KSME International Journal, Vol. 11, No. 1, pp. 77~87, 1997

A Numerical Study of the Performance of a Turbomolecular Pump

Young-Kyu Hwang* and Joong-Sik Heo**
(Received March 20, 1996)

In the free molecular flow range, the pumping performance of a turbomolecular pump has been predicted for various values of the dimensionless blade velocity ratio C by employing the integral method and the test particle Monte-Carlo (MC) method in the calculation of the transmission probability. Also, new approximate method combining the double row solutions, so called double-approximation (DA), is presented here. The calculated values of transmission probability for the single row agree quantitatively with the previous known numerical results. For a six-row pump, the MC method is employed to calculate the overall transmission probability for the entire set of blade rows. When the results of the approximate method combining the single row solutions are compared with those of the MC method at $C=0.4$, the previously known approximate method overestimates as much as 34% than does the MC method. But, the new DA method gives more accurate results within 10% of relative error with respect to the MC method.

Key Words: Free Molecular Flow Range, Turbomolecular Pump, Transmission Probability, Integral Method, Monte-Carlo Method, Double-Approximation

Nomenclature

b	: Blade length
C	: Dimensionless blade-velocity ratio, V/V_m
h	: Blade height
K_{max}	: Maximum compression ratio
m_{12}	: Probability, see Eq. (4)
N_1	: Number of molecules incident on the blade row per unit time per unit area from the blade entrance
N_{net}	: Net flux of molecules through the blade row
p	: Pressure
P_{12}	: Probability, see Eq. (1)
P_{21}	: Probability, see Eq. (1)
P_{U2}	: Probability, see Eq. (5)
P_{L2}	: Probability, see Eq. (5)
Q	: N_{net}/N_1
Q_{max}	: Dimensionless maximum pumping speed
R	: Ordinary gas constants
s	: Blade spacing
S_g	: Dimensionless clearance between blade and pump housing, δ/h
S_h	: Dimensionless blade height, h/b
S_o	: Spacing-chord ratio, s/b
T	: Absolute temperature
V	: Blade velocity
V_m	: Most probable molecular velocity($\sqrt{2RT}$)

Greek Symbols

α	: Blade angle
δ	: Clearance between blade and pump housing
σ_{x2}	: Probability, see Eq. (6)
σ_{y2}	: Probability, see Eq. (6)

Subscripts

1	: Blade entrance
2	: Blade exit

* Professor, Department of Mechanical Design, Sung Kyun Kwan University
** Graduate school, Sung Kyun Kwan University

j : Number of spacing region between blade rows
J : Number of rows
L : Lower blade
U : Upper blade

1. Introduction

Vacuum technology has been rapidly developed according to the variety of practical uses and the importance of industrial techniques. It is widely used from the food and medicines which are necessary for our life to the latest industrial activities such as nuclear fusion, particle accelerator, flight and space industry, including electronic parts, industrial materials, and semiconductors. Not only highvacuum but also clean vacuum without contamination of oil is required in various fields of science and industry. Recently, because of the above reasons, turbomolecular pump (TMP) is widely utilized for the semiconductor and nuclear fusion researches.

A TMP is an axial-type compressor consisting of a set of alternate rotors and stators as shown in Fig. 1, and the velocity of a rotor tip usually reaches 150~450 m/s for a normal TMP. In the molecular flow range, the mean free path lengths of the particles are larger than the distance between the rotor blades. Therefore, the particles collide with one another infrequently while collisions with the blades are more frequent. In this way, the blade velocity is imposed on the particles as an additional component. This is so called molecular drag principle (Hablanian, 1990).

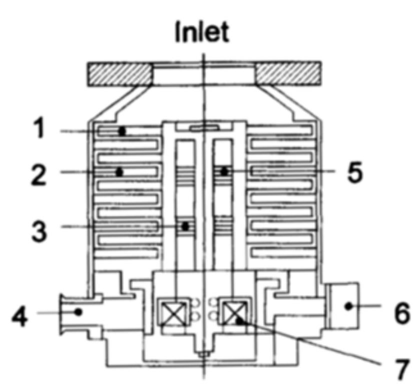

Fig. 1 Turbomolecular pump
1: Rotor 2: Stator 3: Motor 4: Outlet
5: Radial electromagnet 6: Connector
7: Axial electromagnet

The TMP invented by Becker in 1957 became commercially available in 1958, and the ultimate pressure is about 10^{-10} Torr. Advantages of a TMP are that it can produce cleaner and higher vacuum environment compared to an oil-diffusion pump and that since it does not use oil, the possibility of backstreaming of oil is removed. Furthermore, it reaches full operating speed within short periods after being switched on, and the lower power requirement produces a lower operating cost compared to a cryogenic pump (Hablanian, 1990; Hucknall, 1991).

A theoretical and experimental study on the pumping mechanism of a TMP was first executed by Kruger & Shapiro (1961). Thereafter, the performance characteristics of the infinite blade height (two-dimensional (2D) analysis; Tu & Yang, 1987, Tu et al., 1988) and finite blade height considering clearance between blade and pump housing (three-dimensional (3D) analysis; Sawada et al., 1971; Sekiya & Kitora, 1990, and 1991) were examined by the integral method and the Monte-Carlo (MC) method.

