low coefficient of thermal conductivity;

-to have low hygroscopicity;

-to be resistant to pressing;

-to be free of smell;

-not to be assailable by rodents, fungi, molds etc.;

- to be stable to chemical influences;

-to be easily processed;

- to be cheap.

One of the most important qualities required of an insulating material is not to be hygroscopic, because the absorption of water or water vapor leads to increased volume and diminished its insulating properties. By ingress of water vapor into the insulated wall, condensation and even freezing can occur. These considerations lead to the conclusion that the condensation process is carried out when the process has the partial pressure of water vapor in a given layer higher than the vapor saturation pressure corresponding to the temperature in that layer, according to the Fig.1, in which:

p_s= partial saturation pressure of water vapor at temperatures t_1, t_2, t_3, t_4

The wall distribution of partial vapor pressures is shown in Figure 1.

In order to avoid condensation, the curve indicating the variation in the partial pressure of water vapor (p_v) must be below the saturation pressure curve and not intersect, so that the vapor does not reach the dew point. The following recommendations shall be taken into account when introducing the vapor barrier:

-the vapor barrier is always applied on the warm side of the wall;

-the vapor barrier is not applied to the outer walls of rooms with internal temperatures above –30C, as well as to the partition walls where the heat flow can be reversed;

- no vapor barriers are applied between the layers of insulating material, they are stuck with bitumen, not in continuous layer but through points.

A. *Insulation of the exterior walls of the frozen products storage room*

For construction elements, the following materials, placed from the outside to the inside (Fig.2), shall be used:

1. layer of brick

thickness: $\delta_1 = 250\ [mm]$

coefficient of thermal conductivity:

$$\lambda_1 = 0.75\ [kcal/m \cdot h \cdot grd]$$

2. layer of equalizing plaster made of cement mortar

thickness: $\delta_2 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_2 = 0.75\ [kcal/m \cdot h \cdot grd]$$

3. bitumen layer

thickness: $\delta_3 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_3 = 0.72\ [kcal/m \cdot h \cdot grd]$$

4. layer of polystyrene insulation

thickness: $\delta_4 = \delta_{iz}$

coefficient of thermal conductivity:

$$\lambda_4 = 0.035\ [kcal/m \cdot h \cdot grd]$$

5. layer of interior plaster

thickness: $\delta_5 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_5 = 0.75\ [kcal/m \cdot h \cdot grd]$$

Heat transmission coefficient:

$$K = \frac{1}{\frac{1}{\alpha_e}+\sum\frac{\delta}{\lambda}+\frac{\delta_{iz}}{\lambda_{iz}}+\frac{1}{\alpha_i}}\left[\frac{W}{m^2} \cdot grd\right] \qquad [7]$$

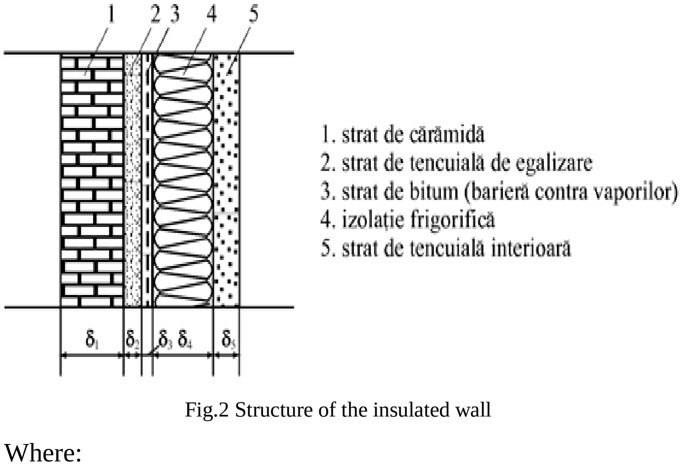

Fig.2 Structure of the insulated wall

Where:

α_e = heat transfer coefficient from the outside air to the outside surface of the walls;

$\alpha_e = 25\ [kcal/m^2 \cdot h \cdot grad]$ for walls exposed to the wind.

