Waves in a gas centrifuge

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Abstract.
Impact of the pulsed braking force on the axial gas circulation and gas content in centrifuges
for uranium isotope separation was investigated by the method of numerical simulation. Pulsed
brake of the rotating gas by the momentum source results into generation of the waves which
propagate along the rotor of the centrifuge. The waves almost doubles the axial circulation flux
in the working camera in compare with the case of the steady state breaking force with the
same average power in the model under the consideration. Flux through the hole in the bottom
baffle on 15% exceeds the flux in the stationary case for the same pressure and temperature in
the model. We argue that the waves reduce the pressure in the GC on the same 15%.

1. Introduction
Isotope separation in gas centrifuges (hereafter GC) are explored for production of 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 [2]. Scoops located at the bottom and top ends of
the rotor are used to eliminate product and waste UF6 the GC. Simultaneously the scoops brake
the gas. The braking force results into axial circulation of the gas. Additionally, the interaction
of the supersonically rotating gas with the scoops is accompanied by formation of waves which
propagate in the working camera forming spiral waves. The waves propagate in the
axial direction and are quickly transformed into linear waves. Scheme of the propagation of the
shock wave in the axial direction is shown in 1.

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 [14], [15].
This mechanism of excitation of the axial circulation essentially differs from the traditional
methods of the circulation excitation. Therefore, it is important to understand the physics of
the waves in the GC and their impact on the characteristics of the GC.

2. Properties of the linear waves in the GC
Shock waves are damped quickly. They are transformed into linear waves propagating in the
main part of the GC. The characteristics of the linear waves were investigated in [3]. The
dispersion law for linear waves in strong centrifugal field is shown in fig. 2. It can be seen that
three families of the linear waves are in the strong centrifugal field: upper, lower and sound.

Upper and lower families of the waves are damped quickly because energy of these waves is
concentrated near the axis of rotation. The energy of the sound waves is concentrated near the
rotor wall. According to our estimates the damping length of these waves always exceeds the
Figure 1. Scheme of the shock wave in the gas centrifuge

Figure 2. Dispersion law for the linear waves in strong centrifugal field. Lines 1-4 upper and lower families, 5 sound wave

length of the rotor. This prediction was confirmed in [4] by the numerical simulation. Only one type of the waves which corresponds to the dispersion law $\omega = kc$ survives in the GC.

3. The impact of the waves on the axial circulation

3.1. Formulation of the problem

The waves produced by the scoops are stationary in the laboratory frame system. Computer modeling of the gas flow in the GC is performed in rotating frame system [5, 6, 7, 8, 9]. In this frame system the waves are not stationary. They propagate along the GC as running spiral waves. 2D axisymmetric model of source-sinks is explored for modeling of the gas flow in the GC [7]. We use axisymmetric model of the sources and sinks in the rotating frame system as well. The sources of the momentum and energy are not stationary in our model. Therefore, they generate running axisymmetric waves.

Special computer code has been developed in MEPhI for numerical simulation of the non-stationary gas dynamics in strong centrifugal fields. The results of verification of the code were presented in [10, 11].
We use a model which contains two cameras as it is shown in fig. 3. The GC 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 waves in the simplest model without mixing with other processes which has no direct relation to our problem. A small region is selected in the upper camera where the source of the momentum and energy is introduced into the flow. We consider two types of the source. The first one is the conventional steady state source. The second one is the pulsed source of energy and momentum with the same as in the first case integral of the breaking force over the period of rotation. The shape of the pulse of the momentum source is shown in fig. 4. The largest part of the breaking force affects the gas during 1/10 period of rotation of the rotor. The working camera is located under the upper camera. They are separated by the baffle having two concentric holes: near the axis and at the wall of the rotor. These holes make possible free circulation of the gas in the rotor.

