The influence of the geometric parameters of the evaporator on the process of ice formation in the SAR

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Abstract. Fossil resources are the foundation of the global economy. However, the extraction, transportation and consumption of this energy source are harmful to the environment. Economic reasons and the search for new solutions based on energy recovery have generated a growing interest in adsorption technology.
In recent decades, the number of studies on adsorption refrigeration systems has increased significantly, because, unlike vapor compression refrigeration units, they cause less harm to the environment. [1]

1. General information

SAR are a special type of refrigeration apparatus in which there is no compression. In such devices, cyclic processes occur, consisting of successive stages: adsorption / evaporation (during the day) and desorption / condensation (at night). [2]

The technology of adsorption refrigeration technology uses refrigerants with zero ozone depletion potential and zero global warming potential and can operate without electricity consumption, as well as without moving parts. A distinctive feature of SAR is the lack of a compressor. Conventional refrigeration systems convert the energy consumed into mechanical work by compressing the working fluid. The functioning of the adsorption refrigeration system is based on the variable adsorption capacity of the selected working pair, which occurs in connection with a periodic change in temperature in the adsorbent. In SAR, the pressure in the system at night during adsorption is determined by the parameters of the evaporator. Due to the lack of control devices, pressure is given more importance to the selection of the geometric parameters of the evaporator [3]

2. Statement of the problem

In the refrigerator compartment there is a reservoir with water, inside of which there is an evaporator filled with methanol. Due to the fact that the work of the SCAT is periodic, during the cold production process it is important to obtain ice, which will be used as an accumulator of cold in the daily part of the cycle. Problem statement: Choose the design of the evaporator for the designed experimental model of SHAT. Amount of heat carrier 1 (methanol): 6 kg. Amount of heat carrier 2 (water): 15 kg. Carry out a thermal calculation and analyze the conditions of ice formation.

Two evaporator geometries are considered: rectangular and cylindrical.
3. Calculation formulas

The overall heat balance of the system:

\[ Q_\Sigma = Q_1 + Q_2 + Q_3, \]

(3.1)

where: \( Q_\Sigma = M_{\text{met}} \times r_{\text{met}} \) – the total amount of heat removed, J.

\( M_{\text{met}} \) – mass of methanol in the system, kg;

\( r_{\text{met}} = 1,12 \times 10^6 \) – the heat of vaporization of methanol, J / kg.

The heat removed from methanol to cool it, J:

\[ Q_1 = M_{\text{met}} \times C_{p_{\text{met}}} \times (t_{\text{met start}} - t_{\text{met end}}), \]

(3.2)

where: \( C_{p_{\text{met}}} \) – heat capacity of methanol at 0 °C, J / kg \( \times \) K;

\( t_{\text{met start}}, t_{\text{met end}} \) – methanol temperature at different points in time, °C.

The heat removed from the water to cool it, J:

\[ Q_2 = M_{\text{water}} \times C_{p_{\text{water}}} \times (t_{\text{water start}} - t_{\text{water end}}), \]

(3.3)

where: \( M_{\text{water}} \) – mass of water in the system, litters;

\( C_{p_{\text{water}}} \) – heat capacity of water at 0 °C, J / kg \( \times \) K;

\( t_{\text{water start}}, t_{\text{water end}} \) – water temperature at different points in time, °C.

Heat removed from water to form ice, J:

\[ Q_3 = M_{\text{ice}} \times r_s, \]

(3.4)

where: \( M_{\text{ice}} \) – mass of formed ice, kg; \( r_s \) – solidification heat of water J / kg.

The heat balance equation for estimating the heat removed necessary for cooling methanol:

\[ \frac{d}{dt} \times r_{\text{met}} = M_{\text{met}} \times C_{p_{\text{met}}} \times \frac{dt_{\text{met}}}{dt}, \]

(3.5)

In the calculation, we make the assumption that the methanol consumption in the system is constant.

In order to examine in detail, the temperature distribution, we depict a section of the evaporator wall.