α_i = heat transfer coefficient from the inner wall to the air of the room;

$\alpha_i = 10\ [kcal/m^2 \cdot h \cdot grad]$.

And:

$$\sum_{i=1}^{n}\frac{\delta_i}{\lambda_i} = \left(\frac{\delta_1}{\lambda_1}+\frac{\delta_2}{\lambda_2}+\frac{\delta_3}{\lambda_3}+\frac{\delta_5}{\lambda_5}\right)+\frac{\delta_{iz}}{\lambda_{iz}}$$

If the type of insulation material as well as the method of execution of insulation was chosen, then at an estimated thermal flux, the necessary thickness of the insulation layer, according to the above notations, is two polystyrene plates, which each have thickness of 60 [mm].$\delta_{iz} = 2 \cdot 60 = 120\ [mm] = \delta_4$

Using (7), result $K = 0.25\ [kcal/m^2 \cdot h \cdot grd]$

A.I Checking the chosen insulation

At a large temperature difference between the neighboring rooms, the possibility of moisture condensation on the surface of the dividing construction element should be checked, especially for walls between floors and partition walls. Two checks are carried out:

a) Checking the insulation thickness to prevent condensation of water vapor from the air on the outside surface.

Condition to be met:

$K \cdot (t_e - t_i) = \alpha_e \cdot (t_e - t_{pe})$, where:

t_e = outside temperature;

t_i = inside temperature;

t_{pe} = outside wall temperature;

K = heat transfer coefficient.

In order not to condense, the outside wall temperature must be $t_{pe} > t_r$, where t_r = dew point temperature, determined by the relative humidity of the air in the warmer room.

So, the final condition is:

$$K \le \alpha_e \cdot \frac{t_e - t_r}{t_e - t_i}. \qquad (8)$$

For $\phi = 60$ [%] şi $t_e = 30\ [^oC]$, using diagram i– x ⇒ $t_r = 19.8\ [^oC]$.

$$\alpha_e \cdot \frac{t_e - t_r}{t_e - t_i} = 5.1 > K = 0.25\ [kcal/m^2 \cdot h \cdot grd]$$

The condition is met, hence the result that condensation does not occur.

b) Checking the insulation when the condensation area appears inside the outer wall.

The wall being inhomogeneous, the unit heat flow is:

$$q=\frac{\lambda_1}{\delta_1}\cdot(t_e-t_i)=\frac{\lambda_2}{\delta_2}\cdot(t_1-t_2)=\frac{\lambda_3}{\delta_3}\cdot(t_2-t_3)=\frac{\lambda_4}{\delta_4}\cdot(t_3-t_4)=\frac{\lambda_5}{\delta_5}\cdot(t_4-t_5) \qquad (9)$$

Total wall thickness is:

$$\delta_1+\delta_2+\delta_3+\delta_4+\delta_5=430\ [mm]$$

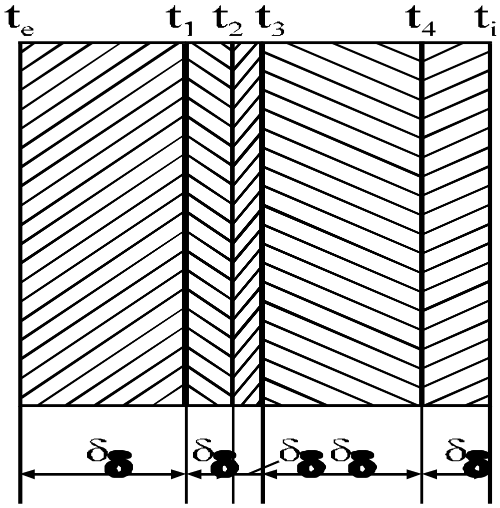

Fig. 3 Temperature distribution

The unit heat flow through this wall is (9):

$$q\ \ =13.02\ [kcal/m^2\cdot h]$$

Calculate the intermediate temperatures, using the relationship (9) as such:

$$t_1=25.6\ [^oC],\ \ t_2=25.32\ [^oC]\ ,\ \ t_3=24.98\ [^oC]$$

$$t_4=-19.66\ [^oC]\ t_i=-20\ [^oC]$$

The moisture flow per unit surface is:

$$W=\frac{\mu}{\delta}\cdot(p_e-p_i) \qquad (10)$$

where: μ = water vapor permeability coefficient of the layer considered;

p_e = outside vapor pressure;

p_i = inside vapor pressure.

