HEFAT2007
5th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
Sun City, South Africa
Paper number: RJ1

APPLICATION OF CFD TO THE OPTIMAL DESIGN OF AN ENERGY-SAVING PNEUMATIC VACUUM PAD

Jyh-Chyang Renn[1] and Dian-Yu Jan[2]
1. Professor
2. Graduate student
Department of Mechanical Engineering
National Yunlin University of Science and Technology
No. 123, University Road Section 3, Douliu, 640 Yunlin, Taiwan, R.O.C.
Tel: +886-5-5342601 ext. 4112
Fax: +886-5-5312062
E-mail: rennjc@yuntech.edu.tw

ABSTRACT

This paper is concerned with the development of a new energy-saving vacuum pad using CFD-technique. Nowadays, application of pneumatic vacuum pads may be found in many different real industries, especially in the field of automatic conveyer system, automatic assembly line, semiconductor industry as well as silicon wafer factory, etc. Traditional vacuum pads generally utilize nozzles to create the effect of vacuum. In this paper, however, a new idea to generate the effect of vacuum is proposed by designing a structure similar to that of an aerostatic bearing. In details, the air is guided to flow through an optimally designed restrictor inside the vacuum pad and flow out through the outlet between the vacuum pad and the sucked work-piece. Therefore, according to Bernoulli’s equation, the air pressure near the center line of the vacuum pad decreases because of the increased airflow velocity. Consequently, the effect of vacuum is generated.

To achieve two preset requirements, that is, large suction force output and low air consumption, the commercial CFD-RC software is utilized to simulate the air flow field and design the optimal geometry inside the vacuum pad. Experimental results further prove that the new vacuum pad with two preset features is successfully developed and implemented in this study.

Keywords: CFD, Vacuum pad, Pneumatics, Vacuum, Automation

INTRODUCTION

Nowadays, vacuum technology is widely applied in many different industries, especially in the field of vacuum packing machinery, clean room technology, semiconductor manufacturing process and high-precision measurement devices like the mass spectrometer, SEM, TEM, etc. In these applications, vacuum pump is generally utilized to create the effect of vacuum [1-3]. In this paper, however, a new energy-saving pneumatic vacuum pad is proposed and developed by using the CFD-technique. CFD is the abbreviation of Computational Fluid Dynamics, which is a powerful tool to provide an effective insight into the flow field numerically [4]. Instead of vacuum pump, the vacuum generating principle of the developed vacuum pad is based on the Bernoulli’s equation. Typical application fields of pneumatic vacuum pad include the automatic conveyer system, automatic assembly line and semiconductor or wafer factory, etc. Traditional vacuum pads generally utilize nozzles to produce the effect of vacuum [5]. In this paper, however, a new idea to generate the effect of vacuum is proposed by designing a structure similar to that of an aerostatic bearing [4]. In details, the air is guided to flow through a well-designed restrictor inside the vacuum pad and flow out through the outlet between the vacuum pad and the sucked work-piece. Therefore, according to Bernoulli’s equation, the air pressure near the center line of the vacuum pad decreases because of the increased airflow velocity. Consequently, the effect of vacuum is generated.

To fulfill two preset requirements, that is, large suction-force output and low air consumption, the commercial CFD-RC software is utilized to simulate the air flow field and design the most suitable geometrical dimension inside the vacuum pad. After some tedious trial-and-errors, a new energy-saving pneumatic vacuum pad is developed and a corresponding prototype is also produced. To test the static performance of the new vacuum pad, a test bench is constructed. Experimental results prove that the developed vacuum pad has fulfilled two preset requirements, that is, the suction force output is large, and meanwhile the air consumption is kept quite low. In the following, the design of the vacuum pad using CFD-simulation will be illustrated.