Sawada et al. (1971), gave the formula taking the effect of the blade thickness into account for a multi-stage. Also the factors which affect the transmission probability for a single row were introduced into the calculations of the overall transmission probability for a multi-stage pump by Sawada et al. (1971). Tu & Yang (1987) and Tu et al. (1988) presented the formula to correct the transmission probability for a single row, and also Tu & Yang (1988) developed new formula to calculate the overall transmission probability, which is suitable for the case of unequal blade length.

In order to investigate the effects of the clearance, Sekiya & Kitora (1990, and 1991) carried out 3D calculations for a single row by using the MC method. For a three-row TMP, they performed the calculations of the overall transmission probability by combining the single row results.

However, most of the previous studies were limited to the analysis of the 2D models, and the 3D calculations were performed only for a single row. In the present study, the calculations considering blade thickness and clearance for a six-row TMP were carried out directly by using the MC method.

To verify the present numerical method, firstly, the results calculated by the integral method and the MC method for a single row were compared with the previous known numerical results (Kruger & Shapiro, 1961; Tu & Yang, 1987; and Sekiya & Kitora, 1990) and experimental data (Sawada & Taniguchi, 1973). Secondly, the various geometrical parameters (blade length b, blade spacing s, blade angle α, blade height h, and clearance δ) were changed to investigate the pumping performance.

For a multi-stage TMP, the overall transmission probability that gas molecules pass through the entire set of blade rows was calculated by utilizing the approximate method (single-approximation, SA) which employs the single row results, and the six-row TMP which considers blade thickness and clearance was analyzed by using the MC method. Also, new approximate method combining the double row solutions, so called double-approximation (DA), was presented here.

To predict the performance of a TMP with accuracy, the MC method must be utilized for the analysis of a normal TMP which consist of several tens or more stages. But, it is not economical to use the MC method due to high expenses and much computational efforts. Thus, the approximate method should be applied. The objective of this study is to examine the accuracy and usefulness of the approximate methods by comparing the previously existing SA method with the present DA method.

2. Numerical Method

2.1 Single row analysis

Consider the free molecular flows through the two-dimensional (2D) blade rows as shown in Fig. 2. In the 2D infinite row case the blades are

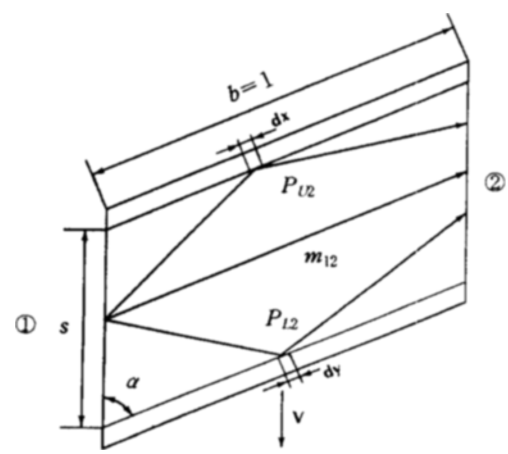

Fig. 2 Geometry of the TMP blade row

moving in a linear manner rather than rotating.

When the free molecular flow is established in the blade rows, the below relationship between the compression ratio K and the pumping speed Q is given by Kruger & Shapiro (1961) provided that entrance area is equal to the exit area.

$$K=\frac{p_2}{p_1}=\frac{P_{12}}{P_{21}}-\frac{Q}{P_{21}} \tag{1}$$

in which P_{12} is the probability that molecules incident on the blade rows from region ① will ultimately pass through the region ② after several collisions with the blade and P_{21} is the probability of transmission to region ① of molecules incident on the blade rows from region ②, as can be seen in Fig. 2. Also, p_1 and p_2 are the pressures at the blade entrance and exit respectively.

Finally, the maximum pumping speed is obtained by $p_1=p_2$ in the Eq. (1) and the maximum compression ratio is obtained by $Q=0$. That is,

$$Q_{\max}|_{p1=p2}=P_{12}-P_{21} \tag{2}$$

$$K_{\max}|_{Q=0}=\frac{P_{12}}{P_{21}} \tag{3}$$

2.1.1 Integral method

This method was first developed by Kruger & Shapiro (1961), and we have used this method to calculate the following probabilities.

