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Analysis of High Vacuum System Based on the Applications of Vacuum Materials

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In this study, the outgassing effects of selected vacuum materials on the vacuum characteristics were simulated by the VacSim^{Multi} simulation tool. This investigation examined the feasibility of reliably simulating the outgassing characteristics of common vacuum chamber materials (aluminum, copper, stainless steel, nickel plated steel, Viton A). The optimum design factors for these vacuum systems were suggested based on the simulation results. The baking-out effects of the modeled systems and materials on the performance of the vacuum system were also analyzed. The simulation predicted that the overall outgassing effect was more significant in the turbomolecular pump system than in the diffusion pump system and that the utilization of a booster pump has a greater effect on the evacuation time than on the ultimate pressure.

Keywords: High vacuum system, Vacuum characteristics, Vacuum materials, Simulation

1. INTRODUCTION

The importance of vacuum techniques has continued to grow with the development of advanced technology. Even greater demands and more stringent conditions are expected to be imposed on vacuum techniques requiring high vacuum qualities. To achieve pressures in the ultra high vacuum (UHV) and especially the extremely high vacuum (XHV) ranges, it is essential to minimize the outgassing from the chamber materials [1,2]. In this work, we simulated the outgassing effects of selected vacuum materials on the vacuum characteristics of modeled vacuum systems. The feasibility of reliably simulating the outgassing characteristics of common vacuum chamber materials was examined in this investigation. Three different UHV systems based on the pumping combinations were modeled by the VacSim^{Multi} simulation tool [12,13]. The outgassing characteristics of stainless steel, anodized aluminum, polished copper, nickel plated steel, and Viton A in the proposed simulation models were examined. Each of the modeled vacuum systems was simulated separately for each of the selected materials with and without the outgassing effects.

The baking effects of the investigated systems and materials on the performance of the vacuum system were also analyzed. The acquired simulation results of the modeled systems and of the probed vacuum materials are plotted in the form of the dynamic pump-down curves.

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2. SIMULATIONS

2.1 Simulation model

Three different UHV systems were modeled in this investigation. The most commonly used vacuum systems in materials processing were selected as the modeling systems. Modeling was also performed on the commercial specifications of vacuum systems used in experimental applications. Three different UHV pumping combinations were employed in this modeling with fixed design factors for the chamber, exhaust pipelines, and valves. The simulation design factors of the modeled UHV systems were fixed; the same parameters were used except for the pumping combinations in each simulation. Three different combinations of pumping systems were employed in this modeling, viz. turbomolecular-rotary, diffusion-rotary, and diffusion-booster-rotary pumps. The proposed UHV systems have a straight pipelines with a length of 0.3 m and a diameter of 0.0254 m. The valves which were employed had internal aperture areas of 5×10^{-4} m^2 and 5×10^{-3} m^2 for rough and high vacuum pumping, respectively, and were normally closed in the absence of a signal. The chamber volume of the modeled UHV systems was fixed at 15 liters. The commercial specifications of the employed pump models are summarized in Tables 1 and 2. The pump models were selected after repetitive simulations to obtain the optimum system modeling. The simulation schematic of one of the modeled UHV systems without outgassing effects is illustrated in Fig. 1.

2.2 Simulation without outgassing

The simulation results of the three different modeled UHV systems without outgassing effects are shown in Fig. 2. The pump-down curves showed that all three of the modeled systems reached the UHV pressure of 10^{-7} Pa. As expected, the evacuation time of the turbomolecular pump (TMP) system required to achieve the UHV pressure was considerably shorter than that of the diffusion pump (DP) systems. The evacuation time for the TMP system to reach 10^{-7} Pa. was less than 4 minutes. After an evacuation time of more than 43 minutes, the DP system without a booster pump attained the UHV pressure. The simulation of the booster pump application also showed better characteristics in terms of both the ultimate pressure and evacuation time of the DP system. Based on the comparison of the commercial specifications with the obtained pump-down characteristics of the pumping systems, it was concluded that the simulation of the modeled systems provides useful results that could be applied to vacuum system design in practice.

