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Impact of the pulsed braking force on the axial circulation in a gas centrifuge

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A B S T R A C T

Impact of the pulsed braking force on the axial gas circulation in centrifuges for a uranium isotope separation was investigated by the method of numerical simulation. Two camera model has been explored. The pulsed braking of the rotating gas results into generation of waves which propagate along all length of the rotor of the centrifuge. The wavelength appears in accordance with predictions of our analytic theory. Pulsations almost doubles the axial circulation flux in the working camera in comparison with the case of the steady state breaking force with the same average power.

1. Introduction

Isotope separation in a gas centrifuge (hereafter GC) is the most efficient method of production of the enriched uranium for nuclear power stations. Rotors of contemporary gas centrifuges rotate with linear velocities 600–700 m/s and have radius 6–8 cm [8]. The efficiency of the separation is defined by the primary effect of radial separation in the strong centrifugal field and by the axial gas circulation inside the rotor [1].

Product and waste UF_6 leave the working camera of the centrifuge through scoops located at the bottom and top ends of the rotor. Simultaneously the scoops brake the gas. The braking force results into axial circulation of the gas. Additionally, the interaction of the supersonic rotating gas with the scoops is accompanied by formation of the shock waves which propagate in the working camera of the rotor forming spiral waves.

Pressure of the gas in the centrifuges varies with the radius very sharply. Variation of the radius on 1 cm results into variation of the pressure on 5–6 orders of magnitude. Compact sizes, high velocity of rotation and very strong dependence of the gas characteristics on radius make experimental measurements in the gas centrifuges rather problematic. Therefore, numerical simulations are the main source of our knowledge about details of the gas flow in the GC. Conventionally, the numerical simulations are used for prediction of the parameters of the GC and search of the optimal regimes of operation [7,9–12].

Study of the dynamics of the waves in GC is the new direction in the field of numerical simulations of the GC. This direction of works is connected with a possible direct practical application of the results. The acoustic waves are able to produce a specific gas flow due to absorption of the waves and transfer of the momentum from the waves to gas. These are so called acoustic flows [3,4].

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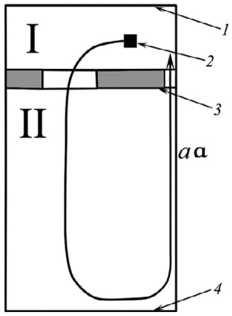

Fig. 1. Scheme of the computational domain. 1—upper end cap, 2—the source of the energy an momentum, 3—the baffle, 4—the lower end cap. I—upper and II—working cameras.

This mechanism of excitation of the axial circulation essentially differs from the traditional methods of the circulation excitation. Therefore, the waves can change the efficiency and working parameters of GC.

2. Formulation of the problem

The best way to investigate the impact of the shock waves on the gas circulation in GC is the full 3D time dependent computer modeling of the gas flow. In the laboratory frame system the shock wave produces a steady state spiral wave in the working camera. This type of simulation demands extremely high accuracy of the calculations because it is necessary to define the variation of the velocity in a few cm/s on the background of rigid body rotation of the gas with the velocity 600–700 cm/s. Therefore, the rotating frame system is used. In this frame system the rigid rotation velocity equals to zero. The governing differential equations written in the rotating cylindrical coordinate system have the form (see [2]):

$$\frac{\partial \rho}{\partial t}+\frac{\partial(r\rho v_r)}{r\partial r}+\frac{\partial(\rho v_\phi)}{r\partial \phi}+\frac{\partial(\rho v_z)}{\partial z}=0, \tag{1}$$

$$\rho\frac{\partial v_r}{\partial t}+\rho\left(v_r\frac{\partial v_r}{\partial r}+\omega\frac{\partial v_r}{\partial \phi}+v_\phi\frac{\partial v_r}{r\partial \phi}+v_z\frac{\partial v_r}{\partial z}-\omega^2 r-2\omega v_\phi-\frac{v_\phi^2}{r}\right)=-\frac{\partial p}{\partial r}+\mu\left(\left(\Delta-\frac{1}{r^2}\right)v_r+\frac{\partial}{3\partial r}\mathrm{div}(\vec{v})\right), \tag{2}$$