The pressure in the GC falls down to the axis of rotation with the rate 3-4 orders of magnitude per 1 cm [1]. There is a vacuum near the axis, where hydrodynamic equations are not applicable. This region is not interesting for us because there is no gas here. To exclude this region from the computational domain an additional boundary is introduced at some radius where the density of the gas is already very small but equations of hydrodynamics is still possible to apply [9, 13]. Boundary conditions on this wall correspond to the rigid adiabatic free slip wall. No slip isothermal walls where assumed at all other walls and the baffle.

3.2. Solution
Parameters of GC are typical for so called Iguasu centrifuge [16, 12]. They are given in table 1. The problem has been solved as a time dependent with time step equal to $\frac{1}{30} \tau_0$ to resolve with an acceptable accuracy the dependence of the braking force on time, where $\tau_0$ is the period of the GC rotation. The simulation has been performed for a sufficiently long time to obtain sustained time dependent flow. The pressure at the lower end cap has been used to control the regime of the flow.

3.3. Axial circulation
The braking force produces unbalanced radial gradient of pressure. The gas moves to the axis of rotation after the slowdown increasing the pressure near the axis. This results into expansion of the gas and its motion through the hole of the baffle. This way the perturbation generated in the upper camera propagates into the working camera. Here the perturbation takes a form of the wave which can propagate to the bottom end cap of the GC. The wave propagates back after
Table 1. Parameters of the model Iguasu GC.

| Parameter                                | Value            |
|------------------------------------------|------------------|
| Molar mass, M                           | 352 g/mol        |
| Radius of the rotor, a                  | 0.065 m          |
| Angular frequency, \( \omega \)         | \( 2\pi \cdot 1700 \, \text{s}^{-1} \) |
| Rotor temperature, \( T_0 \)            | 300 K            |
| Pressure near the rotor wall, \( p_w \) | 80 mmHg          |
| Specific heat at constant pressure, \( c_p \) | 385 J · K/kg     |
| Viscosity, \( \eta \)                  | \( 1.83 \cdot 10^{-5} \, \text{Pa} \cdot \text{s} \) |
| Thermal conductivity, \( \kappa \)      | 0.0061 W/m · K  |
| Length of the working camera, \( L \)   | 0.224 m          |
| The outer radius the hole of the baffle, \( r_h \) | 59.1 mm         |

Figure 4. The dimensionless braking force in the top source versus dimensionless period of rotation. 1 nonstationary case, 2 stationary case

reflection from the bottom end cap. Multiple reflection of the wave from the end caps results into rather complicated time dependent flow. Snapshot of this flow is shown in fig. 6. It follows from this figure that the wave satisfies to the dispersion equation of the form \( \omega = kc \), where \( c \) is the conventional sound velocity, \( k \) is the wave vector and \( \omega \) is the angular frequency of the wave. The existence of this type of waves in strong centrifugal field has been predicted recently in the work [3]. According to this work the waves with another dispersion law are possible. However, these waves are damped due to the molecular viscosity very quickly. On this reason they are not found in our simulations.

Comparison of the velocity field obtained with the stationary breaking force (see fig. 5) with the snapshot of the velocity field with the pulsating breaking force, fig. 6, shows that they are different. In the non-stationary case there are velocity perturbations which exceed the velocity in the stationary case. For the practical applications it is important to estimate the impact of the waves on the separation and efficiency of the GC. However, the snapshot of the flow field does not allow us to do that. It is necessary to consider the averaged flow field.

The axial circulation flow in the rotor can be described by the integral functions showing the mass flux \( m_- \) moving down the rotor and mass flux \( m_+ \) moving up the rotor. In the stationary case they should coincide due to the equation of discontinuity. In the non-stationary case
the same functions after averaging also should coincide with each other. This coincidence is an additional test of the correctness of the simulation. These mass fluxes are shown in fig. 7. It is the most important that the averaged mass flux twice exceeds the mass flux of the axial circulation produced by the steady state breaking force. The nature of this effect can be understood in terms of the acoustic flow [14, 15]. The scoop generates all possible types of waves including ones with fast damping due to the molecular viscosity. These waves transfer their momentum to the gas increasing the mass flux.