![Figure 1. The section of the wall of the evaporator.](image)

\( t_{\text{methanol}} \) – methanol temperature, °C; \( t_{W_{\text{met}}} \) – wall temperature in contact with methanol, °C; \( t_{\text{water}} \) – water temperature, °C; \( t_{\text{ice}} \) – ice temperature, °C; \( t_{\text{water}} \) – water temperature, °C.

The power of the heat flux removed from the refrigerating chamber per unit time, W:

\[ Q = \frac{\delta_{\text{met}}}{3600} \times r_{\text{met}}. \]

(3.6)

where: \( \delta_{\text{met}} \) – accepted average consumption of methanol, kg / h.

Heat balance at the ice-water interface:

\[ Q = \frac{1}{\alpha_{\text{aw,met}} + \delta_w + \delta_{\text{ice}}} \times (t_{\text{ice}} - t_{\text{met}}) \times F_{\text{sum}} = \alpha_{\text{aw,water}} \times F_{\text{sum}} \times (t_{\text{water}} - t_{\text{ice}}), \]

(3.7)

where: \( \alpha_{\text{aw,met}} \) – average heat transfer coefficient from the side of methanol, W/m²K; \( \alpha_{\text{aw,water}} \) – average heat transfer coefficient from the side of water, W/m²K; \( F_{\text{sum}} \) – total contact surface area of the evaporator, m².

Thermal resistance for a rectangular evaporator, m²K/W:

\[ R_R = \frac{1}{\alpha_{\text{aw,met}} + \delta_w + \delta_{\text{ice}}} \]

(3.8)

where: \( \delta_w \) – evaporator wall thickness, m; \( \delta_w \) – heat capacity of the evaporator wall, W / m; \( \delta_{\text{ice}} \) – the thickness of the formed ice, m; \( \lambda_{\text{ice}} \) – heat capacity of ice, W / m.
Thermal resistance for a cylindrical evaporator, m²K/W:

\[ R_C = \frac{1}{\alpha_{aw,met}} + \frac{\ln(r_2/r_1)}{2\pi \lambda_w L} + \frac{\ln(r_{\text{ice}}/r_2)}{2\pi \lambda_{ice} L}, \]  

(3.9)

where: \( r_2 \) – outer radius of the cylinder, m; \( r_1 \) – inner radius of the cylinder, m; \( \lambda_w \) – heat capacity of the material of the walls of the evaporator, W / m²K; \( L \) – cylinder height, m; \( r_{\text{ice}} \) – the sum of the outer radius of the cylinder and the thickness of the ice, m.

Transform the formula (2.7):

\[ Q = \frac{1}{R_{\text{term}}} (t_{\text{ice}} - t_{\text{met}}) \times F_{\text{sum}} = \alpha_{aw,met} \times F_{\text{sum}} \times (t_{\text{water}} - t_{\text{ice}}), \]  

(3.10)

where: \( R_{\text{term}} \) – thermal resistance, m²K/W

Formula (3.10) shows that \( t_{\text{ice}} \) depends on \( t_{\text{met}} \) and \( t_{\text{water}} \), which in turn will depend on the heat flux and thermal resistance. As previously indicated, the heat flux depends on the consumption of methanol removed from the evaporator.

Mass of ice formed on the surface of the evaporator:

\[ M_{\text{ice}} = F_{\text{sum}} \times \rho_{\text{ice}} \times \delta_{\text{max}}, \]  

(3.11)

where: \( \rho_{\text{ice}} \) – ice density, kg/m³; \( \delta_{\text{max}} \) – maximum possible ice thickness, m.

The heat balance for finding the temperature of methanol during the onset of ice formation assuming that the conditions for ice formation at the ice-water phase boundary are observed:

\[ Q = R_{\text{term}} \times (t_{\text{ice}} - t_{\text{met}}) \times F_{\text{sum}} \]  

(3.12)

4. Comparison of evaporator geometries

The parameters of the selected geometry forms of SCAT evaporators are presented in table 1.

### Table 1. The geometric parameters of the evaporators

| Geometry type | Volume (l) | Area (m²) |
|---------------|------------|-----------|
| Rectangle     | 9          | 0.270     |
| Cylinder      | 9          | 0.303     |

The heat transfer coefficients were calculated. The results are presented in table 2.

