Two optimal working regimes of the ”long” Iguasu gas centrifuge

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Abstract. We argue on the basis of the results of optimization calculations that the dependence of the optimal separative power of the Iguasu gas centrifuge with 2 m rotor has two local maxima, corresponding pressures of $p_{\text{max}_1} = 35 \text{ mmHg}$ and $p_{\text{max}_2} = 350 \text{ mmHg}$. The optimal separative power values in these maxima differ by the value of 0.6%. Low pressure maximum is caused by the thermal drive, whereas high pressure maximum is caused by both thermal and mechanical drives. High pressure maximum is located on wide ”plateau” from $p_1 = 200 \text{ mmHg}$ to $p_2 = 500 \text{ mmHg}$, where the optimal separative power changes in the range of 0.7%. In this way, Iguasu gas centrifuge has two optimal working regimes with different sets of working parameters and close slightly different values of the separative power. Calculations show that high pressure regime is less sensitive to the parameters change than low pressure one.

1. Introduction
Nowadays, gas centrifuges (hereafter GC) are the main tool for the industrial production of enriched uranium for nuclear power stations. One of the most important problems in the GC design is the determination of the optimal working regime of the GC, i.e. determination of maximal separative power and flow parameters required to achieve this separative power. The existing estimates of the optimized separative power are based on the empirical relationships. Although these estimates can give correct predictions of the optimal separative power, they cannot predict flow parameters of the optimal working regime. Theoretical models give incorrect predictions of the optimal separative power as well as optimal flow parameters [2]. At present time, determination of the optimal working regime and the optimal separative power can be performed using the computer simulations.

In this work we present the results of the optimization calculations of the ”long” Iguasu GC, i.e. Iguasu GC with the length of the rotor $L = 2 \text{ m}$ focusing on the dependence of the optimal separative power on the pressure of the working gas at the wall of rotor.

2. Model and method
The modelling of the flow and separation in the Iguasu GC is performed in the rotating frame system. The diameter of the rotor of the GC is $d = 0.12 \text{ cm}$, linear velocity of rotation $v = 600 \text{ m/s}$, the length of the rotor is $L = 2 \text{ m}$. The modelling is performed in axisymmetric approximation. The affect of the waste scoop has been modelled as a source of mass, momentum
and energy distributed over a small toroidal region. The computational domain consists of the working chamber and waste chamber located between two coaxial cylinders. The outer cylinder corresponds to the rotor wall. The inner cylinder is the artificial wall introduced into the model to avoid the simulation in the rarefied gas where the hydrodynamical approximation is not valid. Then product chamber was not included into the computational domain. Its influence was modelled by the pressure imposed at the rotor wall near the low baffle of the working chamber. The mass flux at the outlet has been specified by the conservation of mass.

A linear temperature profile has been specified at the rotor wall. The minimal temperature \( T_0 \) has been specified above the temperature of sublimation of the working gas. At every step of the optimization procedure of the GC the temperature of the gas has been calculated at the pressure exceeding on 10% the current pressure at the wall. This temperature has been taken as \( T_0 \). The sublimation of the gas is avoided due to this procedure.

Internal boundary of the computational domain corresponds to the Knudsen zone where the gas pressure is of the order of 1 Pa. The feed flux has been specified at the surface of this boundary.

To determine the maximal separative power and optimal flow parameters we use BOBYQA [4] direct search method, which requires only calculations of the objective function at certain points [5]. This algorithm is included in a library of nonlinear optimization algorithms, NLopt [6], freely distributed in the Internet. In the beginning of each optimization calculation we fix the pressure at the wall of rotor \( p \). Optimization provides us the values of feed flux \( F \), temperature drop along the wall of the rotor \( \Delta T \) and power of the braking of the gas by the scoop \( W \) at which the optimized value of the separative power \( \delta U_{\text{opt}} \) of the GC is achieved. The calculations were performed for the pressure from \( p_{\text{min}} = 15 \text{ mmHg} \) to \( p_{\text{max}} = 900 \text{ mmHg} \).

All calculations of the gas flow, diffusion of the mixture and optimization were performed at fixed feed cut \( \theta = 0.5 \), rotor diameter \( d = 0.12 \text{ cm} \) and rotor length \( L = 2 \text{ m} \).

### 3. Results and discussion

Fig. 1 shows dependence of optimized separative power \( \delta U_{\text{opt}} \) on the pressure at the wall of rotor \( p \). This dependence has two maxima. The first one corresponds to the pressure \( p_{\text{max}1} = 35 \text{ mmHg} \) and the second one to the pressure \( p_{\text{max}2} = 350 \text{ mmHg} \). It means that "long" Iguasu GC has two optimal working regimes. Optimized separative power values in these regimes differ by 0.6%.

| \( p \), mmHg | \( F \), mg/s | \( \delta T \), K | \( W \), W | \( \delta U_{\text{opt}} \) |
|--------------|--------------|-----------------|----------|-----------------|
| 35           | 33.4         | 58.7            | 0.5      | 16.64           |
| 350          | 178.6        | 20.8            | 21.0     | 16.75           |

Calculated optimal working regimes differ in their optimal parameters. Sets of the optimal parameters are shown in tab. 1. It is clear that all the parameters are significantly different. Another important conclusion is that flow circulation in the first optimal regime is determined by the thermal drive. Indeed, the power \( W \) is relatively low, whereas temperature drop \( \Delta T \) is relatively high. Additional calculations show that all 95% of the separative power at the first regime is caused by the thermal drive and only 5% by the mechanical drive.

Second regime is characterized by higher feed flux, lower temperature drop and higher breaking power. In this regime thermal and mechanical drives give 50% of the optimal separative power.
Figure 1. Dependence of the optimized separative power on the pressure at the wall of rotor.

It is worth to mention that the second regime is less sensitive to the working parameters changing comparing to the first one. A small change in pressure causes a small change in the separative power. Furthermore, there is a "plateau" in the dependence of the optimized separative power on a pressure starting from $p_1 = 200 \text{ mmHg}$ and to $p_2 = 500 \text{ mmHg}$. Optimized separative power on this "plateau" changes in the range of 0.7%.

4. Conclusions
The results of the optimization studies of the "long" Iguasu GC are presented. It is shown that Iguasu GC with 2 m rotor has two optimal working regimes with different flow parameters. The first one (low pressure regime) is reached at low pressure $p_{max1} = 35 \text{ mmHg}$ and determined mostly by the thermal drive. The second one (high pressure regime) is reached at $p_{max2} = 350 \text{ mmHg}$, less sensitive to the change of the parameters comparing to the first one and determined by both mechanical and thermal drives.

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