NOMENCLATURE

A_w	[m2]	area of pressure action
F_s	[N]	suction force output
P_v	[bar]	average gauge pressure acting on the work-piece inside the vacuum pad

DESIGN OF THE VACUUM PAD USING CFD-SIMULATION

Figure 1 shows the scheme of the developed vacuum pad. The air is guided to flow into the vacuum pad at an eccentric inlet A. After passing through the restrictor C, the air flows out of the vacuum pad at two opposite outlets denoted by B. The opening area of the restrictor is adjusted by the screw and nut. There are two most important design parameters regarding the geometrical dimension inside the vacuum pad. One is the angle of the cone-shaped space and the other is the shape of the restrictor. Firstly, three different angles (30^o, 45^o and 60^o) for the cone-shaped space inside the vacuum pad are chosen for CFD-simulations. The initial and boundary conditions for the CFD-simulation are summarized as follows.

(1) The input velocity of the airflow is set to be 12 m/s for the input pressure of 2 bar. For different input pressure, however, different setting of input velocity is necessary.
(2) The airflow is compressible.
(3) The air density is assumed to be $1.189 Kg/m^3$ at room temperature.
(4) The dynamic viscosity of the air is set to be $1.789\times10^{-5} N\cdot s/m^2$ at room temperature.
(5) The room temperature is set to be $20^\circ C$ or $293^\circ K$.
(6) The reference acoustic velocity of air is assumed to be 340 m/s.
(7) The boundaries of the flow field are considered as the wall, which means that no airflow across the boundaries is allowed.
(8) No heat transfer and chemical reaction exists in the flow field.
(9) The outlet conditions are set to be atmospheric pressure and room temperature.

Figures 2-4 show the corresponding simulation results of pressure distribution for three different cone-angles respectively. It is observed that Fig. 4 possesses the lowest average pressure near the center line of the vacuum pad. Among three different angles, therefore, it is clear that the most suitable cone-shape space angle is 60^o. On the other hand, three different shapes for the restrictor are also chosen for CFD-simulations as shown in Fig. 5. After comparing the CFD-simulation results shown in Figures 6-8, it is observed that the lowest average pressure near the center line of the vacuum pad occurs in Fig. 8. Thus, the cone-shaped restrictor of Fig. 5(c) is chosen for the design. Finally, the CFD-simulation result of pressure distribution for the whole developed vacuum pad is shown in Fig. 9. The picture of the developed prototype is shown in Fig. 10.

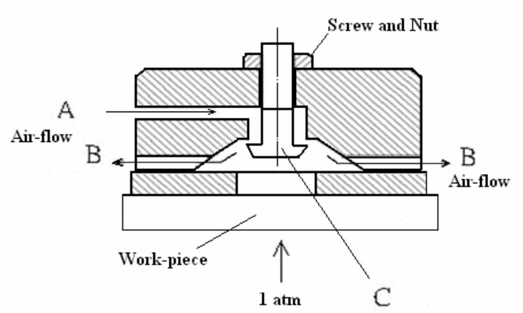


Figure 1 Scheme of the developed vacuum pad

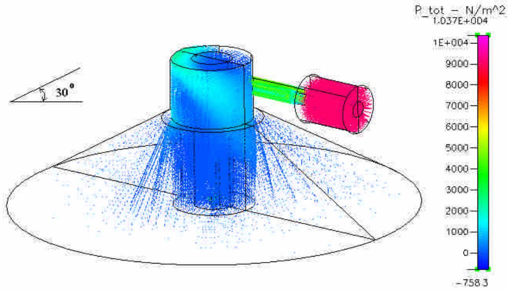


Figure 2 Simulation result of the pressure distribution (cone-shaped space angle = 30^o)

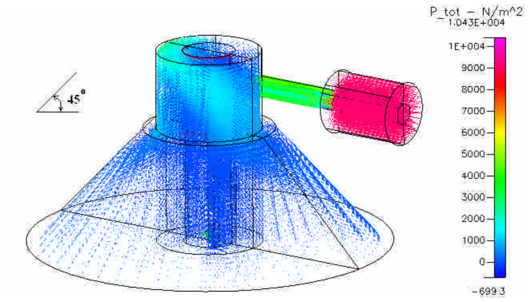


Figure 3 Simulation result of the pressure distribution (cone-shaped space angle = 45°)