2.3 Simulation with outgassing

The simulation schematic with outgassing effects of the DP system is illustrated in Fig. 3. All of the models with outgassing were also simulated to compare the outgassing behaviors of the systems. The outgassing characteristics obtained *in situ* are plotted in the form of the pump-down curves in Fig. 4. The dynamic pump-down curves with and without the outgassing effects are indicated by the dotted and solid lines, respectively. Stainless steel was selected as the investigated material due to its common applications in vacuum systems. The simulation results indicated that the overall outgassing effects are more significant in the TMP system than in the DP systems. The ultimate stabilized pressure of the TMP system with outgassing effects was 10^{-4} Pa. (Fig. 4(a)), which is approximately three orders of magnitude higher than that of the TMP model without outgassing effects (10^{-7} Pa.). No outgassing effect was observed within the initial evacuation time of 40 seconds. In addition, the pumping pressure was rapidly stabilized within one minute after the outgassing effects were noticed. DP systems with outgassing effects, the ultimate stabilized pressure was almost 10^{-5} Pa. (Fig. 4(b)). The employment of a booster pump had a greater effect on the evacuation time than on the ultimate pressure. The initial outgassing effects of both DP systems were reflected in their evacuation times of about 510 seconds without a booster pump and 73 seconds with a booster pump. The simulation results of the outgassing effects confirmed the feasibility of utilizing simulation modeling in design applications.

2.4 Simulation of outgassing characteristics of vacuum materials

The outgassing of the chamber materials places a limitation on attaining very low pressures in UHV systems [3-5,11]. The simulation results of the outgassing characteristics of the selected vacuum materials are illustrated in Fig. 5. The VacSim[Multi] simulator supports the five different materials which are com-

Table 1. Commercial specifications of employed turbomolecular pump (Edwards Ltd.).

model name	EXT70-DN63CF
compression ratio	$N_2 > 1\times10^8$ He 6000 H_2 500
nominal rotational speed	90,000 rpm
standby rotational speed	63,000 rpm
cooling method	free convection or forced air or water
quiescent electrical power	10 W
pumping speed	N_2 65 L/s He 60 L/s H_2 50 L/s
ultimate pressure	$< 3.8\times10^{-10}$ torr
weight	3.4 kg

Table 2. Commercial specifications of employed rotary mechanical pump (Edwards Ltd.).

model name	E2M275
pumping speed (pneurop 6602, 50 Hz)	255 m^3/h
number of stages	2
ultimate vacuum without gas ballast	7.7×10^{-4} torr
weight	225 kg
motor power	7.5 kW (10 hp)

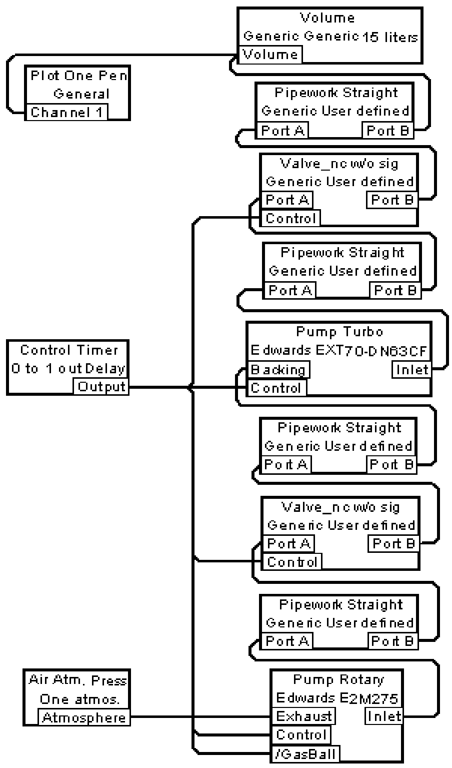

Fig. 1. Simulation schematic of TMP-MP system without outgassing.