Molecules incident on the TMP blade rows have the following three probabilities; the probability which will impinge directly on the upper blade surface (P_U), the probability which will impinge directly on the lower blade surface (P_L), and the probability which will directly pass through the blade row without collisions (m_{12}). Taking the sum of the above three probabilities. Then

$$P_U + P_L + m_{12} = 1 \quad (4)$$

Also, as shown in Fig. 2, the probability P_{12} that molecules incident on the blade rows from region ① will ultimately reach region ② consists of the following three components; the probability P_{U2} that molecules from region ① will directly impinge on the upper blade surface and then will ultimately reach region ② after several collisions with blade surface, the probability P_{L2} from the lower blade surface, and the probability m_{12}. Then

$$P_{12} = P_{U2} + P_{L2} + m_{12} \quad (5)$$

Let $\sigma_{x2}(\sigma_{y2})$ be the probability that molecules emitted from $dx(dy)$ will ultimately reach region ②. Let $P_{1x}(P_{1y})$ be the fraction of all molecules entering blade passage from region ① which impinge directly on the unit area $dx(dy)$. In terms of these quantities, the probability P_{12} can be evaluated as follows:

$$\begin{aligned} P_{12} &= P_{U2} + P_{L2} + m_{12} \\ &= \int_0^b \sigma_{x2} P_{1x} dx + \int_0^a \sigma_{y2} P_{1y} dy + m_{12} \quad (6) \end{aligned}$$

Each term on the right of Eq. (6) is evaluated by the numerical integrations, and Table 1 shows the results corresponding to the number of segments of the integration intervals. These results are nearly constant if the number of segments is more than 200.

Table 1 Effect of number of nodes on the transmission probability

No. of nodes	$\alpha=20^\circ$, $S_o=1.0$ $C=0.5$	$\alpha=40^\circ$, $S_o=1.0$ $C=0.5$
	P_{U2}	P_{U2}
10	0.031499	0.098821
50	.032661	.102696
100	.032789	.103114
150	.032807	.103204
200	.032816	.103231
250	032819	.103241

2.1.2 Monte-Carlo method

2-dimensional analysis

The flow range which is treated in this work is the free molecular flows. Accordingly, the test particle MC method, which is suitable for the case of collisionless flows, can be used. Many thousands of molecular trajectories are generated in the computer and the molecules incident on the entrance of the blade rows collide serially with the blade surface. The probability P_{12} is thus obtained by calculating the number of molecules reached the blade exit.

It is assumed that the veloity distribution at entrance of a TMP blade rows is Maxwellian. The velocities and positions of molecules at the blade entrance can easily be obtained as the same way provided in the literature (Sekiya & Kitora, 1990). Also, to reduce numerical errors, the number of molecules was selected more than 400,000.

3-dimensional analysis

A 3D analysis considering the clearance between pump housing and blade tip is required to improve the evaluation of the performance of a TMP, and it may be expected to reduce the discrepancy between experimental result and analytical one.

The molecular motions in the direction of the blade height were added to the 2D model. The velocities and positions of molecules colliding with the blade surface and housing were calcu-

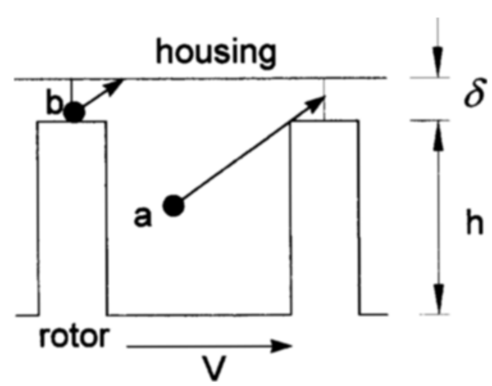

Fig. 3 Periodic condition of the molecules flowing clearance between blade and housing

lated according to the diffuse reflection model (Kruger & Shapiro, 1961). The molecule **a** passing through the clearance(δ) and flowing out of the solution domain, on the other hand, was replaced with **b** flowing into the solution domain as in Fig. 3 (Sekiya & Kitora, 1990).

2.2 Multi-stage analysis

2.2.1 Approximate method

Since a TMP consists of a set of blade rows, the overall transmission probability must be calculated to analyze the performance characteristics of a pump.

The overall transmission probability that gas molecules pass through the entire set of blade rows was calculated by utilizing the approximate method (single-approximation, SA) which employs the single row results, and the following formula suggested by Tu & Yang (1988), which is suitable for the case of unequal length of blades, was used:

$$P_{1(j+1)} = \frac{(A_{J-1}+A_{\varepsilon(J-1)})A_J P_{1j} P_{j(j+1)}}{(A_{J-1}+A_{\varepsilon(J-1)})A_J P_{j(j+1)}+(A_J+A_{\varepsilon J})A_{J-1}P_{j1}-A_{J-1}A_J P_{j1} P_{j(j+1)}} \tag{7}$$

$$P_{(j+1)1} = \frac{(A_J+A_{\varepsilon J})A_{J-1}P_{j1}P_{(j+1)j}}{(A_{J-1}+A_{\varepsilon(J-1)})A_J P_{j(j+1)}+(A_J+A_{\varepsilon J})A_{J-1}P_{j1}-A_{J-1}A_J P_{j1} P_{j(j+1)}} \tag{8}$$

in which $A_{\varepsilon J}$ is the blocking area (due to blade thickness) of the J row and A_J is the effective pumping area of the J row.