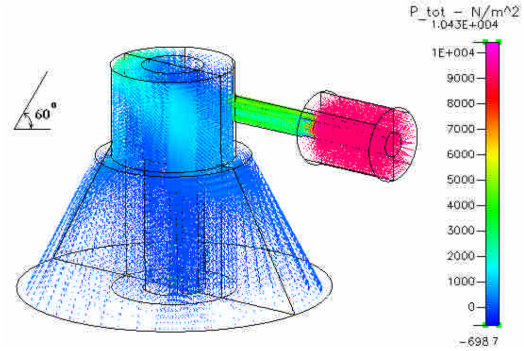
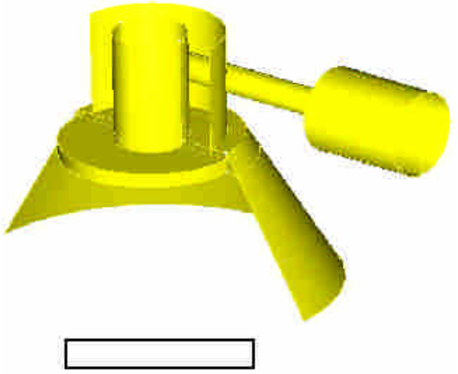
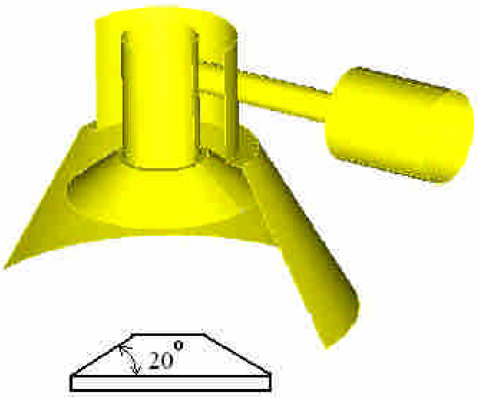


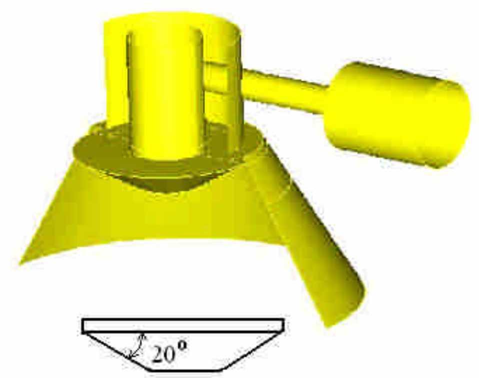
Figure 4 Simulation result of the pressure distribution (cone-shaped space angle = 60°)



(a)



(b)



(c)

