Effect of Rotor Clearance on Pressure Ratio and Pumping Speed of Molecular Pump

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Nomenclature

d/b = clearance ratio
L/b = aspect ratio
N_i = molecular number incident on the blade row per unit time from region i
p_i = pressure in region i
P_1 = probability that molecules incident from low-density side of a blade with clearance will be transmitted through the blades
Q = ratio of the net through flow in molecules per unit time per unit area to the incident flux upon the blade from upstream side
Q_1 = probability that molecules incident from high-density side of a blade with clearance will be transmitted through the blades
s/b = spacing/chord ratio
S = ratio of the mean mass speed of the gas, relative to the blades, to the most probable molecular speed; speed ratio
α = blade angle with the tangential direction
Σ = transmission coefficient in the clearance area
Σ_{12} = transmission coefficient (the fraction of molecules incident on side 1 of the blade row, which ultimately emerge to side 2)

Subscripts

$1,2$ = upstream and downstream sides of the blade row, respectively
f = finite blade height
inf = infinite blade height

Theme

THE problem of free molecular flow in an axial flow molecular pump has been investigated experimentally and theoretically by Kruger and Shapiro[1] and others.[2] The study was predominantly on parallel flat-plate blades, and calculations were made on single-row and multirow blades by numerical and Monte Carlo methods. Kruger treated the blades assuming infinite blade height, whereas Sawada et al.[2] studied flat blades with finite height. The purpose of the present investigation is to study the effect of rotor clearance, which exists between a rotor tip and pump housing on the pressure ratio, and the pumping speed of a single rotor as well as a multistage pump.

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Figure 1 shows a schematic of a finite height blade with clearance d between rotor tip and the rotor housing. The transmission coefficients in the clearance area (Σ) for both sides of the clearance are the same. (This will be proved later.) Therefore, the net flux of molecules (W_c) through the clearance is equal to

$$W_c = \Sigma(N_1 - N_2) \tag{1}$$

Assuming that upstream and downstream molecules obey Maxwellian distributions with equal temperatures, that the molecular mean free path is large as compared with all blade dimensions and that the gas temperature does not change by molecular collision with the blades or the casing walls, we can write Eq. (1) as:

$$Q_c = -\Sigma[(p_2/p_1) - 1] \tag{2}$$

where Q_c is defined as the ratio of the net flux through the clearance to the incident flux N_1 upon the clearance. We know that at the steady state the net flux of molecules through the blade is

$$W = N_1[\Sigma_{12} - (p_2/p_1)\Sigma_{21}] \tag{3}$$

Therefore, the net flux of molecules through a blade disk with clearance d divided by N_1 is equal to

$$Q_N = (\Sigma_{12})_f - (p_2/p_1)(\Sigma_{21})_f - (d/L)\Sigma[(p_2/p_1) - 1] \tag{4a}$$

$$Q_N = (\Sigma_{12})_f + (d/L)\Sigma - (p_2/p_1)[(\Sigma_{21})_f + (d/L)\Sigma] = P_1 - (p_2/p_1)Q_1 \tag{4b}$$

The maximum pumping speed can be obtained by setting $p_2/p_1 = 1$ in Eq. (4b), which is equal to $P_1 - Q_1$. The maximum pressure ratio can be obtained by putting $Q_N = 0$ in Eq. (4b), which is equal to P_1/Q_1.

The calculation of Σ_{12} and Σ_{21} for a rotor with infinite blade height for different blade parameters and blade speeds has been reported by Kruger and Shapiro.[1] The finite blade analysis for a single row has been reported by Sawada et al.,[2] but they dealt only with $s/b = 0.5$ and $L/b = 1$.

Now we calculate the transmission coefficient of molecules through the clearance of a rotor. We could consider the clearance as a blade with blade angle of 90 deg and blade spacing to blade chord ratio of $d/b\sin\alpha$ (Fig. 1) with zero

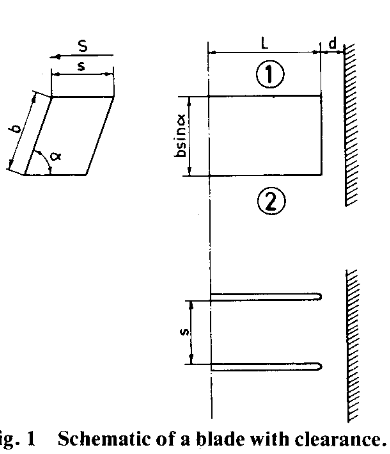

Fig. 1 Schematic of a blade with clearance.