However, in the present study, new approximate method (double-approximation, DA) combining the double row solutions was also presented here. The transmission probability passing through the double row was first calculated by using MC method, and then this result was introduced into Eqs. (7) and (8). That is, in Eqs. (7) and (8), with $j=2$ and $J=2$, P_{13} and P_{31} are obtained, and next with $j=4$ and $J=4$ (but, in the previous SA method, $j=3$ and $J=3$), P_{15} and P_{51} are obtained, and so on. It will be shown that the present DA method will give more accurate results than the previous SA method.

2.2.2 Monte-Carlo method

The approximate method in Sec. 2.2.1 assumes that the velocity distribution of molecules between blade rows is Maxwellian. But, the velocity distribution of molecules between blade rows is, in general, not Maxwellian. In this case, the MC method is the only way to calculate accurately the overall transmission probability passing through the entire set of blade rows.

The six-row TMP model (Fig. 4) which considers blade thickness and clearance was analyzed by using the MC method.

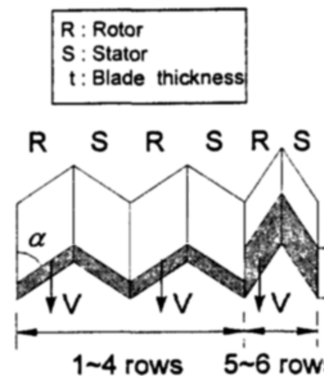

Fig. 4 The model for Monte-Carlo analysis(in the case of 6-rows)

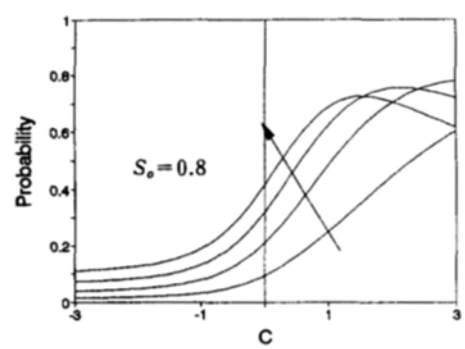

Fig. 5 Transmission probability as a function of C at $S_o=0.8$. The arrow indicates increasing α for $\alpha=10°$, 20°, 30°, and 40°

3. Numerical Results

3.1 Results for the single row analysis

The transmission probability P_{12} for a blade row with $S_o=0.8$ and $\alpha=10°$, 20°, 30°, and 40° was calculated by using the integral method and

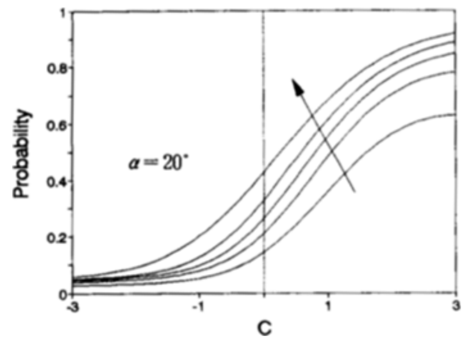

Fig. 6 Transmission probability as a function of C at $\alpha=20°$. The arrow indicates increasing S_o for $S_o=0.5, 0.8, 1.0, 1.2, 1.5$.

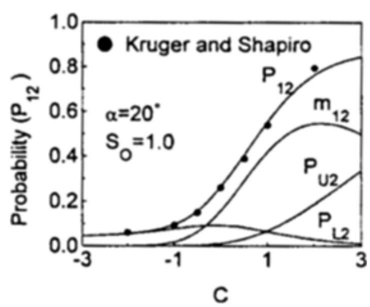

Fig. 7 Comparison of present results with Kruger & Shapiro(1961)

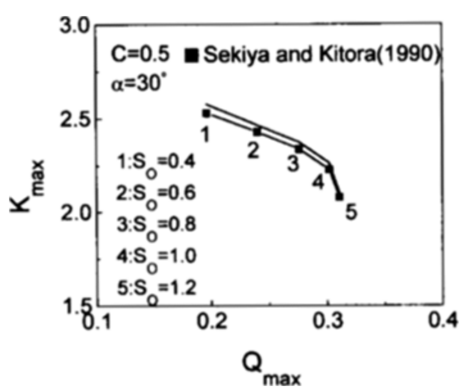

Fig. 8 Comparison of present Monte-Carlo results with Sekiya & Kitora(1990)

the MC method, and the results are shown in Fig. 5. In this figure the probabilities corresponding to the negative C ($=V/V_m$, where V is the blade tip velocity and V_m is the most probable molecular

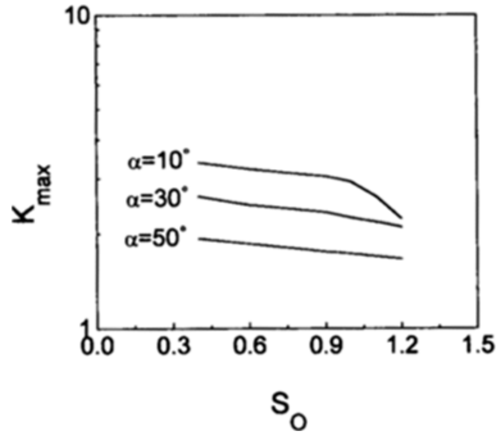

Fig. 9 Calculated curves for K_{max} as a function of S_o at $\alpha=10°$, $30°$, and $50°$

velocity) express the probability P_{21}. It is seen that the blade velocity ratio C at the maximum probability P_{12} decreases with α, and that in the range $0<C<1$ that TMP is normally operated, the probability P_{12} increases with α.

