Vacuum 109 (2014) 349–353

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

The direct jumping of molecules through the compression of gas centrifuge

V.I. Tokmantsev*, V.D. Seleznev

Department of Technical Physics, Ural Federal University, Ekaterinburg 620002, Russia

ARTICLE INFO

Article history:
Received 28 February 2014
Received in revised form
28 May 2014
Accepted 8 June 2014
Available online 18 June 2014

Keywords:
Compression ratio
Rarefied gas
Centrifuge

ABSTRACT

A 3D numerical simulation of pressure distribution in the helicoid multi-groove Holweck pump as the compression of a gas centrifuge is carried out. It was shown that the combination of the free molecular regime and clearance between the compression rotor and stator leads to an appreciable effect of collisionless jumping, which essentially influences the pressure in a high vacuum chamber. When neglecting the jumping effect, the limit compression ratio is very large. The jumping considerably reduces the compression ratio to approximately the same moderate value for different gases. As a result of the simulation, the limit compression ratio can be obtained as an optimizable function of variable parameters such as the groove depth, width and angle of inclination. The numerical results can be interpreted within the framework of a simple phenomenological model.

1. Introduction

The well-known Holweck pumps with helical grooves [1] are successfully used as molecular compressions in gas centrifuges (GC) for uranium isotopes separation [2]. The compression provides pumping out of space between a fast rotating inner cylinder and a motionless case, reducing the gas dynamic friction to an acceptable value. A high vacuum in this chamber is an essential condition of stable rotation and reliability in GC operation. The problem is that the long rotors of industrial GC are inclined to vibration; therefore a trouble-free design involves an appreciable radial clearance between the rotor and the compression stator. This is the difference of the molecular compressions of GC from modern compact turbomolecular pumps (TMP), using the opportunity to reduce considerably the radial clearance and to lower the back-leakage at the Holweck exhaust stage [3]. Moreover, in contrast to the drag stage of TMP working at a rather high pressure in the transitional and viscous regimes [4], i.e. when Knudsen number is small, $Kn \ll 1$, the operation mode of compression is close to the free molecular regime, $Kn > 1$. Here, the Knudsen number is determined as $Kn = \lambda/b$, where $\lambda = \mu v_m/p_f$ is the molecular equivalent free path in the fore vacuum chamber with the pressure p_f, μ is the viscosity, v_m is the most probable molecular speed, b is the groove depth. The combination of the free molecular flow regime and the compression clearance results in an appreciable direct collisionless jumping of gas particles from the higher pressure side into the side of low pressure. Since a steady-state gas flow through the compression is zero, the basic characteristic of the problem under consideration is not the pumping speed, but the compression ratio defined as $K = p_f/p_h$ where p_h is the pressure on the higher vacuum side.

To model the viscous or transitional regimes of the flow, especially in weakly nonequilibrium conditions, the Navier–Stokes equations [5–7] are used including the slip boundary conditions [8–12]. In papers dealing with the transitional and the molecular regimes, the kinetic Boltzmann equation [13–15] and a more laborious direct simulation Monte Carlo (DSMC) method [9,16] are applied. In the paper [17], a 2D free-molecular model is considered, not allowing taking into account the clearance. In the papers [3,9–11], a 3D numerical simulation of Holweck pump is carried out.

The incompleteness of a number of papers is the absence of simple and physically well-founded models confirming the obtained computational results. In the present work, not only the results of a numerical simulation of the compression of GC using DSMC method are presented, but also a qualitative phenomenological analysis of the jumping effect through the compression clearance is performed.

2. Statement of problem

Consider the 3D molecular compression of the standard Iguaçu-type centrifuge [18] consisting of smooth internal rotor with the given linear speed $U = 600$ ms^{-1} and motionless cylindrical

* Corresponding author.
E-mail addresses: tokmvi@ru66.ru (V.I. Tokmantsev), SelVD@yandex.ru (V.D. Seleznev).

http://dx.doi.org/10.1016/j.vacuum.2014.06.005
0042-207X/

external bushing of inner radius R and height H as a stator, in which N helical grooves are made forming a set of pumping channels as is shown in Figs. 1 and 2. Here, α is the angle of groove inclination, $R - h = 0.06$ m is the given rotor radius, h is the clearance. The temperature $T = 300$ K of the walls is uniform, the gas is ideal, and the pressure $p_f \leq 1$ Pa on the fore vacuum side is specified. The compression radius R, the width of groove d and the angle of inclination α determine the angular size of groove cross-section $\gamma = d/(R\sin\alpha)$.

There are no internal gas sources in the high vacuum chamber (such as desorption from the surface etc.) so that the steady-state pressure depends only on the penetration of molecules from the fore vacuum side through the compression. The purpose is to find the residual pressure p_{0h} in the high vacuum chamber and the limit compression ratio $K_0 = p_f/p_{0h}$.