From diagram $i-x\ at\ t_e=30\ [^oC]\ \phi=60\ [\%]\ results$:

$$p_e=26.5\ [mmHg]$$

The relative humidity relationship:

$$\phi=\frac{p_e}{p_s} \qquad (11)$$

where: p_s = saturation pressure of vapor

(11) results

$$p_s=44.16\ [mmHg]=p_e^{''}$$

For food, relative humidity inside is:

$$\phi=90\ [\%]\ \Rightarrow\ p_i=1.02\ [mmHg]$$

$$p_s=4.57\ [mmHg]=p_i^{''}$$

The moisture flow per unit surface is (10):

$$W=\frac{p_e-p_i}{\sum_{i=1}^{n}\frac{\delta_i}{\mu_i}}\quad or\quad W=\frac{p_e-p_i}{\frac{\delta_1}{\mu_1}+\frac{\delta_2}{\mu_2}+\frac{\delta_3}{\mu_3}+\frac{\delta_4}{\mu_4}+\frac{\delta_5}{\mu_5}} \qquad (12)$$

where:

$\mu_1=0.014\ [g/m\cdot h\cdot mmHg]$

$\mu_2 = 0.0001\ [g/m.\cdot h\cdot mmHg]$

$\mu_3=0.012\ [g/m\cdot h\cdot mmHg]$

$\mu_4=\mu_5 = 0.035\ [g/m.\cdot h\cdot mmHg]$

The intermediate pressures are calculated using the relationship (10):

$p_1=15.7\ [mmHg],\ p_2=15.58\ [mmHg]$

$p_3=1.24\ [mmHg],\ p_4=1.12\ [mmHg]$

$p_5=1.02\ [mmHg]=p_i$

It is noticed that partial pressures have lower values than saturation ones, which means that condensation does not occur in the insulation layer.

B. *Exterior walls insulation*

The insulation contains the following layers:

1. layer of brick

thickness: $\delta_1=250\ [mm]$

coefficient of thermal conductivity:

$$\lambda_1=0.75\ [kcal/m\cdot h\cdot grd]$$

2. layer of equalizing plaster made of cement mortar

thickness: $\delta_2=20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_2=0.75\ [kcal/m\cdot h\cdot grd]$$

3. bitumen layer (vapor barrier)

thickness: $\delta_3=10\ [mm]$

coefficient of thermal conductivity:

$$\lambda_3=0.72\ [kcal/m\cdot h\cdot grd]$$

4. layer of polystyrene

thickness: $\delta_4 = \delta_{iz}$

coefficient of thermal conductivity:

$$\lambda_4 = 0.035\ [kcal/m \cdot h \cdot grd]$$

5. layer of interior plaster

thickness: $\delta_5 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_5 = 0.75\ [kcal/m \cdot h \cdot grad]$$

Are chosen: $\alpha_e = 25\ [kcal/m^2 \cdot h \cdot grd]$

$$\alpha_i = 10\ [kcal/m^2 \cdot h \cdot grad]$$

$K = 0.35\ [kcal/m^2 \cdot h \cdot grd]$ - for the outer walls

Two polystyrene plates with thickness of 60 [mm] and 20 [mm] are adopted ($\delta_{iz} = 80\ [mm]$), so K has calculated value (7):

$$K = 0.307\ [kcal/m^2 \cdot h \cdot grd$$

a) The thickness check to prevent condensation of water vapor from the air on the outside surface is done using the relation (8):

where: $t_i = 0\ [^oC]$

$t_e = 30\ [^oC]$

$t_r = 19.8\ [^oC]$

$\alpha_e = 25\ [kcal/m^2 \cdot h \cdot grd]$

$$\alpha_e \cdot \frac{t_e - t_r}{t_e - t_i} = 8.5 > K = 0.3\ [kcal/m^2 \cdot h \cdot grd]$$