Received Aug. 27, 1976; synoptic received April 29, 1977; revision received July 26, 1977. Full paper available from National Technical Information Service, Springfield, Va., 22151, as N77-27408 at the standard price (available upon request).
Index category: Rarefied Flows.

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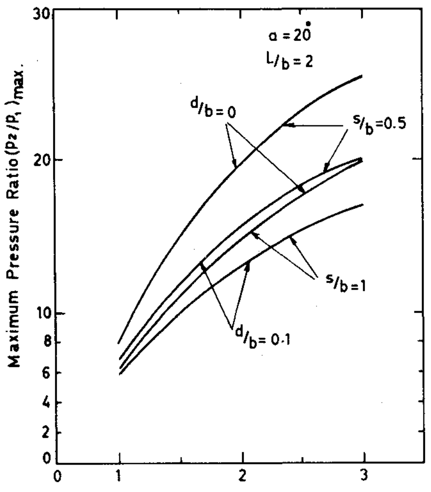

Fig. 2 Maximum pressure ratios for two sets of blades of finite height having zero and finite clearance vs speed ratio.

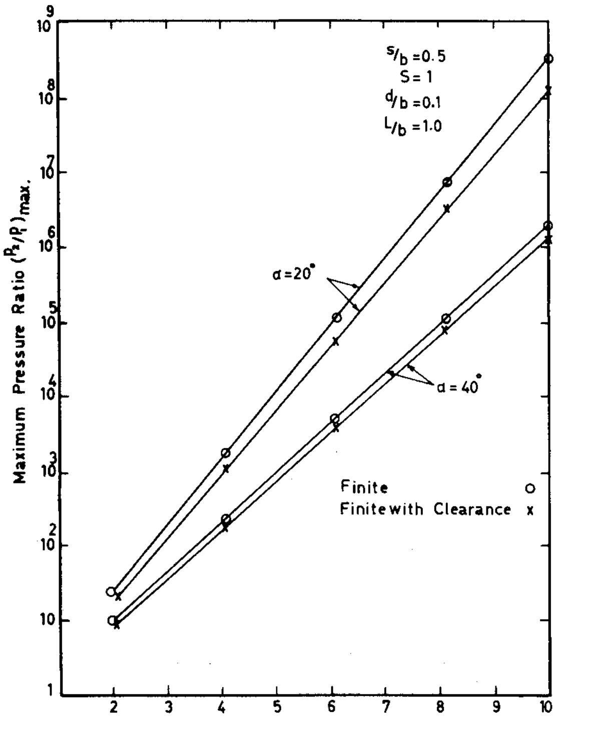

Fig. 3 The effect of clearance on pressure ratio for a compressor vs the number of blade rows.

blade speed. We then consider only molecules which are transmitted directly from one region to another region and molecules which are transmitted by single collision with rotor housing; therefore neglecting the transmission of molecules by collision with rotor. Although this assumption may change the value of true transmission, we believe that this simplified analysis gives us a rough estimate of the clearance effect.

Kruger[1] used an approximate method to find the transmission coefficients of a multistage machine as a function of single row transmission coefficients based on the assumption of infinite blade height. Here we have used their method to find the effect of clearance in a multistage compressor.

Figure 2 shows an example of the maximum pressure ratios for two sets of blades of finite height, having zero and finite clearance vs speed ratio. The calculation shows that the ratio of maximum pressure for a rotor with clearance to that of a finite height blade with zero clearance decreases as L/b decreases, whereas this ratio increases as the blade angle, or s/b, increases.

Figure 3 shows an example of the effect of clearance on pressure ratio for a machine of up to 10 rows. The calculation shows that maximum pressure ratio decreases with clearance, and this drop increases as blade angle, or s/b, becomes smaller. For example, for a 10-row machine with a blade angle of 20 deg, $s/b = 0.5$, and aspect ratio of 2, the maximum pressure ratio drops by a factor of 21. In summary, the results indicate that the values of the blade angle and spacing chord ratio are enough for prediction of the pressure ratio and the pumping speed of the pump by assuming infinite blade height for large blade angles, large spacing chord ratios, and small clearance ratios. But the exact prediction of the pressure ratio and the pumping speed for the small values of blade angles, small spacing chord ratios, and large clearance ratios must be made by considering the effect of rotor clearance.

References

[1] Kruger, C.H. and Shapiro, A.H., "The Axial-Flow Compressor in the Free Molecular Range," *Rarefied Gas Dynamics*, edited by L. Talbot, Academic Press, New York, 1961.

[2] Sawada, T., Suzuki, M., and Taniguchi, O., "The Axial-Flow Molecular Pump, 1," *Institute of Physics and Chemical Research, Japan*, Vol. 62, Feb. 1968, p. 49.

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