2.1. Phenomenological analysis

Let us begin with the phenomenological analysis of the penetration through the clearance and grooves in the free molecular regime ($Kn \gg 1$) considering the local equilibrium gas state as a result of collisions of molecules with compression inner walls. Let us suppose that the statistical ensemble of gas molecules in each volume element of relaxation size $\Delta z \approx d,h << H$ (see Fig. 1) consists of the main part being in the local equilibrium with walls and a nonlocal addition caused by a collisionless jumping effect. The total free molecular gas flow through the compression cross-section z can be written as the sum of independent flows

$$J = J_1 + J_2 + J_3 + J_4, \tag{1}$$

where J_1, J_2 are the flows caused by the pressure or density local gradients (so-called Poiseuilles flows) in the grooves and clearance, respectively, J_3 is the pumping local stream, and J_4 is the nonlocal flow taking account of the molecules, which come directly to the cross-section concerned from the external chambers.

The Poiseuilles flow along the grooves through cross-section z can be approximately written as [14]

$$J_1(z) \approx -C_1 \frac{\mathrm{d}n}{\mathrm{d}z}, \tag{2}$$

where the gas local number density $n(z)$ is assumed to be homogeneous in a cross-section z, $C_1 = a_1 v_t S_1 d\sin\alpha$, $v_t = \sqrt{8kT/\pi m}$ is the average thermal speed of gas particles, m is the molecular mass, S_1 is the total cross-sectional area of all grooves, d is the groove width, $a_1 \leq 1$ is a phenomenological numerical factor taking into account all unknown details of the grooves permeability in z-direction.

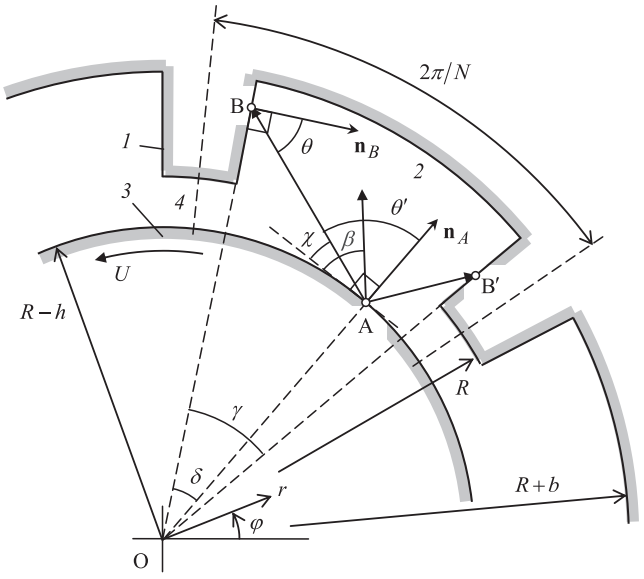

Fig. 2. Cross-section of the 3D molecular compression by the plane of rotation: *1* – ridge, *2* – groove, *3* – rotor, *4* – clearance.

The similar flow along the clearance reads [13]

$$J_2(z) \approx -C_2 \frac{\mathrm{d}n}{\mathrm{d}z}, \tag{3}$$

$C_2 = a_2 v_t S_2 h$, $S_2 = \pi h(2R - h)$ is the clearance cross-sectional area, $a_2 \leq 1$ is a numerical factor.

In order to find the pumping flow we should take into account that it is a result of the difference in the two flows incident upon each groove side walls from the rotor surface. It is known that in equilibrium state the elementary free molecular flow from area $d\sigma_A$ about a point A to area $d\sigma_B$ about a point B is given as [19]

$$d^2 J_{AB} = \frac{n v_t}{4\pi} \cos\theta \cos\theta' \frac{d\sigma_A d\sigma_B}{l_{AB}^2}, \tag{4}$$

where l_{AB} is the distance between the points A and B, θ',θ are the angles which the direction AB makes with normals $\boldsymbol{n}_A$ and $\boldsymbol{n}_B$.

We will adopt the following assumptions:

(i) It is useful, specifically for a strong rotation, to consider the 2D projection on a cross-section plane (see Fig. 2) and then

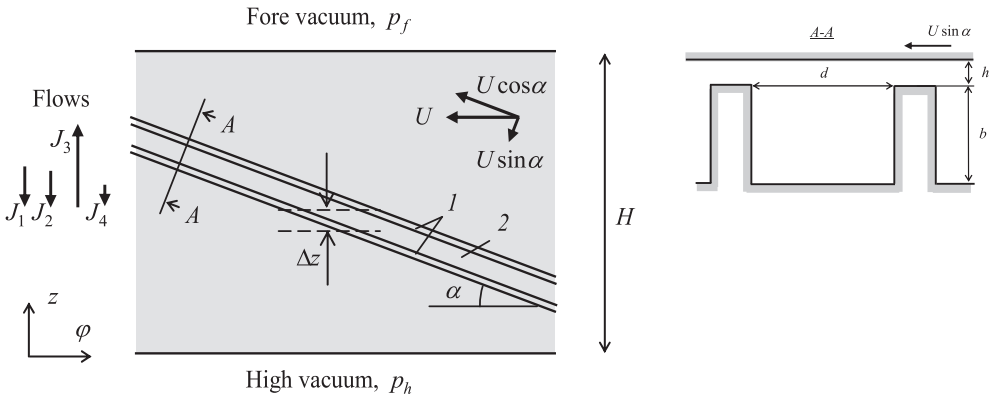

Fig. 1. 2D scheme of the pumping channel: *1* – ridges, *2* – groove.