The probability P_{12} for $\alpha=20°$ and $S_o=0.5$, 0.8, 1.0, 1.2 and 1.5 was also obtained by using the integral method and the MC method, and the results are shown in Fig. 6. The effect of increasing S_o is just to increase the probability P_{12}.

The comparisons of the present results with the previous known numerical results are presented in Figs. 7~8 and Table 2.

Each component of the probability P_{12} in Eq. (5) is plotted as a function of C for $\alpha=20°$ and $S_o=1.0$ in Fig. 7. Also shown are seven points obtained by Kruger & Shapiro (1961). They assumed in their calculations of the P_{12} that the probability P_{U2} (the fractions that molecules from the entrance directly impinge on the upper blade surface and then ultimately reach the exit) is larger than the probability P_{L2}. The above assumption is opposite to the present results. But, the transmission probability P_{12} is nearly identical to Kruger & Shairo (1961) even though each component of the probability (P_{U2} or P_{L2}), differs in values.

The performance curves for $\alpha=30°$ and $C=0.5$ are obtained by using the MC method, and they are illustrated in Fig. 8, and also the present results are compared with Sekiya & Kitora (1990). This figure shows that the present results provide a good agreement.

The comparison of the present numerical results with Tu & Yang (1987) is given in Table 2(a). The examination of the results in case 1 reveals that the relative error of the probability P_U is about 50%. However, since the absolute values of P_U are much smaller than P_L or m_{12}, its error can be neglected. In other cases in Table 2(a), the relative errors are smaller than 6%. The transmission probability P_{12} is nearly identical to Tu et al. (1988) even though the probability P_U in Table 2(a) differs in values (Table 2(b)).

Table 2(a) Compared numerical values of P_U, P_L, m_{12}

Case 1		Case 2		Case 3	
Tu & Yang (1987)	Present study (Integral Method, MC)	Tu & Yang (1987)	Present study (Integral Method, MC)	Tu & Yang (1987)	Present study (Integral Method, MC)
$C=0.5$, $S_o=1.0$, $\alpha=20°$		$C=1.0$, $S_o=1.0$, $\alpha=20°$		$C=1.0$, $S_o=1.0$, $\alpha=35°$	
P_U 0.0750	0.0401, 0.0394	0.0847	0.0851, 0.0862	0.2297	0.2299, 0.2334
P_L 0.6348	0.6697, 0.6715	0.4958	0.4955, 0.4959	0.2768	0.2765, 0.2765
m_{12} 0.2902	0.2902, 0.2891	0.4195	0.4194, 0.4179	0.4935	0.4936, 0.4901

Table 2(b) Compared numerical values of P_{12}

Case 1	
Tu *et al.* (1988)	Present study
$C=0.5$, $S_o=1.0$, $\alpha=20°$	
$P_{12}=0.4030$	$P_{12}=0.4065$

The maximum compression ratio (K_{max}) and maximum pumping speed (Q_{max}) versus S_o for $\alpha=10°$, 30°, and 50° at $C=0.5$ are respectively shown in Figs. 9 and 10. It is seen that K_{max} decreases as S_o increases, and that the low value of the blade angle is to increase K_{max}. The value Q_{max} increases with S_o, and of particular interest in this plot is the fact that Q_{max} for $\alpha=30°$ becomes larger than that for $\alpha=50°$ at the spacing-chord ratio S_o above 0.8.

The 3D calculations were performed by using the MC method, and the effects of $S_h(=h/b)$ and $S_g(=\delta/h)$ on the performance were examined.

The compression ratio as a function of S_h for $S_g=0$ and $C=0.4$ is presented in Fig. 11. Also included on this figure are calculated results based on the 2D model, which are represented as solid dots. The value K_{max} decreases rapidly with the blade height h, and if S_h is larger than 2.0, the results approach the 2D results. This figure suggests that the 2D analysis is possible to predict the single row performance because S_h is larger than 1.0 in a normal TMP.

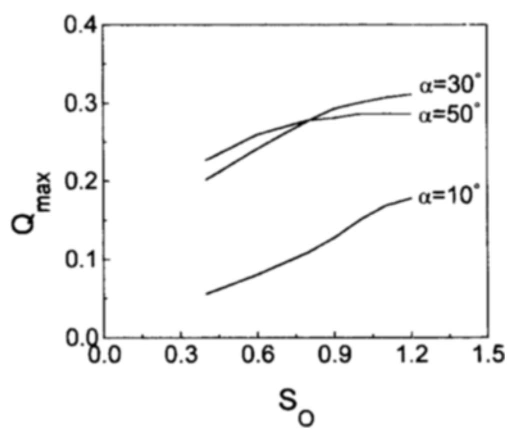

Fig. 10 Calculated curves for Q_{max} as a function of S_o at $\alpha=10°$, 30°, and 50°

