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Original Article

Separative Power of an Optimised Concurrent Gas Centrifuge

Sergey Bogovalov[*] *and Vladimir Borman*

National Research Nuclear University (MEPHI), Kashirskoje shosse, 31, Moscow, 115409, Russia

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ABSTRACT

The problem of separation of isotopes in a concurrent gas centrifuge is solved analytically for an arbitrary binary mixture of isotopes. The separative power of the optimised concurrent gas centrifuges for the uranium isotopes equals to $\delta U = 12.7\ (V/700\ m/s)^2(300\ K/T)(L/1\ m)$ kg·SWU/yr, where L and V are the length and linear velocity of the rotor of the gas centrifuge and T is the temperature. This equation agrees well with the empirically determined separative power of optimised counter-current gas centrifuges.

1. Introduction

Separation of heavy isotopes in gas centrifuges (hereafter GCs) has been used for industrial production of enriched uranium from the middle of the past century. It is likely that this method of isotope separation will remain the most efficient, from the economical point of view, for the next few decades. Despite the long history of using this method, a lot of important problems of the physics of the isotope separation remain unsolved. The problem of the separative power of GCs is the most important among them. Knowledge or estimation of the separative power of GCs is necessary for design of efficient GCs and important for experts dealing with the problem of nonproliferation of the separation technology.

An attempt to estimate the separative power of GCs has been made, starting with Dirac [1]. He has shown that the separative power δU_{max} of any GC can not exceed the value

$$\delta U_{max} = \frac{\pi \rho D L}{2}\left(\frac{\Delta M V^2}{2RT}\right)^2, \quad (1)$$

where ρD is the density of uranium hexafluoride (UF_6) times the coefficient of self-diffusion of uranium isotopes ^{238}U and ^{235}U. ΔM is the mass difference between two uranium isotopes, R is the gas-law constant, T is the gas temperature, L is the length of the GC rotor, and V is the linear velocity of the rotor rotation.

In the early 1960s an Onsager group from US developed a theory called *the pancake approximation* that reduced the

* *Corresponding author.*
E-mail address: svbogovalov@mephi.ru (S. Bogovalov).
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problem of the GC gas dynamics to the solution of linear elliptical equations of the sixth-order partial derivatives for two variables [2,3]. This approach gave the following equation for the separative power of the GC:

$$\delta U = (0.038V - 11.5)L, \ \text{kg·SWU/yr}. \tag{2}$$

It is important to note that, in contrast to Eq. (1) where the separative power increases as V^4, in Eq. (2) the separative power grows linearly with V.

Experimental data collected with the help of a large number of Russian GCs have shone new light on this question. According to Senchenkov [4], the separative power is defined by the following empirical equation:

$$\delta U = 12L\left(\frac{V}{700\ \text{m/s}}\right)^2\left(\frac{2a}{12\ \text{cm}}\right)^{0.4}, \ \text{kg·SWU/yr}, \tag{3}$$

where L is measured in meters. Recently this result has been well confirmed by more extended experimental data [5].

The proportionality of δU to V^2 in the empirical Eq. (3) dramatically contradicts simple theoretical arguments. Let coefficient q be defined as the ratio of the concentration of U235 in the product flux over the concentration in the waste flux. At relatively small q the separative power equals

$$\delta U = \theta(1-\theta)\frac{F(q-1)^2}{2}, \tag{4}$$

where $\theta = P/F$ is the ratio of the product mass flux P over feed mass flux F [6]. Radial separation in the centrifugal field gives the following dependence of q on V

$$q = \exp\frac{\Delta M \gamma V^2}{2RT}, \tag{5}$$

which unambiguously gives, $\delta U \sim V^4$. This dependence takes place in Eq. (1) but does not agree with the experiment. For many years, this problem has remained a challenge for specialists. Recently a new equation defining the separative power of GC has been proposed in Kemp [7].