$$\rho\frac{\partial v_\phi}{\partial t}+\rho\left(v_r\frac{\partial v_\phi}{\partial r}+\omega\frac{\partial v_\phi}{\partial \phi}+v_\phi\frac{\partial v_\phi}{r\partial \phi}+v_z\frac{\partial v_\phi}{\partial z}+2\omega v_r+\frac{v_\phi v_r}{r}\right)=-\frac{\partial p}{r\partial \phi}+\mu\left(\Delta-\frac{1}{r^2}\right)v_\phi+f_\phi, \tag{3}$$

$$\rho\frac{\partial v_z}{\partial t}+\rho\left(v_r\frac{\partial v_z}{\partial r}+\omega\frac{\partial v_z}{\partial \phi}+v_\phi\frac{\partial v_z}{r\partial \phi}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\Delta v_z+\frac{\partial(\mathrm{div}(\vec{v}))}{3\partial z}\right), \tag{4}$$

$$\begin{aligned}\rho c_p\frac{\partial T}{\partial t}+\rho c_p\left(v_r\frac{\partial T}{\partial r}+\omega\frac{\partial T}{\partial \phi}+v_\phi\frac{\partial T}{r\partial \phi}+v_z\frac{\partial T}{\partial z}\right)&=\frac{\partial p}{\partial t}+v_r\frac{\partial p}{\partial r}+\omega\frac{\partial p}{\partial \phi}+v_\phi\frac{\partial p}{r\partial \phi}+v_z\frac{\partial p}{\partial z}+\lambda\Delta T\\&+\mu\left(\left(\frac{\partial v_z}{\partial r}+\frac{\partial v_r}{\partial z}\right)^2+\left(\frac{\partial v_\phi}{\partial z}+\frac{\partial v_z}{r\partial \phi}\right)^2+\left(\frac{\partial v_r}{r\partial \phi}+\frac{\partial v_\phi}{\partial r}-\frac{v_\phi}{r}\right)^2+\frac{1}{2}\left(\frac{4\partial v_r}{3\partial r}-\frac{2\partial v_\phi}{3r\partial \phi}-\frac{2v_r}{3r}-\frac{2\partial v_z}{3\partial z}\right)^2\right.\\&\left.+\frac{1}{2}\left(\frac{4\partial v_\phi}{3\partial \phi}+\frac{4v_r}{3r}-\frac{2\partial v_r}{3\partial r}-\frac{2\partial v_z}{3\partial z}\right)^2+\frac{1}{2}\left(\frac{4\partial v_z}{3\partial z}-\frac{2\partial v_r}{3\partial r}-\frac{2\partial v_\phi}{3r\partial \phi}-\frac{2v_r}{3r}\right)^2\right)+q.\end{aligned} \tag{5}$$

In the rotating frame system the waves are not steady state. The scoops produce running wave with frequency equal to the frequency of the rotor rotation. 3D modelling of the time dependent flow demands large computer memory and processor time. Therefore, it is reasonable to perform computer simulation of the gas flow in GC in axisymmetric model. Conventionally, in this model the scoops are replaced by the sources/sinks of the momentum, energy and mass [7]. To create the running wave in the axisymmetric model a nonstationary source of the momentum should be used. In this case we have axisymmetric waves in the model which do not perfectly reproduce the spiral waves in the real GC. Nevertheless, this approach looks reasonable as the first approximation of the problem and allows us to estimate the role of these waves in the physics of the GC.

In our model we use a model which contains two cameras as it is shown in Fig. 1. The model is closed. We do not consider here the problems connected with feed, product and waste fluxes. This allows us to investigate the role of the wave in the simplest model without mixing with other processes which has no direct relation to our problem.

In the upper camera a small region is selected where the source of the momentum and energy is introduced into the flow. We consider two types of the sources. The first one is the conventional steady state source. The second one is the pulsed source