Optimal working regimes of the hyper-speed long Iguasu gas centrifuge

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Abstract. Rapid development of technologies for production of new materials may provide design of gas centrifuges (hereafter GC) with rotor speed above 1000 m/s. The question about efficiency of such GCs remains open. At present no experimental or theoretical studies regarding the separation efficiency of such GCs exist. We present the results of calculations of the optimized separative power of the hyper-speed Iguasu GCs with a length of 1 to 5 meters and rotational speeds from 1000 to 1500 m/s. The calculations were performed in axisymmetric approximation in frameworks of the source-sink model. It is shown that for the hyper-speed GCs the optimized separative power, pressure at the rotor wall, feed flux and gas friction power linearly grow with the rotor length, while the temperature drop along the rotor does not depend on the rotor length.

1. Introduction
At present time, gas centrifuges provide the most effective method for enrichment of uranium for nuclear fuel. The main parameter of a single gas centrifuge, showing its efficiency, is the separative power. The separative power of a single GC can be increased by increase of the speed of rotation or the length of the rotor. Currently rotation speed does not exceed 800 m / s [?] and therefore most studies were focused at speed not exceeding 1000 m/s [2-4]. However, thanks to the progress in development of high-tech materials [5] possibly in the foreseeable future it will be possible to achieve rotor speed of rotation above 1000 m/s[6]. Operation of GC at so high speed of rotation is not studied very well. It remains unknown whether the separation of the mixture of isotopes will be ensured at such speed, what will be the optimal operating modes and whether it will be possible to achieve them. The aim of this work is to study GC with rotation speeds of more than 1000 m/s and search for their optimal working regimes at different rotor length.

2. Model and method
Modeling of the flow in the rotor of GC is performed in a rotating frame system in the axisymmetric approximation. The system of hydrodynamic equations is presented in the form [7]:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho v_i}{\partial x_i} = 0,
\]
\[
\frac{\partial \rho v_i}{\partial t} + \frac{\partial}{\partial x_k}(\rho v_i v_k) = -\frac{\partial p}{\partial x_i} + \frac{\partial {\tau}_{ik}}{\partial x_k} - \rho \omega^2 r_i + 2\rho \varepsilon_{ijk} \omega_j v_k, \tag{2}
\]

\[
\frac{\partial}{\partial t}(\rho \varepsilon_{\text{tot}}) + \frac{\partial}{\partial x_i}(\rho v_i h_{\text{tot}}) = \frac{\partial}{\partial x_i}(\kappa \frac{\partial T}{\partial x_i}) + \frac{\partial v_k \tau_{ik}}{\partial x_i} + \rho \omega^2 v_i r_i, \tag{3}
\]

where \(\varepsilon_{ijk}\) - Levy-Civita symbol, \(r_i\) - cylindrical radius, \(p\) - pressure, \(\rho\) - density, \(T\) - temperature, \(v_i\) - velocity components, \(\tau_{ik}\) - \(\mu\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3} \frac{\partial v_l}{\partial x_l}\right)\) - stress tensor, \(\mu\) - dynamic viscosity, \(\kappa\) - thermal conductivity, \(\varepsilon_{\text{tot}} = c_V T + v^2/2\) - total energy per unit mass, \(h_{\text{tot}} = c_P T + v^2/2\) - total enthalpy per unit mass, \(c_V\) and \(c_P\) - specific heat capacities at constant volume and pressure respectively.

In order to calculate the separative power, these equations are supplemented by the equation of convective diffusion for the concentration \(C\) of the light isotope \(U^{235}\) of uranium hexafluoride \(UF_6\):

\[
\frac{\partial \rho C}{\partial t} + \frac{\partial}{\partial x_i}(\rho v_i C - \rho D \frac{\partial C}{\partial x_i} + \frac{\Delta M}{M} C(1 - C) \frac{\partial \ln(p)}{\partial x_i}) = 0 \tag{4}
\]

The program code for solution equations (1)-(4) is based on second-order Godunov scheme[8]. The numerical code was verified using methods described in [9-11].

Figure 1 presents the scheme of the computational domain. The solution of equations (1)-(4) was performed in the region near the rotor wall where the approximation of continuum fluid dynamic is valid [12]. Braking action of a scoop for withdrawal of the heavy fraction is modeled as an azimuthally symmetric sink of mass, angular momentum and energy [13,14]. The product chamber is not included in to the computational domain. Its influence is replaced by specification of the pressure at the rotor wall.

![Figure 1. The scheme of the computational domain](image)

In this work the GC was optimized to find the maximum separative power (\(\delta U\)) varying four parameters: pressure at the rotor wall (\(P\)), feed flux (\(F\)), temperature drop along the rotor wall (\(\Delta T\)) and rotational speed (\(\Omega\)).
(\Delta T), and gas friction power on the gas scoop (W). The separative power \( \delta U \) is taken as a function

\[
\delta U = L'V(C') + L''V(C'') - LV(C)
\]

where \( L, L', L'' \) - feed, product and waste flows, respectively. \( C, C', C'' \) - are the concentrations in these flows. \( V(C) \) - value function which depends on the concentration in the stream. It equals:

\[
V(C) = (2C - 1) \ln \frac{C}{1 - C}
\]

The search for optimal parameters was carried out by the BOBYQA algorithm [15]. This method is included in the library of nonlinear optimization methods NLopt [16].

Calculations were performed at fixed feed cut \( \Theta = 0.5 \) and rotor diameter equal to \( d = 0.12 \) m.

3. Results and discussion

Figures 2-6 show dependence of the calculated optimal parameters on the length of the rotor at various speeds of the rotor rotation.

![Figure 2. Dependence of the separative power on the length of the rotor](image-url)
Figure 3. Dependence of the pressure (in arbitrary units) at the wall on the length of the rotor

Figure 4. Dependence of the feed flux (in arbitrary units) on the length of the rotor
According to our results the separative power, gas pressure at the wall of the rotor, feed flux and gas friction power grow linearly with increase of the rotor length. The optimal temperature drop at the wall of the rotor remains approximately the same, regardless of the length and speed of rotation of the rotor.

\[
\delta U_{opt} \sim L \\
P_{opt} \sim L \\
F_{opt} \sim L
\]
\[ \Delta T_{\text{opt}} \approx \text{const} \]
\[ W_{\text{opt}} \sim L \]

The obtained results do not agree with our previous works [2-4], because the procedure of optimization was modified. In the previous studies the GC was not optimized on the radius of the baffle separating the working and product chambers.

4. Conclusions
The results of the optimization studies of the hyper-speed Iguasu GC are presented. It is shown that the optimal parameters of hyper-speed GC as separative power, gas pressure at the wall of the rotor, feed flux and gas friction power grow linearly with increasing rotor length, while the optimal temperature difference along the side wall remains approximately the same for any GC.

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