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DYNAMICS OF UF_6 DESUBLIMATION WITH THE INFLUENCE OF TANK GEOMETRY FOR VARIOUS COOLANT TEMPERATURE

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Abstract. Mathematical model of UF_6 desublimation in a vertical immersion tank is presented in the article. Results of calculations of the filling dynamics of the tanks with 1m^3 volume at various coolant temperatures, with and without ellipticity of the end walls are given. It is shown that allowance for the ellipticity of the end walls of the tanks leads to a significant increase in the time of desublimation of UF_6.

1 Introduction

Desublimation process is widely used in various sectors of the economy, including in the nuclear fuel cycle. Gaseous UF_6 is used as the working medium at the plants of uranium enrichment. Uranium hexafluoride desublimate into special containers at the output of the separation cascade. Tanks with depleted UF_6 are sent to the warehouse for long-term storage. Tanks with uranium enriched in ^{235}U transported to plants for transfer UF_6 to UO_2 and production fuel rods.

Several stationary or quasi-stationary mathematical models describing the UF_6 desublimation process in a single tank developed to date. Detailed descriptions of these mathematical models presented in the review [1]. Their common disadvantages are:

- The use of empirical data;
- Lack of consideration of the motion of gaseous UF_6;
- Lack of consideration of the ellipticity of the tank end walls (tank is represented in the cylinder form) and the availability of desublimation at its bottom section.

Actually UF_6 desublimation process is nonstationary and essentially depends on the coolant temperature and the gas pressure inside the tank. Desublimation layer thickness on the inner surface of the container increases during filling. The result is that there is deterioration in conditions of heat exchange between the UF_6 phase transition surface and coolant and the desublimation speed varies nonlinearly.

Two-dimensional non-stationary mathematical model of UF_6 desublimation in a vertical immersion tank was developed by us [2], in there are no disadvantages of known stationary

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or quasi-stationary models. Verification of the mathematical model [2] is shown that it adequately describes occurring at UF_6 desublimation process heat and mass transfer.

The impact of geometry of the vertical submersible tank on the dynamics of filling the solid UF_6 at different coolant temperatures is investigated, using created mathematical model.

2 Object of study

UF_6 desublimation to a vertical cylindrical tank (fig. 1) was considered.

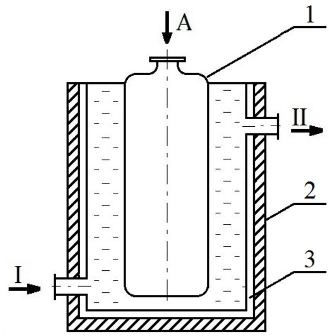

Fig. 1. Immersed vertical tank.

Tank (1) is in thermostat (2). The thermostat is filled with saturated $CaCl_2$ solution (streams I, II), which is cooled by liquid nitrogen (3). Gaseous UF_6 is fed through a valve located at the top of the tank (stream A). The upper part of the tank with the branch pipe protrudes from the thermostat filled with coolant, and is not involved in heat exchange.

3 Description of mathematical model

In the construction of the mathematical model was made the following assumptions:

1) UF_6 gas does not contain impurities;

2) desublimation process occurs only on the side and bottom parts of the tank (top part of the tank with the branch pipe protrudes from the thermostat with the coolant);

3) the outer surface temperature of the tank wall is considered to be constant;

4) the desublimation process of gas phase is determined by heat removal through the tank walls and the UF_6 solid layer;

5) UF_6 desublimation speed throughout the heat exchange surface is averaged at each time step;

6) the phase transition temperature is determined by the equilibrium temperature and pressure above the desublimate layer.

The computational domain was divided by uniform grid, which solved the integral equations of gas dynamics:

$$\begin{cases} \dfrac{d}{d\tau}\iint\limits_S r\rho dxdr + \oint\limits_G (\rho u dr - \rho v dx) = 0, \\ \dfrac{d}{d\tau}\iint\limits_S r\rho u dxdr + \oint\limits_G r\left[\left(\rho u^2 + p\right)dr - \rho uv dx\right] = 0, \\ \dfrac{d}{d\tau}\iint\limits_S \rho v dxdr + \oint\limits_G \left[\rho uv dr - \left(\rho v^2 + p\right)dx\right] = \iint\limits_S p dxdr, \\ \dfrac{d}{d\tau}\iint\limits_S E dxdr + \oint\limits_G r\left[(E+p)u dr - (E+p)v dx\right] = 0, \end{cases} \tag{1}$$

$$E = \rho\left(e + \frac{u^2 + v^2}{2}\right), \qquad e = \frac{p}{\rho(\gamma - 1)},$$

where G is arbitrary closed contour, which limits the area S in the plane of variables x, r of cylindrical coordinate system, the beginning of which is placed on the axis of symmetry in the inlet section; τ is time; p is pressure; ρ is density of gas; e is UF_6 specific internal energy; E is UF_6 apparent energy; γ is adiabatic exponent of gas; u, v are projections of the velocity vector on the axis x, r respectively.