Figure 5 Three different shapes for the restrictor

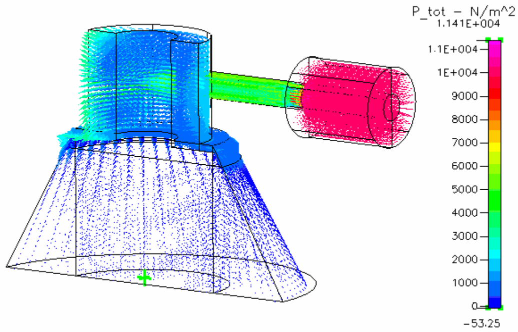


Figure 6 Simulation result of the pressure distribution for shape a

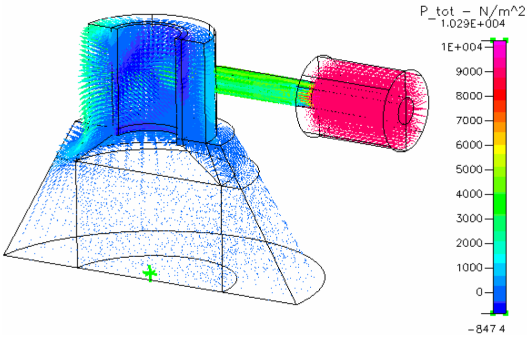


Figure 7 Simulation result of the pressure distribution for shape b

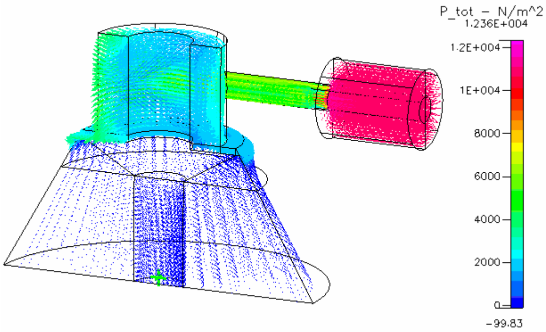


Figure 8 Simulation result of the pressure distribution for shape c

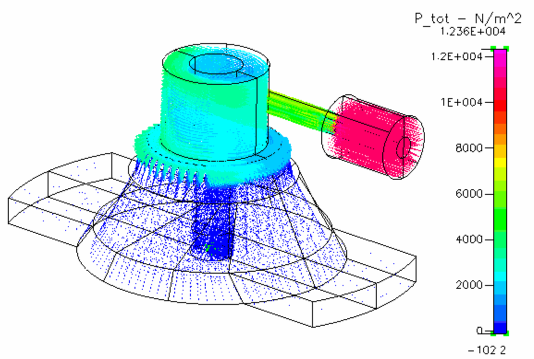


Figure 9 Simulation result of pressure distribution inside the vacuum pad

Figure 10 Prototype of the developed vacuum pad

DESIGN OF TEST DEVICE

To test the static performances of the developed pneumatic vacuum pad, a test device is constructed to measure the vacuum pressure, suction-force output and the consumed air flow-rate. The circuit layout of the entire test device is shown in Fig. 11. The air supply pressure is fixed at 6 bar and a pressure-reducing valve is utilized to adjust the input pressure to the vacuum pad. To measure the consumed air flow-rate, a mass flow-rate meter (Hasting, HFM-200) is employed. Figure 12 and Fig. 13 show the schemes for measuring the vacuum pressure and suction force output, respectively. In details, a vacuum pressure sensor (SMC, ZSE30/ISE30) is inserted into the work-piece, so that the vacuum pressure at the center of the vacuum pad can be measured. In addition, to measure the suction force output of the vacuum pad, a digital push/pull force gauge (IMADA, Z2 series) is connected to the work-piece. If the pulling force is increased until the work-piece separates from the vacuum pad, the suction force output of the vacuum pad can be observed.

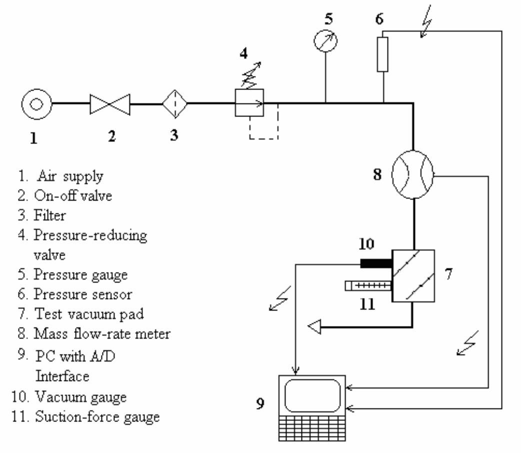


Figure 11 Layout of the test device for pneumatic vacuum pad

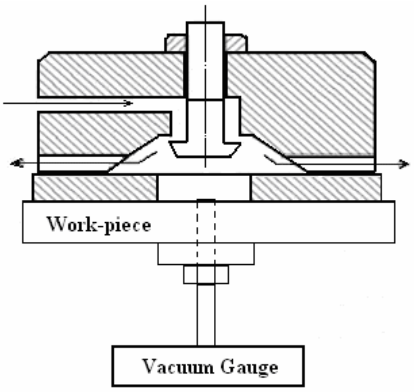


Figure 12 Scheme of test device for measuring vacuum pressure

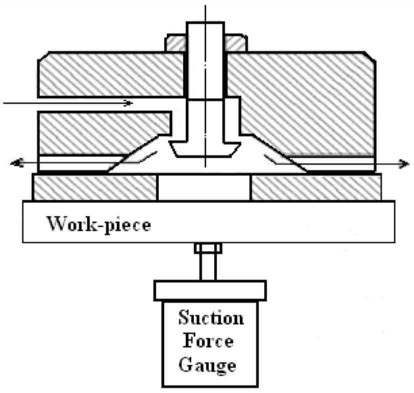
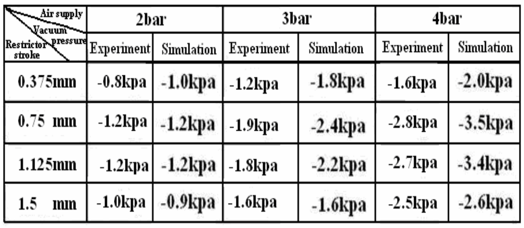