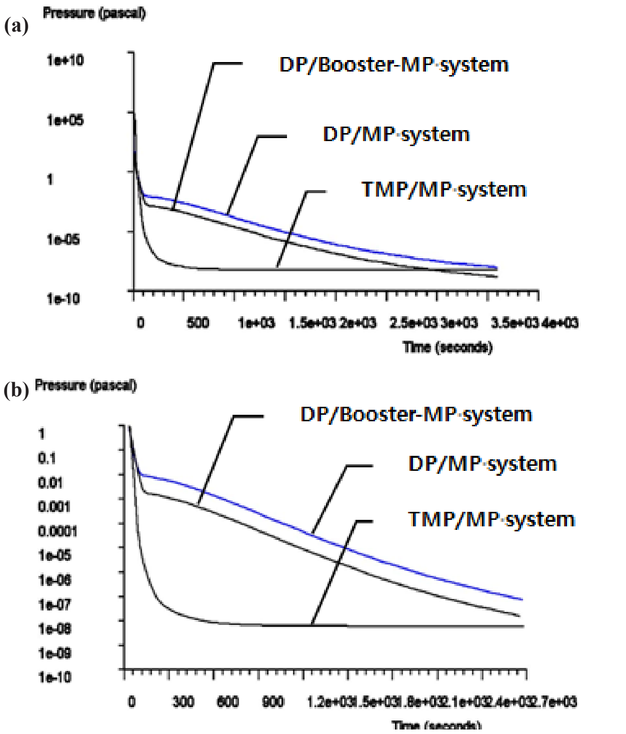

Fig. 2. (a) Simulation results of modeled systems without outgassing (b) and enlargement of curve (a).

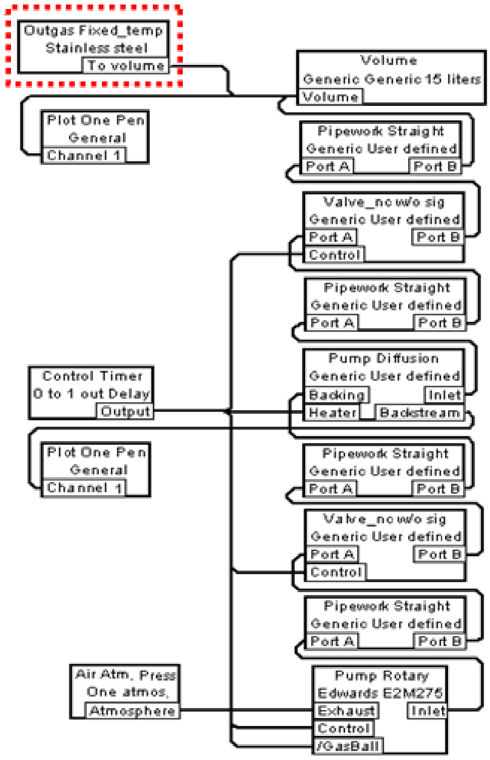

Fig. 3. Simulation schematic of DP-MP system with outgassing.