The condition is met, so there is no condensation on the outside surface.

b) Check the insulation layer so that the condensation zone does not form in it.

$$t_i = 0\ [^oC];\ t_e = 30\ [^oC]$$

Heat flow (9):

$$q = 11.15\ [kcal/m^2 \cdot h]$$

Calculated temperatures of the intermediate layers:

$t_1 = 26.28\ [^oC]$, $t_2 = 25.98\ [^oC]$,$t_3 = 25.83\ [^oC]$

$t_4 = 0.34\ [^oC]$, $t_5 = 0\ [^oC]$

Moisture flow per unit surface (10):

$$W = 0.058\ [g/m^2 \cdot h]$$

Using (11), results:

$p_1 = 15.96\ [mmHg]$, $p_2 = 15.86\ [mmHg]$

$p_3 = 4.26\ [mmHg]$, $p_4 = 4.16\ [mmHg]$

$$p_5 = 4.12\ [mmHg], p_5 = p_i'' = 4.12\ [mmHg]$$

It is noticed that partial pressures have lower values than saturation ones, which means that condensation does not occur in the insulation layer.

Wall thickness is:

$$\delta = 250 + 20 + 10 + 80 + 20 = 380\ [mm]$$

C. *Wall insulation between the refrigeration and locker room*

Interior temperature is $t_i = -1\ [^oC]$ and temperature into locker room is $t_e = 15\ [^oC]$

The materials that are used for the respective building elements are:

1. layer of exterior plaster

thickness: $\delta_1 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_1 = 0.75\ [kcal/m \cdot h \cdot grd]$$

2. brick layer

thickness: $\delta_2 = 120\ [mm]$

coefficient of thermal conductivity:

$$\lambda_2 = 0.75\ [kcal/m \cdot h \cdot grd]$$

3. equalizing plaster layer

thickness: $\delta_3 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_3 = 0.75\ [kcal/m \cdot h \cdot grd]$$

4. bitumen layer (vapor barrier)

thickness: $\delta_4 = 10\ [mm]$

coefficient of thermal conductivity:

$$\lambda_4 = 0.72\ [kcal/m \cdot h \cdot grd]$$

5.insulation layer (Pex)

thickness: $\delta_5 = \delta_{iz}$

coefficient of thermal conductivity:

$$\lambda_5 = 0.035\ [kcal/m \cdot h \cdot grd]$$

6. layer of interior plaster

thickness: $\delta_6 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_6 = 0.75\ [kcal/m \cdot h \cdot grd]$$

For interior walls, at temperature between −1 and 15 [ºC], are chosen:

$$K = 0.50\ [kcal/m^2 \cdot h \cdot grd]$$

$$\alpha_i = 7\ [kcal/m^2 \cdot h \cdot grd]$$

$$\alpha_e = 7\ [kcal/m^2 \cdot h \cdot grd]$$

$$\Rightarrow\ \delta_{iz} = 51.4\ [mm]$$

It's chosen a polystyrene plate of 60 [mm].

Recalculate the value of K (7):

$$K = 0.465\ [kcal/m^2 \cdot h \cdot grd]$$

This type of insulation is used for the partition wall between the refrigeration room and the packaging room (locker).

Wall thickness is:

$$\delta = 20 + 120 + 20 + 60 + 10 + 20 = 250\ [mm]$$

The verification calculation is no longer made because it was made in the most disadvantageous situations.

D. *Wall insulation between the refrigeration warehouse and offices*

Inside temperature is $t_i = 0\ [^oC]$ and temperature of equipment room is $t_e = 15\ [^oC]$.

