Three-dimensional modeling of the flow around the gas scoop under optimal working regime of the Iguassu gas centrifuge at the hyper fast rotation.

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Abstract.
The problem of the gas withdrawal from an Iguassu gas centrifuge (GC) at the speed of rotation, over 1000 m/s is considered. We focus our attention on the problem of achieving of optimal waste flow and friction power of the gas scoop simultaneously. Calculations were carried out in a three-dimensional approximation for supersonic flow of UF₆ around a stationary gas scoop taken as a Pitot tube with a diameter of 2 mm. Attempts to achieve the optimal working regime of GC for the selected particular gas scoop were not successful. On the basis of this results we conclude that the optimal gas withdrawal and creation of the optimal axial circulation can be problematic for the hyper-speed gas centrifuges.

1. Introduction
The centrifugal separation of uranium isotopes is the most economically efficient way to obtain enriched uranium for nuclear fuel. It is used to separate more than twenty heavy mass chemical elements in industrial scale [1],[2] for the further use in medicine, materials technology and science. While existing gas centrifuges (GC) are widely used for commercial needs, development of new gas centrifuges to reduce the cost of the enrichment process is actively underway. The main direction of improving centrifugal separation technology is increasing the dimensions of the GC and its rotation speed [3]. Rapid development of new materials that has begun in recent years, especially those based on carbon fibers and carbon nanotubes, additionally spurs research in the field of GC technologies. Rotation speed of the GC achieving 1000 m/s very recently seemed fantastic, but today it looks real. However, there is no information about what will happen at such speed and whether the separation process will be possible at all.

Impossibility of direct measurements of parameters of the gas flow in full-scale experiments is the basic problem in study of GC. In recent decades, with development of computer technology, numerical modeling is actively used for study of physics of separation GC [4],[5],[6],[7]. These methods made it possible to achieve significant progress in understanding the physics of separation in the GC. The most important is that dependence of the optimal separation power and optimal parameters of the GC on the rotation speed[8], length[9] and diameter [10] of the rotor have been obtained [11]. These results were obtained in an axisymmetric approximation.
[12],[13]. The GC scoops were modeled using the approximation of sources - sinks by specifying the value of friction power [14]. Geometric features of the scoop and three-dimensional features of the surrounding flow were completely ignored. The scoop is a curved Pitot tube. The power friction on the scoop is determined by its location in relation to the rotor rotation axis and its geometry. At rotation speed above 1000 m/s, when the most of the rotor volume occupied by a high vacuum [15],[16], the question arises about the possibility of with drown of the gas using the Pitot tube.

In this work, we present results of study of the possibility to achieve an optimal working regime for the hyper-speed Iguassu GC [11]. It is shown, that for linear velocity of rotor above 1000 m/s it is impossible to achieve simultaneous compliance with the optimal feed flux and the power of gas friction. This conclusion is obtained by using 3D modeling of the supersonic flow of gaseous UF$_6$ around a Pitot tube.

In addition, it follows from the modelling that uranium hexafluoride can be heated to temperatures above 1300 K, which creates additional problems in implementation of the optimal working regimes of the GC Iguassu of hyper-high rotor speeds.

2. Model
The main objective of the work is to clarity, can the waste scoop to provide the optimal value of the friction power $W_{opt}$ and the optimal waste flow $F_{Wopt}$ simultaneously?

![Figure 1. Scheme of the computational domain](image-url)

Modeling of the flow is performed in three-dimensional approximation on a small volume at the rotor wall, as it is shown in Fig. 1 [17], [18]. The stationary scoop is taken as a curved Pitot tube with diameter $d=2$ mm. The feed cut $\theta$ is 0.5, so the optimal waste flow $F_{Wopt}$ is equal to half of the optimal feed flow $F_{opt}$. The rotor rotates with angular velocity $\Omega$ around the Z axis. Linear temperature profile at the rotor wall is assumed. If we consider gas motion
in the "rigid-body" approximation \[19\], then the azimuthal component of the gas velocity and pressure from radius is \(v_\phi(r) = \Omega r\) and \(P = P_{\text{opt}} \exp(-A^2(1 - (r/a)^2))\). Here \(P_{\text{opt}}\) is the optimal gas pressure at the rotor wall. \(R_0\) is the radius of the scoop center relative to the rotation axis.

Calculations were performed for rotation speeds of 1000 m/s, 1100 m/s and rotor lengths of 1 m, 3 m and 5 m, for a rotation speed of 1500 m/s only for a length of 1 m. At the first step of the calculation procedure, the position of the scoop \(R_{0F}^W\) corresponding to the optimal value of waste flow \(F_{W_{\text{opt}}}\) was determined. After that, the value of gas friction power \(W\) for this scoop was calculated. In the second step, on the contrary, the position \(R_{0W}^W\) at which the optimal value of gas friction power \(W_{\text{opt}}\) is achieved was found. Then we calculate the value of waste flow \(F_p\). In the optimal working regime, \(R_{0F}^W\) and \(R_{0W}^W\) must be the same.

3. Results

Tables 1-3 show the results of calculation \(R_{0F}^W\) and \(R_{0W}^W\). The calculated values of the gas scoop positions \(R_{0F}^W\) and \(R_{0W}^W\) do not coincide in any case. This means that achieving the optimal working regime in practice is impossible for the selected geometrical characteristics of the scoop.