Thus, the waves generated by the scoops essentially change the integral characteristics of the axial circulation. This can result into difference between the calculated in the conventional (stationary) model parameters of the GC and real parameters.

4. The impact of the waves on the gas content

4.1. Formulation of the problem

The scheme of the computational domain for this case is presented in fig. 8. The domain consists of three cameras: top, working and bottom. Product (enriched) and waste (depleted) fluxes are removed in the bottom and top cameras, respectively by the sinks shown by solid points 6 and 2. Feed flow ($F$) is injected at the middle of the working camera. Circulation flow ($C$) is induced due to two mechanisms: temperature gradient $\Delta T$ at the rotor wall and brake of the gas in the top camera. The braking force is located in the point source 2. Parameters used for the computer simulation of the Iguasu centrifuge are presented in tab. 1 with some changes. The length of the rotor is equal 0.526 m and $\Delta T$ is equal 10 K. We used the same boundary conditions as in previous section and compared the cases with steady state and pulsed sources. The dependence on time of the pulsed braking force is shown in fig. 4.

4.2. Gas content

Initially the solution has been performed for the steady state case. The waste flux has been specified in the point 2 equal to 0.55 of the feed flux. The pressure in the working camera is
Figure 6. The waves in the working camera of the GC: (a) axial velocity; (b) \((p - p_0) e^{-\frac{M^2 r^2}{2 R T_0}}\),
where \(p = p_w e^{-\frac{M^2 (r^2 - a^2)}{2 R T_0}}\).

Figure 7. Dependence of \(m_+\) (solid lines) and \(m_-\) (dashed lines) on axial coordinate \(z\). Zero of this coordinate corresponds to the point right under the upper baffle. 1 averaged nonstationary case, 2- stationary case

obtained in the process of the solution. It equals to 79 mm Hg. This pressure provides the product flux satisfying to the mass conservation. It equals to 7.2 mg/s. The stream lines of the stationary flow are shown in fig. 9.

In the transient case the sink fluxes and pressure were taken initially like in the stationary one. The simulations show that in the transient flow the flux through the hole in the bottom baffle appears 15% higher than the product flux. This means that the mass is not conserved in the transient case. The mass conservation will take place when the pressure in the working
Figure 8. Scheme of the computational domain. $F$, $P$, $W$ feed, product and waste fluxes, respectively, and $C$ circulation flow. 1 top cap, 2 source of the momentum and energy, sink of the waste flux, 3 the top baffle, 4 rotor wall, 5 the bottom baffle, 6 sink of the product flux, 7 the bottom cap.

Figure 9. The stream line in the case of the stationary braking force. Scale in radial direction multiplied 15 times.

camera falls down to reduce the mass flux through the hole in the bottom baffle to the value equal to the product flux. But this takes a lot of computational time. Duration of such simulation exceeds a reasonable value. Nevertheless, we can conclude from this simulation that the waves
can essentially change the working pressure in the GC.

5. Conclusion
The influence of the linear waves on the hydrodynamic flow in the GC is investigated. We obtained that the axisymmetric waves with dispersion law \( = kc \) are excited due to this force in accordance with the theoretical predictions.

The pulsating breaking force almost twice increases the mass flux in the axial circulation flow in compare with the mass flux at the stationary breaking force in the closed GC with two cameras. Conventional axisymmetric models of the gas flow in the GC do not take into account this effect. This could result into incorrect estimate of the optimal breaking force.

The product flux in the transient case 15% exceeds the product flux of the stationary case for the same pressure and temperature in the working camera in the case of the GC with three cameras. This means that in the steady-state regime the pressure in the working camera of the transient case is expected to be lower than the pressure in the stationary case approximately on the same 15%.

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