The materials that are used for the respective insulating layout are:

1. layer of exterior plaster

thickness: $\delta_1 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_1 = 0.75\ [kcal/m \cdot h \cdot grd]$$

2. brick layer

thickness: $\delta_2 = 120\ [mm]$

coefficient of thermal conductivity:

$$\lambda_2 = 0.75\ [kcal/m \cdot h \cdot grd]$$

3. equalizing plaster layer

thickness: $\delta_3 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_3 = 0.75\ [kcal/m \cdot h \cdot grd]$$

4. bitumen layer (vapor barrier)

thickness: $\delta_4 = 10\ [mm]$

coefficient of thermal conductivity:

$$\lambda_4 = 0.72\ [kcal/m \cdot h \cdot grd]$$

5. insulation layer (Pex)

thickness: $\delta_5 = \delta_{iz}$

coefficient of thermal conductivity:

$$\lambda_5 = 0.035\ [kcal/m \cdot h \cdot grd]$$

6. layer of interior plaster

thickness: $\delta_6 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_6 = 0.75\ [kcal/m \cdot h \cdot grd]$$

For interior walls, at temperatures between 0 and 15 [ºC], are adopted:

$$K = 0.50\ [kcal/m^2 \cdot h \cdot grd]$$

$$\alpha_i = 7\ [kcal/m^2 \cdot h \cdot grd]$$

$$\alpha_e = 7\ [kcal/m^2 \cdot h \cdot grd]$$

$$\Rightarrow\ \delta_{iz} = 55.9\ [mm]$$

It's chosen a polystyrene plate of 60 [mm].

Recalculate the value of K (7):

$$K = 0.428\ [kcal/m^2 \cdot h \cdot grd]$$

This type of insulation is used for the partition wall between the refrigeration warehouse and the offices.

Wall thickness is:

$$\delta = 20 + 120 + 20 + 60 + 10 + 20 = 250\ [mm]$$

The verification calculation is no longer made because it was made in the most disadvantageous situations.

E. *Roof insulation of the refrigeration room*

Inside temperature is $t_i = -1\ [^oC]$

Chosen values:

$$K = 0.50\ [kcal/m^2 \cdot h \cdot grd]$$

$$\alpha_i = 7\ [kcal/m^2 \cdot h \cdot grd]$$

$$\alpha_e = 7\ [kcal/m^2 \cdot h \cdot grd]$$

The materials used for the roof are:

1. plaster layer

thickness: $\delta_1 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_1 = 0.75\ [kcal/m \cdot h \cdot grd]$$

2. reinforced concrete layer

thickness: $\delta_2 = 100\ [mm]$

coefficient of thermal conductivity:

$$\lambda_2 = 1.3\ [kcal/m \cdot h \cdot grd]$$

3. insulating layer (PEX)

thickness: $\delta_3 = \delta_{iz}$

coefficient of thermal conductivity:

$$\lambda_3 = 0.035\ [kcal/m \cdot h \cdot grd]$$

4. mineral cork layer

thickness: $\delta_4 = 100\ [mm]$

coefficient of thermal conductivity:

$$\lambda_4 = 0.08\ [kcal/m \cdot h \cdot grd]$$

5. bitumen layer

thickness: $\delta_5 = 20\ [mm]$

coefficient of thermal conductivity:

$$\lambda_5 = 0.72\ [kcal/m \cdot h \cdot grd]$$

6. layer of tar paper

thickness: $\delta_6 = 0.5\ [mm]$

coefficient of thermal conductivity:

$$\lambda_6 = 0.15\ [kcal/m \cdot h \cdot grd]$$

$$\Rightarrow\ \delta_{iz} = 0.065\ [mm]$$

For chosen value $\delta_{iz} = 90\ [mm]$ the recalculated K value is (7):

$$K = 0.34\ [kcal/m^2 \cdot h \cdot grd]$$

IV. CONCLUSIONS

The determination of the thickness of a refrigeration plant (cold store) insulation constitutes an optimization problem, taking into account the insulation costs and the operating costs of the related refrigeration plant respectively.

In this work, the thickness of the insulation was determined so that the surface of the wall had a temperature above the dew point temperature (tp > tr), in all areas with thermal contact resistance in the design thermal insulation structure. This has been verified for all types of calculated insulation.

Also, the insulation is sized and calculated in such a way as to prevent the occurrence of condensation inside the layers of the wall, provided that the characteristic pressure curve does not intersect the curve of the partial saturation pressure. Thus, on all contact surfaces of component layers in the insulating structure the partial vapor pressure is less than the saturation pressure.

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