Impact of waves on the circulation flow in the Iguasu gas centrifuge

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Abstract. 2D axisymmetric transient flow induced by a pulsed braking force in the Iguasu gas centrifuge (GC) is simulated numerically. The simulation is performed for two cases: transient and stationary. The braking forces averaged over the period of rotation are equal to each other in both cases. The transient case is compared with the stationary case where the flow is excited by the stationary braking force. Two models of the gas centrifuge is simulated. There are two cameras in the first model and three cameras in the second one. In the transient case for the two cameras model pulsations almost doubles the axial circulation flux in the working camera. In the transient case for the three cameras model the gas flux through the gap in the bottom baffle exceeds on 15 % the same flux in the stationary case for the same gas content and temperature at the walls of the rotor. We argue that the waves can reduce the gas content in the GC on the same 15 %.

1. Introduction
Separation of heavy isotopes in strong centrifugal fields is used for industrial production of enriched uranium. Rotors of gas centrifuges (GC) rotate with linear velocity a few hundreds meters per second [1]. The centrifugal acceleration can reach \( \sim 10^6 g \) at the radius of the rotor of a few centimeters. Nevertheless, strong centrifugal field is not the only factor which results into efficient isotope separation in GC. A range of physical processes is explored to produce an additional axial circulation, which essentially increases the efficiency of separation of the GC [2]. This secondary circulation is one of the key feature of the industrial GC.

A pair of scoops located near the end caps of the GC are used to remove enriched and depleted gas mixture from the GC. Simultaneously, they provide the additional axial circulation due to the mechanical brake of the gas. Mach number of the gas in GC is of the order 7 because the sound velocity of the working gas \( U_{F6} \) is of the order 86 m/s at room temperatures. Interaction of the gas with the scoop is accompanied by formation of strong shock wave which propagates along the rotational axis. Figure 1 schematically shows that the shock wave forms a spiral wave propagating from one end of the GC to another. It can reflect from the end caps of the GC forming waves running in both directions along the rotational axis. The amplitude of the shock waves is damped rather quickly. In the largest part of the rotor, they propagate as small amplitude waves.

It is well known that the waves can produce the flow of gas due to their absorption [4]. These are so-called acoustic flows described by Rayleigh [5, 6]. They are produced due to transfer of the energy and momentum from the waves to the gas due to the molecular viscosity. This way the waves generated by the scoops can provide an additional mechanism of generation of the...
secondary axial circulation in GC. This mechanism can essentially differ from the conventional mechanism of the circulation generation. The waves can propagate and therefore transfer the breaking torque at larger distance from the scoops than it happens at the axisymmetric brake. Recently, authors have shown that conventional acoustic waves are essentially modified in strong centrifugal fields \[3\]. Exploration of this mechanism can change efficiency of the isotope separation and working parameter of the GC.

2. Formulation of the problem

The waves produced by the scoops are stationary in the laboratory frame system. Computer modelling of the gas flow in the GC is performed in rotating frame system \[7, 8, 9, 10, 11\]. 2-D axisymmetric model of source-sinks is applied \[9\]. In this work we use axisymmetric model of the sources and sinks in the rotating frame system as well. The waves are not stationary in this model. 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 \[12, 13\].

The schemes of the computational domain is presented in Figure 2. The first domain consists of two cameras: top and working. 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. In the upper camera a small region is selected where the source of the momentum and energy is introduced in to the flow. The circulation flow is induced by this source.

The second 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.

We consider two types of the sources in both cases. 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 steady state case integral of the breaking force over the period of rotation. The shape of the pulse is determined by the following equation:

$$A(t) = A'e^{-15\sin(0.25t/\tau)}.$$  

\[1\]
Figure 2. (a,b) – Schemes of the computational domain. (a) – Scheme of the two cameras domain. 1 – upper end cap, 2 – the source of the energy and momentum, 3 – the baffle, 4 – the lower end cap. I – upper and II – working cameras. (b) – Scheme of the three cameras domain. F,P,W – feed, product and waste fluxes, respectively, and C – circulation flow. 1 – the top cap, 2 – source of the momentum and energy, sink of the waste flux, 3 – the top baffle, 4 – the rotor wall, 5 – the bottom baffle, 6 – sink of the product flux, 7 – the bottom cap. (c) – The dimensionless braking force in the top source versus dimensionless period of rotation. 1 – non-stationary case, 2 – stationary case. $A_0$ is the force in the stationary case, $\tau_0$ is the period of rotation.

where $\tau_0$ is the period of the rotation.

The dependence on time of the pulsating braking force in the time interval $(0 - \tau_0)$ is shown in Figure 2. In the transient case the duration of the braking force is about $\frac{\tau_0}{10}$. Amplitude is equal $A' = 27A_0$, where $A_0$ is the amplitude of the force in the stationary case. This reproduces the impact of the rotating scoop on the gas.

Rotation of the gas results into high pressure gradient in radial direction about $10^5$ Pa per 1 cm at the wall of the rotor. At a certain radius the pressure becomes so small that hydrodynamical approximation fails. At this radius free slip and adiabatic boundary conditions are specified according to [11]. No slip boundary condition is specified at the rotor wall. The wall is rotating with angular velocity $\omega$.