Figure 13 Scheme of test device for measuring suction force output

SIMULATION, EXPERIMENTAL RESULTS AND DISCUSSION

In this section, both simulation and experimental results concerning the developed vacuum pad are summarized and discussed. Firstly, Table 1 shows different values of the average vacuum pressure derived by simulation and experiment respectively. It is also noticeable that the vacuum pressure is represented by the gauge pressure, which is actually a negative value. The restrictor stroke is adjusted from 0.375 mm to 1.5 mm by turning the screw and the inlet pressure to the vacuum pad is varied from 2 bar to 4 bar by adjusting the pressure reducing valve. The initial input air velocity for the CFD-simulation is set to be 17 m/s for the input pressure of 3 bar, and 22 m/s for the input pressure of 4 bar. After calculations, the maximal deviation between simulation and experimental result is found to be 26%. If the restrictor stroke is gradually increased from 0.375 mm to 1.125 mm, meaning that the opening area of the restrictor increases, then the absolute value of gauge pressure also increases because of the high velocity of jet flow through the restrictor. However, if the restrictor stroke is too large, for example 1.5 mm, meaning that the metering orifice is fully open and the effect of restriction no longer exists, the absolute value of gauge pressure will decrease. Moreover, larger opening area also means higher air consumption which is not acceptable in this study. Therefore, the best recommended restrictor stroke for the developed vacuum is in the range from 0.375 mm to 1.125 mm.

Table 1 Simulation and experimental results concerning the vacuum pressure

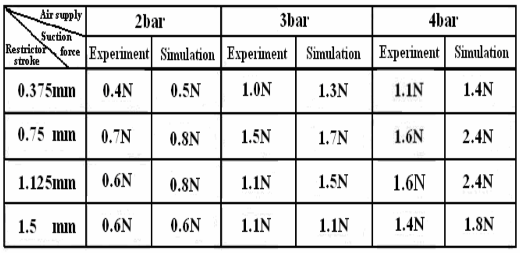


Air supply Vacuum pressure Restrictor stroke	2bar		3bar		4bar	
	Experiment	Simulation	Experiment	Simulation	Experiment	Simulation
0.375mm	-0.8kpa	-1.0kpa	-1.2kpa	-1.8kpa	-1.6kpa	-2.0kpa
0.75 mm	-1.2kpa	-1.2kpa	-1.9kpa	-2.4kpa	-2.8kpa	-3.5kpa
1.125mm	-1.2kpa	-1.2kpa	-1.8kpa	-2.2kpa	-2.7kpa	-3.4kpa
1.5 mm	-1.0kpa	-0.9kpa	-1.6kpa	-1.6kpa	-2.5kpa	-2.6kpa

On the other hand, Table 2 shows the calculated and measured results with respect to the suction force output of the developed vacuum pad. Similarly, the maximal error is about 30%. The formula for calculating the suction force output is

$$F_s = -P_v \cdot A_w , \qquad (1)$$

Table 2 Simulation and experimental results concerning the suction force

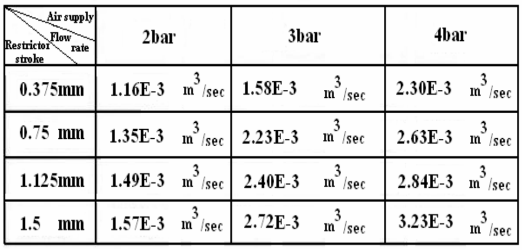


Air supply Suction force Restrictor stroke	2bar		3bar		4bar	
	Experiment	Simulation	Experiment	Simulation	Experiment	Simulation
0.375mm	0.4N	0.5N	1.0N	1.3N	1.1N	1.4N
0.75 mm	0.7N	0.8N	1.5N	1.7N	1.6N	2.4N
1.125mm	0.6N	0.8N	1.1N	1.5N	1.6N	2.4N
1.5 mm	0.6N	0.6N	1.1N	1.1N	1.4N	1.8N