### Table 2. Comparison of the characteristics of evaporators of the same volume

|          | Averaged heat transfer coefficient between wall and methanol (W/m²K) | Averaged heat transfer coefficient between wall and water (W/m²K) |
|----------|---------------------------------------------------------------------|------------------------------------------------------------------|
| Rectangle| 128.1                                                               | 137.4                                                            |
| Cylinder | 381.6                                                               | 412.3                                                            |

The values of thermal resistance are determined depending on the thickness of the accumulated ice. The results are presented in table 3.
Table 3. The calculation results of the thermal resistance of evaporators.

| Ice thickness (m) | Thermal resistance for rectangle (m²K/W) | Thermal resistance for cylinder (m²K/W) |
|-------------------|-----------------------------------------|--------------------------------------|
| 0                 | 0.0080                                  | 0.0070                               |
| 0.01              | 0.0123                                  | 0.0115                               |
| 0.02              | 0.0170                                  | 0.0160                               |
| 0.03              | 0.0210                                  | 0.0200                               |
| 0.04              | 0.0260                                  | 0.0230                               |
| 0.05              | 0.0300                                  | 0.0270                               |
| 0.06              | 0.0350                                  | 0.0300                               |

Figure 2. Graphical comparison of the results of calculation of thermal resistance: ■ – values for a rectangular evaporator, □ – cylinder evaporator values.

Analyzing the data in table 3, we can conclude that when using a cylindrical evaporator in SCAT, ice will grow better.

Calculations were made of the temperature of methanol at which the continuation of ice formation after reaching the indicated thickness will be guaranteed. The results are presented in table 4.
Table 4. The results of the calculation of the required temperature of methanol

| Ice thickness (m) | \( t_{\text{met}} \) for cylindrical evaporator (°C) | \( t_{\text{met}} \) for rectangular evaporator (°C) |
|------------------|--------------------------------------------------|--------------------------------------------------|
| 0                | -3,42                                            | -3,36                                            |
| 0.01             | -5,90                                            | -5,95                                            |
| 0.02             | -8,21                                            | -8,55                                            |
| 0.03             | -10,27                                           | -11,14                                           |
| 0.04             | -11,80                                           | -13,74                                           |
| 0.05             | -13,86                                           | -16,33                                           |
| 0.06             | -15,40                                           | -18,93                                           |

Figure 3. Graphical comparison of the results of calculating the required temperature of methanol: ■ – values for a rectangular evaporator, □ – values for cylindrical evaporator.

Analyzing table 4, we can conclude that, provided the heat flow is constant, in order to create an ice crust 60 mm thick for a cylindrical evaporator, the required methanol temperature is higher than for a rectangular evaporator. This suggests that the cylindrical shape of the evaporator is more effective for cooling water.

Conclusion
The sizes of rectangular and cylindrical evaporators with a volume of 9 liters were adopted, and the contact surface areas were calculated. A comparison of the rectangular and cylindrical geometry of the evaporator. Revealed:
- For a cylindrical shape, the value of thermal resistance is less than for a rectangular evaporator with equal values of the ice thickness.
- The required temperature of methanol to create the maximum possible thickness of the ice crust for a cylindrical evaporator is higher than for a rectangular one.

We can conclude that the cylindrical shape is more suitable for the future prototype of the SCAT evaporator.

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Nomenclature
SAR – solar adsorption refrigerator.

References
[1] Samson I. F. Improving the characteristics and development of a method for calculating a solar adsorption refrigeration unit of periodic action: dis. ... cand. those. Sciences: 05.04.03. - M., 2015. —132
[2] Echarri R., Samson I., Gariaev A., Sartarelli A. Dynamic Simulation of Absorber for Solar Adsorption Refrigerator: A Validated Numerical Model // Energy and Power Engineering. - 2017. - №9.
[3] Mateo1 M., Echarri R., Samson I. Thermal Analysis and Experimental Validation of Parabolic Trough Collector for Solar Adsorption Refrigerator // Energy and Power Engineering. - 2017. - №9