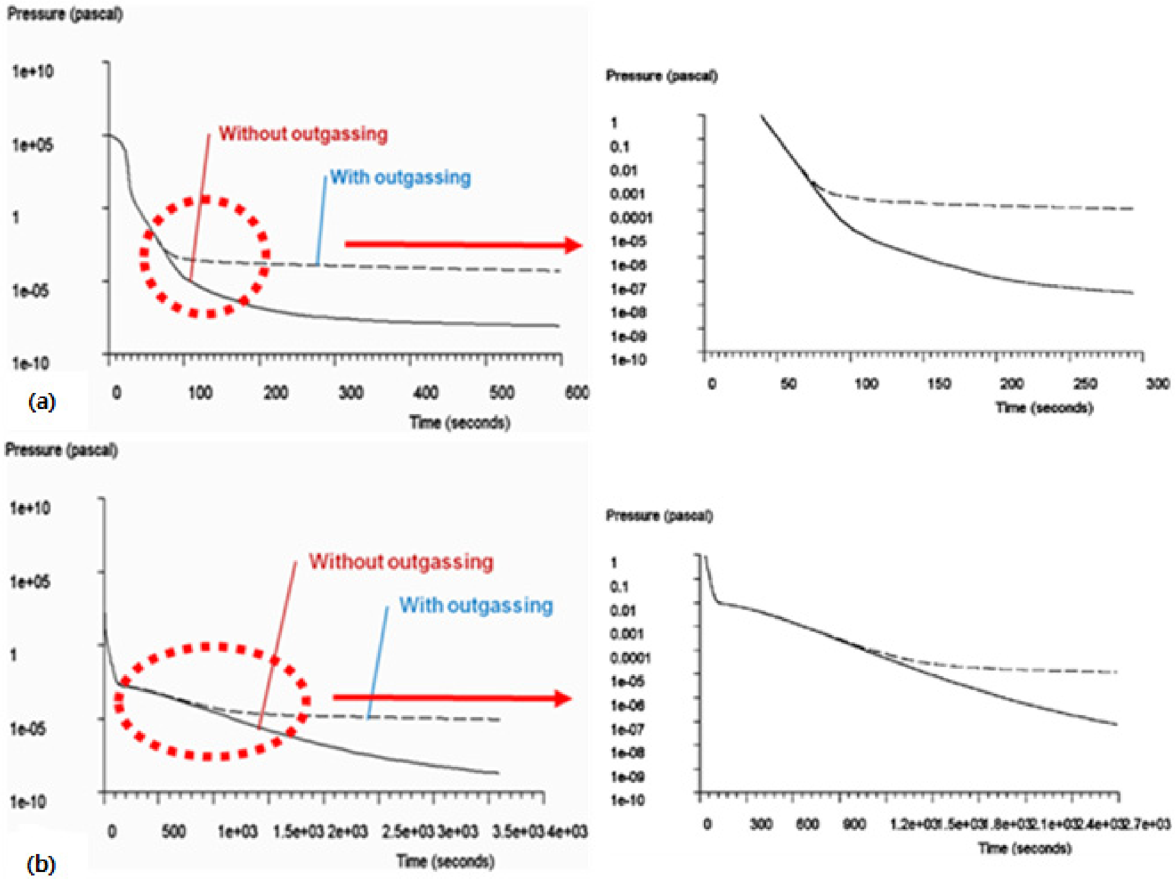

Fig. 4. Comparison of simulation results with and without outgassing effects of modeled systems [(a)TMP-MP system and (b) DP-MP system without booster pump].

Table 3. *In-situ* simulation data of vacuum materials plotted as pump-down curves in Fig. 5.

(a) TMP-MP system

materials / evacuation time	Al-andoized	Cu-polished	Stainless steel	Steel-Ni plated	Viton A
111 sec	4.25×10^{-4} Pa	1.25×10^{-5} Pa	2.74×10^{-4} Pa	5.00×10^{-5} Pa	1.80×10^{-3} Pa
300 sec	1.69×10^{-4} Pa	2.16×10^{-6} Pa	1.10×10^{-4} Pa	1.72×10^{-5} Pa	7.68×10^{-4} Pa
483 sec	1.04×10^{-4} Pa	1.29×10^{-6} Pa	6.47×10^{-5} Pa	1.01×10^{-5} Pa	4.25×10^{-4} Pa