It is worth mentioning that the deviations between experimental and simulation results are inevitable. One most important reason is that all the initial and boundary conditions for CFD simulation are based on ideal assumptions. In the real flow field, however, many time-varying parameters as well as the complicated turbulent flow may exist, which are quite difficult to be modeled and numerically determined.

Table 3 shows different measured flow-rate data used to evaluate the air consumption. Generally speaking, the air consumption corresponding to spool stroke in the range from 0.375 mm to 1.125 mm is kept quite low. It can therefore be concluded that the developed vacuum pad utilizes very few amount of compressed air to generate adequate suction force output and provides a very quiet operating environment that fulfills the preset requirement of energy-saving. Figure 14 shows an experimental example, where the generated suction force makes successfully a CD-disk adhere to the developed vacuum pad. The supply pressure is adjusted to be 2 bar and the weight of the CD-disk is approximately 16 g.

Table 3 Measured flow-rate data used to evaluate the air consumption



Air supply Flow rate Restrictor stroke	2bar	3bar	4bar
0.375mm	1.16E-3 m^3/sec	1.58E-3 m^3/sec	2.30E-3 m^3/sec
0.75 mm	1.35E-3 m^3/sec	2.23E-3 m^3/sec	2.63E-3 m^3/sec
1.125mm	1.49E-3 m^3/sec	2.40E-3 m^3/sec	2.84E-3 m^3/sec
1.5 mm	1.57E-3 m^3/sec	2.72E-3 m^3/sec	3.23E-3 m^3/sec

Figure 14 An experimental example showing the developed vacuum pad with a sucked CD-disk

CONCLUSION

In this paper, a new energy-saving vacuum pad was successfully developed. After experimental tests, it is proved that the vacuum pad can be integrated into the automated manufacturing system and serves as the gripping component for conveyer system, etc. In addition, four conclusions may be drawn from this research.

(1) The most important feature of the developed vacuum pad is the introduction of a metering restrictor, which can be used to meter the airflow and control the air consumption such that the energy-saving requirement can be fulfilled.

(2) The CFD-technique is utilized to determine the most suitable geometrical dimension of the vacuum pad such that significant vacuum effect can be achieved.

(3) The recommended restrictor stroke is in the range from 0.375 mm to 1.125 mm. Larger restrictor stroke does not mean larger suction force output. On the contrary, larger restrictor stroke may cause higher air consumption.

(4) Generally speaking, higher air supply pressure will give rise to larger suction force output. However, it also contributes to higher air consumption. Therefore, the optimal adjustment of supply pressure as well as restrictor stroke depends chiefly on the demand of real application.

ACKNOWLEDGEMENT

The financial support of the DELTA ELECTRONICS, INC. Taiwan is greatly appreciated.

REFERENCES

1. N. N., 2003, Adjustable Vacuum Valve, Pump of the world, Volume 2003, Issue 446, Elsevier Science.
2. Holbrook, A. E. K., 1997, “Design of rotary vacuum pumps for an automated manufacturing system,” IEE Colloquium on Successful Cases of Integrated Product Design with Manufacturing Technology (Digest No: 1997/168), Pages: 6/1 - 6/4.
3. Shen, S., Kishiyama, K., Parker, J.M. Wilson, N.G. and Schrage, D., 1997, “APT/LEDA RFQ vacuum pumping system”, Proceedings of the Particle Accelerator Conference, Volume 3 , pp. 3625 – 3627.
4. Renn, J. C. and Hsiao, C. H., 2004, “Experimental and CFD study on the mass flow-rate characteristic of gas through orifice-type restrictor in aerostatic bearings,” Tribology International, Vol. 37, pp. 309-315.
5. N. N., 2000, SMC-Best Pneumatics, Vol. C003, Catalogue of SMC Corporation.