Parameters used for the computer simulation of the Iguasu centrifuge are presented in Table 1 [14].

3. Results
3.1. Two cameras model
The braking force produces unbalanced radial gradient of pressure. The gas moves to the axis of rotation after the slow down increasing the pressure near the axis. This results into expansion of the gas and motion of its part 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. After reflection from the bottom end cap of the GC the wave propagates into reversed direction. Multiple reflections of the wave from the end caps result into rather complicated time dependent flow. Snapshot of this flow is shown in Fig. 3. 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.
Table 1. Parameters of the Iguasu centrifuge

| Parameter                          | Value               |
|------------------------------------|---------------------|
| Molar mass, \( M \)                | 352 g/mol           |
| Specific heat at constant pressure, \( c_p \) | 385 J/kg·K          |
| Viscosity, \( \mu \)               | \( 1.83 \times 10^{-5} \) Pa·s |
| Thermal conductivity, \( \kappa \) | 0.0061 J/(m·s·K)    |
| Angular frequency, \( \omega \)    | 1700 \( \times 2\pi \) s\(^{-1}\) |
| Radius of the rotor, \( a \)       | 0.065 m             |
| Inner radius of the computational domain, \( r_{in} \) | 0.052 m |
| Temperature of the bottom baffle, \( T_{low} \) | 300 K |
| Temperature gradient on the rotor wall between top and bottom baffles, \( \Delta T \) | 10 K |
| Force in the stationary case, \( A_0 \) | 17.8 \( \times 10^{-6} \) N |

Comparison of the velocity field obtained with the stationary breaking force (see Fig. 3) with the snapshot of the velocity field with the pulsating breaking force shows that they are well different. In the nonstationary problem 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 average flow field.

![Figure 3](image)

**Figure 3.** (a, b) – The waves in the working camera of the GC: (a) axial velocity; (b) \((p - p_0) e^{\frac{M\omega^2}{2RT_0^2}(r^2-a^2)}\), where \(p_0 = p_w e^{\frac{M\omega^2}{2RT_0^2}(r^2-a^2)}\). (c) – Axial velocity in the working camera of the GC in the stationary case.

The velocity fields for stationary breaking force and the velocity field for pulsating breaking force averaged over last 6 periods of rotation are shown in Figs. 5 and 6. It is seen that the averaged velocity field well coincides with the stationary one. The flow pattern is quite identical. Nevertheless, the quantitative analysis shows that the pulsating breaking force essentially changes the axial circulation of the gas.

The axial circulation flow in the rotor can be described by the integral functions showing the mass flux \( \dot{m}_- \) down the rotor and mass flux \( \dot{m}_+ \) up the rotor. In the stationary case they should
Figure 4. (a) – Velocity under the baffle in the stationary case. (b) – Averaged velocity under the baffle in the case of pulsating breaking force.

coincide due to the equation of discontinuity. In the nonstationary case the same functions after averaging also should coincide with each other. By the way, this coincidence is an additional test of the correctness of the simulation. These mass fluxes are shown in Fig. 5. It is 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 [5, 6]. 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.

Figure 5. Dependence of $\dot{m}^+$ (solid lines) and $\dot{m}^-$ (dashed lines) on axial coordinate $z$. Zero of this coordinate corresponds to the point right under the baffle. 1 – average case, 2 – stationary case.
3.2. Three cameras model
For the three cameras model for the steady state case the waste flux is specified in the point 2 equal to 0.55 of the feed flux. The pressure in the working camera is obtained in the process of the solution. It equals to 79 mm Hg. This pressure provides the product flux satisfying the mass conservation. It equals to 7.2 mg/s.

In the transient case all the fluxes and temperature at the walls of the rotor are taken as in the stationary case. The stationary solution is taken as the initial state for the transient case. In the transient case the flux through the gap in the bottom baffle appears on 15% higher than the same flux in the stationary case. Correspondingly, the product flux increases on 15% as well while the feed and waste fluxes remain fixed. This happens because the decrease of the gas content due to the leakage of the gas through the product sink is insignificant during the simulation. The gas fluxes are not balanced. The mass conservation will take place when gas content in the working camera will fall down to reduce the product mass flux. But duration of simulation of such process exceeds duration of our simulation many times. We do not reach the equilibrium state where all the fluxes are balanced. Nevertheless, we can conclude that the waves have to change the gas content on the same 15% to balance all the gas fluxes in the GC.

4. Conclusion
The numerical simulation allows us to investigate the axial circulation of the gas under impact of the axisymmetric pulsating breaking force in the upper camera of the GC. The axisymmetric waves with dispersion law $\omega = kc$ are excited due to this force in accordance with the theoretical predictions.

In two cameras model the averaged field of velocity qualitatively coincides with the stationary one. However, the pulsating breaking force almost twice increases the mass flux in the axial circulation flow in comparison with the mass flux at the stationary breaking force.

In three cameras model the product flux in the transient case 15 % exceeds the product flux of the stationary case for the same gas content and temperature of the rotor walls. This means that in the steady-state regime, when all the gas fluxes are balanced, the gas content in the transient case is expected to be lower than the gas content in the stationary case approximately on the same 15%. Conventional axisymmetric models of the gas flow in the GC do not take into account this effect. This could result into in correct estimate of the optimal breaking force.

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