Table 1. Gas scoop position, calculated power values friction \(W\) and waste flow \(F_W\), as well as optimal power values friction \(W_{\text{opt}}\) and waste flow \(F_{W_{\text{opt}}}\) at a linear velocity of rotor \(v = 1000\) m/s

| \(L,\) m | \(R_{0F}^W\) | \(W/W_{\text{opt}}, W\) | \(R_{0W}^W\) | \(F_W/F_{W_{\text{opt}}}, \text{mg/s}\) |
|---|---|---|---|---|
| 1 | 56.2 | 41/29 | 56.0 | 30/45 |
| 4 | 56.1 | 130/115 | 56.0 | 174/201 |
| 5 | 56.1 | 166/131 | 55.9 | 166/291 |

Table 2. Gas scoop position, calculated power values friction \(W\) and waste flow \(F_W\), as well as optimal power values friction \(W_{\text{opt}}\) and waste flow \(F_{W_{\text{opt}}}\) at a linear velocity of rotor \(v = 1100\) m/s

| \(L,\) m | \(R_{0F}^W\) | \(W/W_{\text{opt}}, W\) | \(R_{0W}^W\) | \(F_W/F_{W_{\text{opt}}}, \text{mg/s}\) |
|---|---|---|---|---|
| 1 | 56.6 | 59/29 | 56.3 | 27/45 |
| 4 | 56.4 | 171/143 | 56.3 | 174/211 |
| 5 | 56.4 | 208/156 | 56.2 | 192/265 |

Table 3. Gas scoop position, calculated power values friction \(W\) and waste flow \(F_W\), as well as optimal power values friction \(W_{\text{opt}}\) and waste flow \(F_{W_{\text{opt}}}\) at a linear velocity of rotor \(v = 1500\) m/s

| \(L,\) m | \(R_{0F}^W\) | \(W/W_{\text{opt}}, W\) | \(R_{0W}^W\) | \(F_W/F_{W_{\text{opt}}}, \text{mg/s}\) |
|---|---|---|---|---|
| 1 | 57.7 | 220/107 | 57.5 | 49/119 |

Physically, this occurs due to the rapid exponential increase in gas density and the slow linear change in gas velocity along the radial coordinate. The gas flow through the gas scoop is determined by the product of gas density times velocity, but the friction force does not depend
on gas density. In this case, in order to provide the necessary gas flow through the scoop, it is necessary to find the position $R_0$, where the gas velocity is sufficiently high what leads to higher than optimal friction power (see tables 1-3). Reduction of the friction power can be achieved only by shifting the scoop to rarefied gas layers, where it is not possible to provide the necessary waste flux. $R_0^F$ and $R_0^W$ differs by 0.2 to 0.3 mm for all the optimal working regimes. This difference seems insignificant. But at high radial gradual of density the change of the radial coordinate by 0.2 - 0.3 mm, changes the waste flux in 1.5 - 2.6 times. Thus, scoops that provide the optimal waste flow create a gas friction power of 1.3 - 2 times more than the optimal one (see Table 1-3). Scoops providing the optimal friction were able to provide the flow being 1.35-1.6 times less than of the optimal waste flow.

![Figure 2](image.png)

**Figure 2.** Dependence of the waste flow and friction power on the position of the gas scoop $R_0$

Fig. 2 shows dependence of the waste flux and friction power of the gas on the position of the gas scoop $R_0$ for a rotation speed of 1000 m/s. The optimal waste flux and gas friction power are shown as well. The difference in the position of the gas scoop $R_0$, which provides the optimal values of the friction power and the waste flow, is a fraction of a millimeter, which at the considered rotor speeds leads to the actual impossibility of achieving the optimal regime.

Another problem related to gas extraction in hyperspeed GC is the problem of heating the working gas in the shock wave. The higher the rotational speed, the higher the intensity of the shock wave, which leads to an increase in the gas temperature. Figs. 3-4 show the distribution of gas temperature near the scoop. The maximum temperature is $804.1K$ for the speed equal 1000 m/s, while the temperature increases to $1356K$ for speed 1500m/s.
Figure 3. Gas temperature near the scoop at rotation speed 1000 m/s

Figure 4. Gas temperature near the scoop at rotation speed 1500 m/s

So high temperature of the gas near the scoop can lead to accelerated dissociation of uranium hexafluoride. Detailed study of this issue is outside the scope of this work. Nevertheless, we point out this problem because it can make an inappropriate transition to GC with ultrahigh rotational speeds.
4. Conclusion

In this work, we have studied problems which can make impossible exploration of GCs with ultrahigh (with a rotation speed of 1000 m/s and more) rotational speeds on the example of the Iguassu GC. It was found that it is problematic to achieve the optimal working regimes with the waste scoop in the form of the Pitot tube with diameter 2 mm. The scoop that provides the necessary friction power, is not able to extract the necessary amount of gas (waste flow is 1.35-1.6 times below the optimal), and the gas scoop that provides the required waste flow provides too high (1.3-2 times more than optimal) friction power. Of course, this result has been obtained only for the waste scoop of particular geometry. It is necessary to study a wider range of possible geometry of the scoops for the final conclusion. However, it is the first time when we collide with the problem of providing of the optimal regime of exploration of GC.

In addition, it was found that at the increase of the rotation speed, the temperature of the working gas in the shock wave increases significantly. At rotational speed of 1500 m/s, the maximum temperature exceeds 1356 K, what makes possible decomposition of uranium hexafluoride $\text{UF}_6$.

The question about perspectives of the hyperspeed GCs remains open and requires an additional research. In particular, it is necessary to answer the question of whether it is possible to provide near-optimal separation, taking into account the discovered limitations.

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