(b) DP-MP system without booster pump

materials / evacuation time	Al-andoized	Cu-polished	Stainless steel	Steel-Ni plated	Viton A
1,493 sec	3.98×10^{-5} Pa	9.12×10^{-6} Pa	2.62×10^{-5} Pa	1.21×10^{-5} Pa	1.30×10^{-3} Pa
2,500 sec	2.00×10^{-5} Pa	3.74×10^{-7} Pa	1.25×10^{-5} Pa	1.94×10^{-6} Pa	8.20×10^{-5} Pa
3,129 sec	1.62×10^{-5} Pa	2.22×10^{-7} Pa	1.01×10^{-5} Pa	1.55×10^{-6} Pa	6.47×10^{-5} Pa

monly used as vacuum materials in the outgassing model. In the TMP system, an ultimate stabilized pressure in the UHV range (10^{-5} ~ 10^{-6} Pa) was observed only in the case of polished copper and nickel plated steel among the studied materials (Fig. 5(a)).

Polished copper showed the lowest pressure of 1.29×10^{-6} Pa. during the simulation. An appreciable amount of outgassing, which was larger than expected, was noticed in the case of anodized aluminum. The lowest pressure obtained in the case of aluminum (1.04×10^{-4} Pa.) was approximately two orders of magnitude higher than that obtained in the case of polished copper. Almost no variation in pumping behavior due to outgassing effects was observed within the initial evacuation time of 80 seconds in the case of the probed materials, except for Viton A. However, in the DP systems, all of the investigated materials except Viton A reached the UHV range during the period of simulation (Fig. 5(b)). On average, in the case of the studied materials, pressure was obtained that was one order of magnitude lower compared to the TMP system (Table 3). The substantial differences of the evacuation time required to reach pressures in the low UHV range for both systems came from the different pumping mechanisms. The pump-down curves obtained for this model are fairly consistent with the previously obtained simulation characteristics.

2.5 Simulation of baking-out effects on vacuum characteristics

The baking out of the chamber at high temperature under vacuum is regularly utilized to reduce outgassing in system operations. In the case of most vacuum materials, it is probable that the higher the bake-out temperature the lower the subsequent outgassing rate [6-8]. The baking out effects of the studied materials on the outgassing were also simulated in the proposed models. The simulation curves of the TMP system are illustrated in Fig. 6. The bake-out temperature was limited to 160℃. It has been reported that, above this temperature, no significant reduction in outgassing is noticed in the case of stainless steel [9,10]. In the baked-out TMP system, a pressure in the UHV range (1×10^{-5} Pa.) was reached with anodized aluminum, which was not achieved without baking out. The evacuation time of Ni plated steel required to reach the UHV region was considerably decreased by baking out (483 seconds→236 seconds : Fig. 5(b)). However, in the high vacuum region, almost no reduction in the evacuation time was obtained by baking out. Due to the instant gas release behavior of these materials, anodized aluminum and stainless steel even showed deteriorated characteristics in this range. A low pressure in the UHV range was obtained for the DP systems by baking out with all of the investigated materials except Viton A.

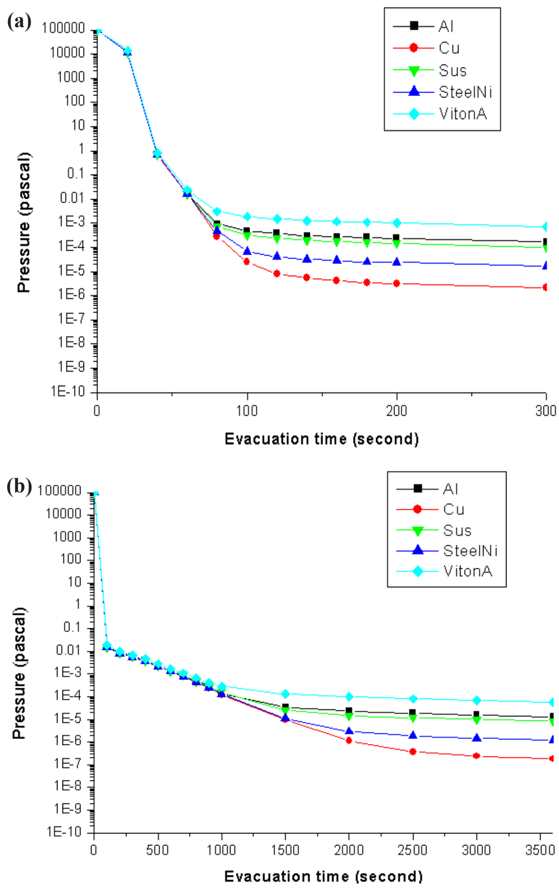

Fig. 5. Outgassing characteristics of vacuum materials ((a) TMP-MP system and (b) DP-MP system without booster pump).