$$\delta U = \left(\frac{V^2 L}{33000}\right)e_E, \ \text{kg·SWU/yr}, \tag{6}$$

where V is measured in meters per second, L is rotor length in meters and e_E is some numerical coefficient. This equation already correctly reproduces the empirical law [Eq. (3)]. Nevertheless, the dependence of the optimised separative power of the GC on the parameters remains an open problem up to now. The solution of this problem is important from the practical point of view. Simple estimates show that the maximal possible separative power defined by Eq. (1) is four to five times higher than the optimal separative power [Eq. (3)] defined experimentally at $V = 700$m/s and $2a = 12$cm. This dramatic difference is due to the different dependence of the separative power on V. In this connection a few fundamental questions arise. What are the physical reasons for V^2 dependence in Eq. (3)? What factors limit the growth of δU with V? Is it possible to dispose these factors and to increase the separative power of the gas centrifuges a few times at the same velocity and length of the rotor? In other words, is it possible to design a gas centrifuge a few times more efficient than existing ones? Indeed, Eq. (3) is not a fundamental law of nature, which makes gas centrifuges with higher separative power impossible.

To answer these questions it is necessary to perform a huge amount of computational work on numerical simulation and optimisation of the counter-current gas centrifuges which are used for industrial enrichment of uranium. Even in this case the success is not guaranteed. The gas flow in the counter-current centrifuges is so complicated that it is difficult to understand the connection between the characteristics of the flow and the final optimized separative power. Therefore, it is reasonable to consider a gas centrifuge with much simpler gas flow which allows us to consider the problem analytically. In this case we have a chance to specify the nature of the dependence of the optimised separative power on the parameters and to find a guidance line for understanding this dependence in the case of the counter-current centrifuge. That is why we propose to answer the specified questions in the model of the concurrent centrifuge. This type of GC has been considered firstly in Cohen [1], where the separative power of this type of GC has been estimated as

$$\delta U = 0.166 \times 2\pi\rho DL\left(\frac{\Delta M V^2}{2RT}\right)^2, \tag{7}$$

which is only 66% less than the maximal possible separative power given by Eq. (1), and follow to V^4 dependence of δU. Nevertheless, the flow field assumed in Cohen [1] was rather artificial. Therefore it is reasonable to reconsider this model once more.

In this work for the first time we give an analytical equation for the separative power of an optimised concurrent gas centrifuge for an arbitrary binary mixture of isotopes. In contrast to the results mentioned above, we show that in the case of uniform axial velocity of the working gas, the optimised separative power is proportional to V^2 which agrees well with the empirical equation given by Eq. (3). This result forces us to assume that in spite of difference in gas flow field in the counter-current and concurrent centrifuges, the dependence of the optimised (or maximal) separative power on the parameters of the centrifuge is universal and does not depend of the design of the centrifuge.

It is necessary to stress that we discuss here the separative power of GC optimised on all parameters which can be controlled by a designer. The separative power is the function of a lot of parameters $\delta U(V,L,T,a,\alpha_1,\alpha_2,\ldots)$, where the series of parameters α_i includes, for example, pressure at the wall of the rotor, F, θ, variation of temperature along the rotor δT and many others. Optimisation of the GC is reduced to a search for the maximum of this function at the variation of all the parameters α_i. Such a search is performed for every series of V,L,T,and a. Therefore, the separative power of the optimised GC depends only on the limited set of the parameters V,L,T,and a. Such a formulation of the problem carries additional difficulties in the solution of the problem because it is necessary not only to calculate the separative power of the GC, but additionally to optimise (to find maximal value) in relation to all possible parameters at fixed V, L, a and T.

In conclusion of this section, it is worth also mentioning that the process of the isotope separation and its efficiency is interesting also in application to liquids which can be subjected to the impact of the centrifugal field achieving $10^6 g$ at the temperature up to 500°C [8]. Therefore it is important to define a general equation, defining the separative power of an