For the tank wall heat conduction equation was solved:

$$\frac{\partial rT}{\partial \tau} = \frac{\partial}{\partial n}\left(\kappa \frac{\partial rT}{\partial n}\right) \tag{2}$$

where κ is thermal diffusivity of the wall material, n is normal coordinate measured from the outer surface inside of the tank, T is temperature.

Calculation of the temperature in the UF_6 desublimate layer was carried out using a mobile system coordinates of the form $\xi=\xi(x,r,\tau)$, $\eta=\eta(x,r,\tau)$, related to the interface of "tank wall-desublimate". Has been solved the Stefan problem with moving boundary of phase transition:

$$\begin{aligned} \frac{\partial(\psi T)}{\partial \tau} = &-\frac{\partial}{\partial \xi}\left[\left(-\lambda\frac{\partial T}{\partial x} + T\frac{\partial x}{\partial \tau}\right)\frac{\partial y}{\partial \eta} - \left(\lambda\frac{\partial T}{\partial y} + T\frac{\partial y}{\partial \tau}\right)\frac{\partial x}{\partial \xi}\right] - \\ &-\frac{\partial}{\partial \eta}\left[-\left(-\lambda\frac{\partial T}{\partial x} + T\frac{\partial x}{\partial \tau}\right)\frac{\partial y}{\partial \xi} + \left(\lambda\frac{\partial T}{\partial y} + T\frac{\partial y}{\partial \tau}\right)\frac{\partial x}{\partial \eta}\right] + \psi g. \end{aligned} \tag{3}$$

where ψ, $\partial x/\partial\xi$, $\partial y/\partial\xi$, $\partial x/\partial\eta$, $\partial y/\partial\eta$ is jacobian and the metric coefficients.

Equation (3) was used for the determination of temperature fields and positions of grid points within desublimate layer.

To determine the UF_6 desublimation speed was used Stefan condition:

$$\rho_U v_W(\tau) L = \frac{\lambda_U r}{l_W(\tau)}\frac{\partial T}{\partial \eta}, \tag{4}$$

where c is specific heat capacity, $l_w(\tau)$ is desublimate thickness, $v_w(\tau)$ is desublimation speed, η is dimensionless coordinate associated with the surface of "tank wall-desublimate", L is heat of desublimation, λ is thermal conduction coefficient. Index U refers to a solid UF_6, S to a tank wall, E to refrigerant.

Consideration of the UF_6 phase transition boundary was produced using a dynamic adaptation grid of the computational domain [3]. Method of V.I. Mazhukin [4] was used for the numerical solution of differential equations of heat conduction. System of the gas dynamics equations was changed to a dimensionless form and was solved numerically using the algorithm SIMPLE [5].

Temperature on the outer surface of the tank was set by boundary condition of the first kind (surface temperature is equal the coolant temperature); on the border "tank wall – desublimate" by wondered conjugation conditions; on the surface of the phase transition – by the boundary condition of the first kind (temperature of the phase boundary is equal to equilibrium temperature of the phase transition).

The condition of sticking and impermeability to UF_6 gas flow rate was set at the upper end of the tank wall. The flow rate of gaseous UF_6 to the heat transfer surfaces is equal to the speed of the desublimation.

Tank cooled to a coolant temperature before the start of desublimation. The desublimate thickness at the initial time is zero.

4 The calculation results

The calculation of the dynamics of filling tank of 1 m^3 (fig. 2a) up to 70% without the ellipticity of the ends tank walls (fig. 2b), with the ellipticity of the bottom of the tank wall only (fig. 2c), with the ellipticity of the two end tank walls (fig. 2d).