The curves for K_{max} as a function of S_g for $C=0.4$ and $S_g=3.0$ are plotted in Fig. 12. This

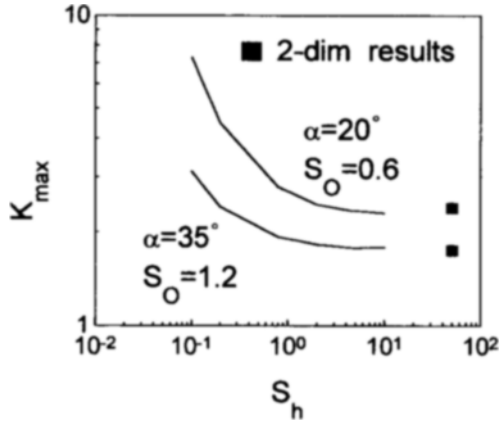

Fig. 11 Calculated curves for K_{max} as a function of S_h

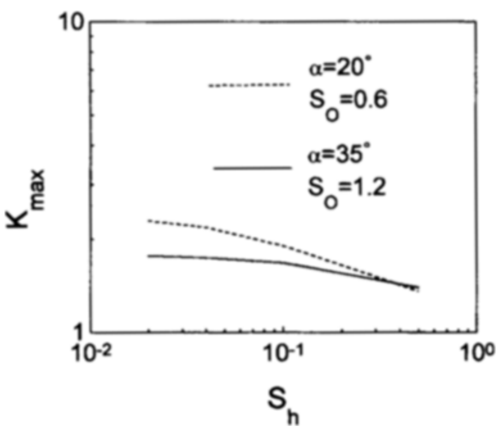

Fig. 12 Calculated curves for K_{max} as a function of S_g

plot indicates that the K_{max} decreases with S_g, and that the effects of S_g on it are very small for the clearance S_g smaller than 0.1.

3.2 Results for the multi-stage analysis

For the purpose of verifying the present numerical method, the results were compared with the previous known experimental data (Sawada & Taniguchi, 1973), and the specifications of the pump are given in Table 3.

Table 3 Data of the multi-stage TMP

Blade row number	α	S_o	Diameter of row	C
1～9	30°	1.0	300 mm	0～0.5
10～25	20°	1.0	300 mm	0～0.5

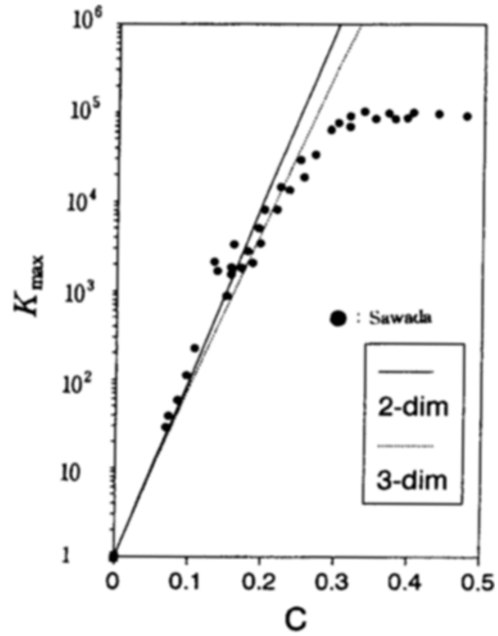

Fig. 13 Comparison of present numerical results with experimental data of Sawada & Taniguchi (1973) for K_{max}

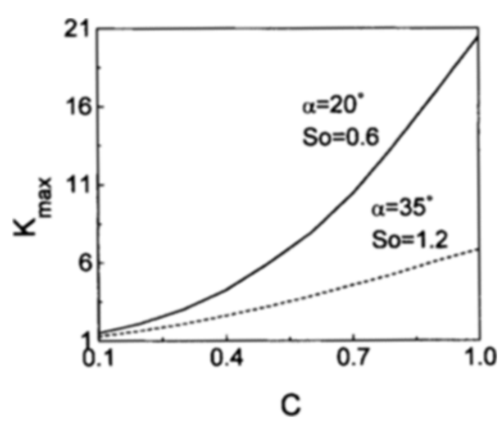

Fig. 14 Calculated curves for K_{max} as a function of C in the case of 2-rows

The comparison of the present results with the resulting experimental data in Table 3 is shown in Fig. 13.

The numerical values of K_{max} and Q_{max} for two kinds of stage (i.e., 1～2 row (or 3～4 row) and 5～6 row in Fig. 4) are first obtained by MC method. These values are shown in Figs. 14～15.