3. RESULTS AND DISCUSSION

To study the reliability and feasibility of using simulation, three different UHV systems were modeled. Also, in order to confirm the consistency of the simulation results, each of the three modeled systems was simulated separately for each of the studied materials without and with outgassing effects. Only the optimum simulation results, which were obtained after numerous repetitive simulations, were illustrated in the figures and tables. The obtained simulation results are plotted in the form of *in situ* dynamic pump-down curves for each model. The simulation predicted that the outgassing effect would be more significant in

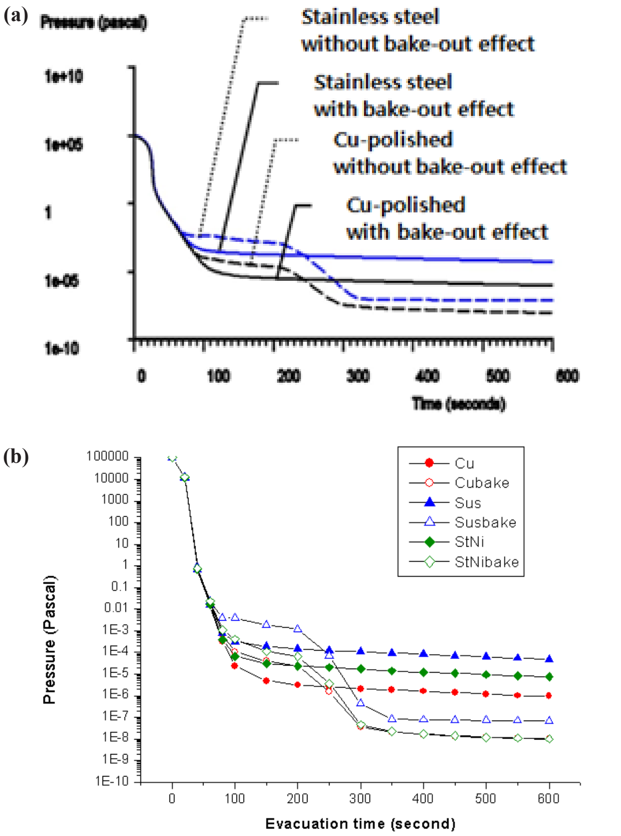

Fig. 6. Comparison of simulation results of vacuum materials with and without baking effect in TMP-MP system ((a) simulation curve and (b) plot of simulation data).

the TMP system than in the DP system. An ultimate pressure in the UHV range could not be reached in the TMP system without the prior baking out treatment of the materials employed. The simulation also indicated that the utilization of a booster pump would have a greater effect on the evacuation time than on the ultimate pressure. A considerable decrease of the evacuation time was observed in the case of the booster DP system with outgassing. An ultimate pressure as low as 10^{-5} Pa. was achieved in the outgassing model of both DP systems. The simulation also suggested that polished copper would be a better candidate as a vacuum chamber material than the other materials to minimize the outgassing. This work indicated that the polishing treatment of copper for vacuum applications could be a useful topic for further research. The appreciable outgassing and slight baking out effect of anodized aluminum on the ultimate pressure showed that the simulation results were in agreement with the previous works [10]. To simulate the overall performance of vacuum systems, it is necessary to consider the tolerance of all of the design factors. However, the present preliminary study enabled us to evaluate the feasibility of using simulation for studying vacuum systems in a reliable manner.

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