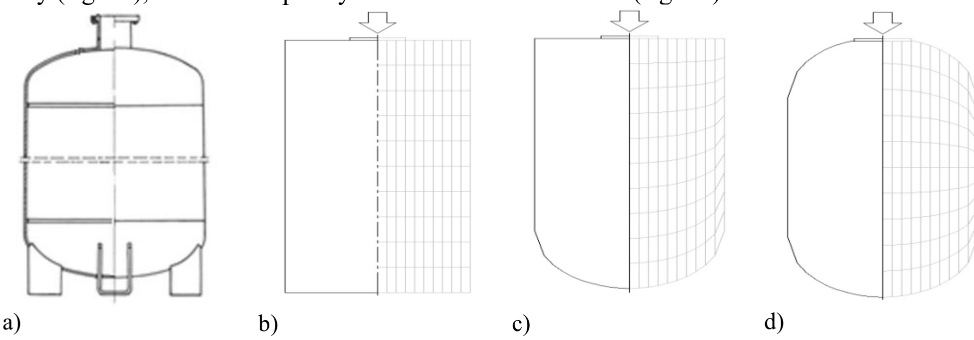

Fig. 2. Transport tank (a) and the corresponding computational domains (b, c, d).

The results of calculation of the dynamics of UF_6 desublimation in a tank volume of 1 m^3 with coolant temperatures –10°C and –20°C are shown in fig. 3 and fig. 4, respectively.

Results of the calculations in fig. 3 is show that the estimated filling time with considering the ellipticity both end tank walls is 405 hours, which 11.1% and 23.5% higher than the estimated filling time of considering only the ellipticity of the tank bottom and without ellipticity end tank walls respectively.

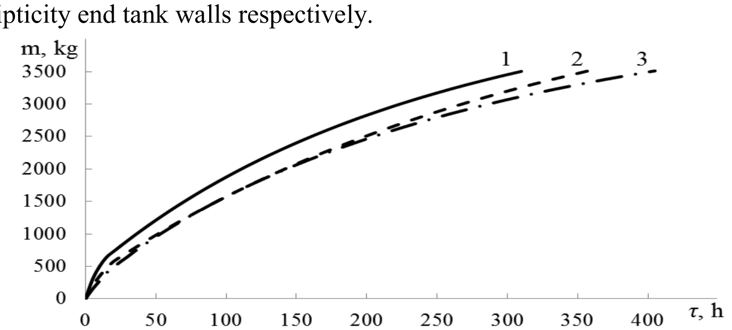

Fig. 3. Dynamics of 1 m^3 tank filling (t_{CaCl} = – 10°C):1 – flat ends of the tank walls, 2 – ellipticity of the bottom wall, 3 – ellipticity of the two end tank walls.

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Results of the calculations in fig. 4 is show that the estimated filling time with considering the ellipticity both ends tank walls is 320 hours, which 10.9% and 23.4% higher than the estimated filling time of considering only the ellipticity of the tank bottom and without ellipticity end tank walls respectively.

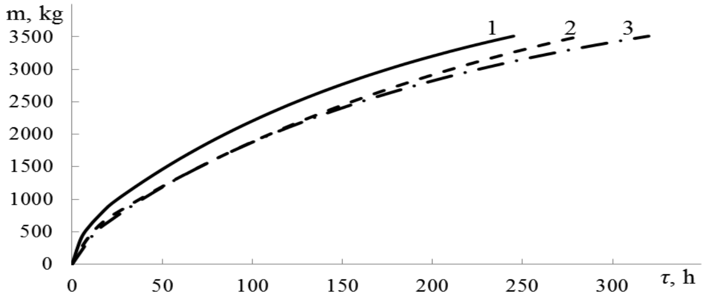

Fig. 4. Dynamics of 1 m^3 tank filling (t_{CaCl} = – 20°C): 1 – flat ends of the tank walls, 2 – ellipticity of the bottom wall, 3 – ellipticity of the two end tank walls.

As the visible pattern dynamics of tank filling from its geometry is maintained at different coolant temperatures. The time of tank filling changing almost in the same proportion for the different geometry.

5 Conclusion

1. Calculations of dynamics of the filling vertical immersion tank 1 m^3 to 70% without ellipticity of the ends tank walls, considering only the ellipticity of the tank bottom, with considering the ellipticity both ends tank walls is performed using the developed UF_6 desublimation nonstationary mathematical model.
2. The calculation results showed that the inclusion of the ellipticity of the ends tank walls substantially increases the value of the estimated time. The pattern of change in the estimated time of filling of the container from its geometry is maintained at different coolant temperatures (–10°C and –20°C).
3. The necessity of taking into account the tank geometry in calculating the dynamics of filling the solid UF_6 is shown.

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