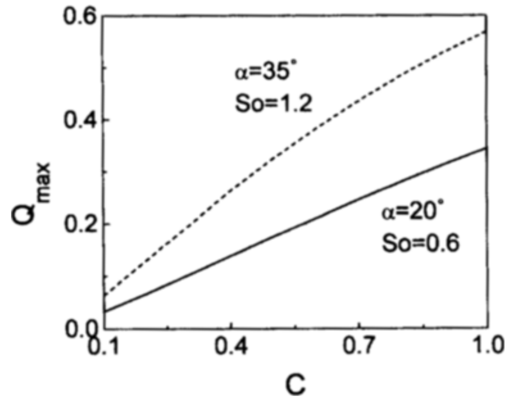

Fig. 15 Calculated curves for Q_{max} as a function of C in the case of 2-rows

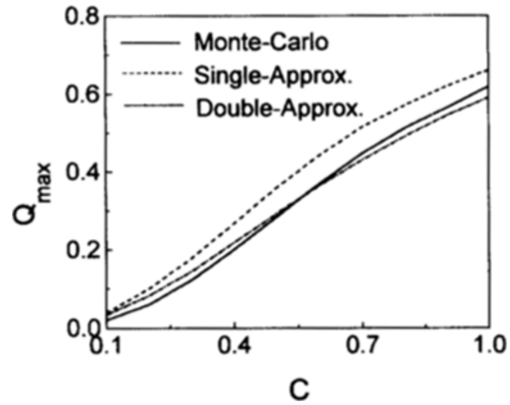

Fig. 17 Calculated curves for Q_{max} as a function of C in the case of 6-rows

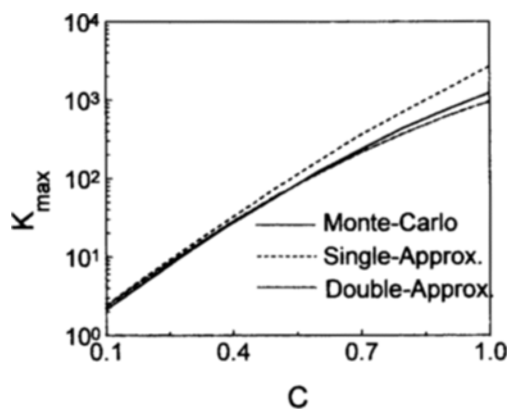

Fig. 16 Calculated curves for K_{max} as a function of C in the case of 6-rows

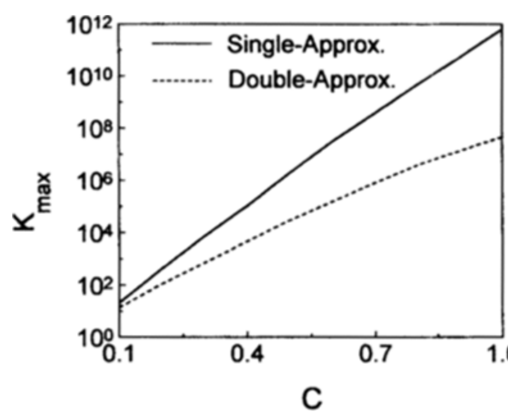

Fig. 18 Calculated curves for K_{max} as a function of C for a test example of multi-stage TMP

Then, the DA method can be available by employing these values for superposition.

The comparisons of the approximate methods (SA and DA) with the MC method for K_{max} and Q_{max} with the six-rows are shown in Figs. 16~17. In the previous study (Sekiya & Kitora, 1991), the 2D model for the three-row TMP was analyzed. In contrast to the three-rows, the new calculations considering blade thickness for the six-row TMP with $S_g=0.02$ and $S_h=3.0$ have been carried out in the present study by using the MC method.

A commercial TMP generally consists of three or four kinds of blade. In this study, the theoretical design of a TMP which has three kinds of blade with 24-rows is made, and the performances are predicted by using the SA and DA methods. The specification of the TMP is shown in Table 4, and the blade angle α and other dimensions of the blades are arbitrarily selected similar to a commercial TMP.

The predicted values of the SA method in Fig. 18 overestimate than do those of the DA method for the entire range of C. According to the catalog data (Osaka Vacuum, 1990), K_{max} is in the range of $10^6\sim10^7$ when the rotational speed is 50000 rpm (nitrogen, C=0.7). Thus, the prediction of the DA method is more reasonable than that of the SA method.

The value Q_{max} of the SA method in Fig. 19 also overestimates than does that of the DA

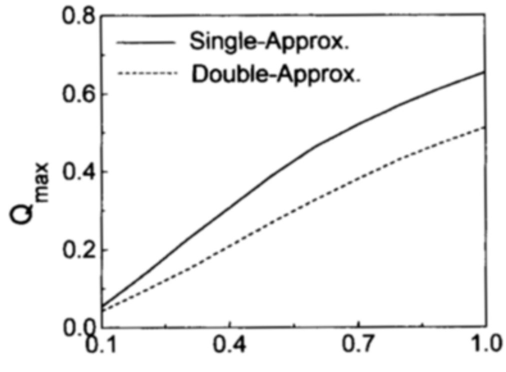

Fig. 19 Calculated curves for Q_{max} as a function of C for a test example of multi-stage TMP

method. When comparing the present calculated values with the measured catalog data of a TMP for the above compression ratio, both results of the SA and DA method lie above the catalog data.

Table 4. Test example of multi-stage TMP

Blade row number	α	S_o	b	S_h	S_g
1~4	36°	1.4	5 mm	5.0	0.04
5~14	23°	1.0	5 mm	4.0	0.05
15~24	18°	0.6	6.5 mm	2.3	0.07

4. Discussions and Conclusions

The performance in the free molecular flow range of a turbomolecular pump is studied numerically by using the integral method and the MC (Monte-Carlo) method. For a single row, it is clear that the integral method and the MC method give almost the same results within 0.5% of relative error (see Figs. 5~6). It is also found that the calculated results agree quantitatively with the previous known numerical and experimental results.

It is shown from our computations for a single row that K_{max} decreases rapidly with the blade height h, and that the 2D results are the asymptotic solutions of the 3D analysis (see Figs. 11 and 12). For a normal TMP, the values of S_h $(=h/b)$ are larger than 1.0 and $S_g(=\delta/h)$ is smaller than 0.1. Thus the effects of S_h and S_g on the pumping performance can be disregarded.

The comparison of the present results with the experimental data (see Fig. 13) for a multi-stage pump shows that the 2D results are more close to the experimental data than the 3D results at the blade velocity ratio C below 0.1. But, as the value of C increases, the 3D results agree well with the experimental data. In order to establish the free molecular flow in the passage of the blade rows, the backing pressure was kept in theorder of 10^{-4} mmHg. The compression ratio is the oretically in the order of 3×10^5 at $C=0.3$, but the experimental results are smaller than the theoretical one as seen in Fig. 13. Since the ultimate pressure is limited by the outgassing effect from the chamber and by the history of the pump system, K_{max} does not increase any more and reaches a constant value.

For a multi-stage pump, as shown in Fig. 16, the relative error of K_{max} between the MC method and the SA (single-approximation) method increases with C. Although the relative error of K_{max} seems to be very large, the discrepancy between the MC method and the SA method may be neglected, because the magnitude of the compression ratio lies normally within a range, typically $O(10^6)\sim O(10^8)$. The maximum relative error of Q_{max} in Fig. 17 is about 86% at $C=0.1$. But, the absolute values of Q_{max} are very small. Also, the relative error tends to be small as the value of C increases. Therefore, the results of the approximate method provide a reasonable approximation to evaluate the compression ratio and the pumping speed for the six-row TMP.

Also, the DA (double-approximation) method combining the double row solutions has been developed, and the results are shown as the dash-dot lines in Figs. 16~17. When the results of the SA method are compared with those of the MC method at $C=0.4$, the former method overestimates as much as 34% than the latter. But, the DA method gives more accurate results, whose relative error is about 10% compared to the MC method, than does the previous SA method.

Evidently, to predict correctly the performance of a TMP, the MC method must be applied to the entire set of blade rows. Since a normal TMP consists of several tens or more stages, however, the more computational efforts and high expenses are required to employ the MC method. If the approximate methods give reasonable results, these methods will be very useful. As discussed above, it is possible to predict the pumping performances reasonably by using the approximate methods.

References

Hablanian, M. H., 1990, *High-Vacuum Technology (A Practical Guide)*, Marcel Dekker, Inc., pp. 231~258.

Hucknall, D. J., 1991, *Vacuum Technology and Applications*, Butterworth Heinemann, pp. 85 ~95.

Kruger, C. H. and Shapiro, A. H., 1961, In *Rarefied Gas Dynamics* (Edited by L. Talbot), Academic Press, New York, pp. 117~140.

Osaka Vacuum, 1990, 1990.12.2000 (UD), Catalog.

Sawada, T., Suzuki, M. and Taniguchi, O., 1971, "The Axial Flow Molecular Pump," *Bull. JSME*, Vol. 14, No. 67, pp. 48~57.

Sawada, T. and Taniguchi, O., 1973, "The Axial Flow Molecular Pump," *Bull. JSME*, Vol. 16, No. 92, pp. 312~318.

Sekiya, S. and Kitora, Y., 1990, "Study of the Performance of Turbomolecular Pumps: 1st Report, The Performance of Finite-Height Blades," *Trans. JSME*, Vol. 525, pp. 178~185.

Sekiya, S. and Kitora, Y., 1991 "Study of the Performance of Turbomolecular Pumps: 2nd Report, The Analysis of the Performance in the Multiple Stages," *Trans. JSME*, Vol. 534, pp. 185 ~192.

Tu, J. Y. and Yang, N. H., 1987, "Theoretical Studies of the Modern Turbomolecular Pump," *Vacuum*, Vol. 37, No. 11-12, pp. 831~837.

Tu, J. Y. and Yang, N. H., 1988, "On the Calculation of the Overall Transmission Probability of a Variable Blade Length Multiple-Stage Turbomolecular Pump," *Vacuum*, Vol. 38, No. 1, pp. 13~14.

Tu, J. Y., Yang, N. H., Pang, S. J. and Zu, Y., 1988, "A Further Exploration of an Important Factor Affecting the Pumping Performance of Turbomolecular Pumps," *J. Vac. Sci. Technol.* A6, pp. 2535~2540.