Effect of Suction Nozzle Modification on the Performance and Aero-acoustic Noise of a Vacuum Cleaner

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The suction nozzle of a vacuum cleaner was modified to enhance the power performance and to reduce the airflow-induced acoustic noise. The suction power efficiencies of the vacuum cleaner were measured for various nozzles: (1) original nozzle, (2) original nozzle with modified trench height, (3) original nozzle with modified connecting chamber, and (4) a combination of (2) and (3). In addition, the suction pressure and sound pressure level around the suction nozzle were measured to validate the reduction of acoustic noise. The power efficiency and mean suction pressure increased when the trench height of the suction nozzle was increased. This was attributed to the suppression of the flow separation in the suction channel. Modification of the connecting chamber in the original nozzle, which had an abrupt contraction from a rectangular chamber into a circular pipe, into a smooth converging contraction substantially improved the suction flow into the connecting pipe. When both modifications were applied simultaneously, the resulting suction nozzle was more effective from the viewpoints of aerodynamic power increase and sound pressure level reduction.

Key Words: Vacuum Cleaner, Suction Nozzle, Aerodynamic Power, Suction Pressure, Sound Pressure Level

Nomenclature

A : Cross-sectional area
AP : Aerodynamic power
AP_{MM} : Maximum air power of suction nozzle
AP_{MO} : Maximum air power without suction nozzle
CR : Contraction ratio
dB : Decibel
h_d : Dynamic pressure in absolute vacuum pressure
h_s : Suction pressure in absolute vacuum pressure
NL : Noise level
P : Surface pressure
P_o : Ambient atmospheric pressure
P_s : Suction pressure
Q : Flow rate
SPL : Sound pressure level
TNL : Total noise level

Δt : Trench height variation
η : Suction efficiency

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1. Introduction

Vacuum cleaners remove debris, fibers, dirt and dust particles from surfaces by means of suction power caused by subatmospheric pressure. They usually consist of several components including a suction nozzle, hoses, electric motor, filters, and accessories. Users of vacuum cleaners desire two opposing characteristics : low noise and high performance. Vacuum cleaner performance is generally determined by the maximum air power and the degree of vacuum pressure.

In general, motors for vacuum cleaners must be of large capacity to give sufficient suction power. For this reason, induction motors are widely used in vacuum cleaners. However, simply increasing the capacity of the motor in a vacuum cleaner to enhance suction power can lead to problems such as increased power consumption and noise emission.

Most studies aimed at improving vacuum cleaner performance have concentrated on improving the efficiency of the driving motor. Bentouati et al. (1999) investigated the design and performance of 1-phase and 3-phase permanent magnet brushless dc motors. In comparison with the universal motor, the 3-phase brushless motor exhibited a 25-35% improvement in power efficiency and a noise level about 8 dB lower. Tuncay et al. (2001) used a simulation package to guide the design of new-generation universal motors for vacuum cleaners with lower manufacturing costs and higher power/weight ratio. They evaluated the validity of the resulting methodology through an experimental performance test. Suzuki et al. (1999) developed a high-efficiency inverter motor with megasonic transducer units and tested their motor design in real vacuum cleaners.

The development of a more effective motor is not the only way to improve vacuum cleaner performance. Improving the design of the hose and nozzle can also enhance performance. For example, the suction power and dust collection capability of a vacuum cleaner increase considerably when the suction nozzle at the end of the connecting tube is removed to pick up heavier dusts. If the suction nozzle is attached again to the connecting tube of a vacuum cleaner, the performance of the vacuum cleaner decreases and aero-acoustic noise increases. To resolve this problem, it is necessary to improve the design of the suction nozzle from a fluid mechanical viewpoint by modifying the airflow path or inlet configuration of the nozzle.

Several attempts have been made to reduce vacuum cleaner noise by modifying components such as the fan and tubing system. Brungart and Lauchle (2001) investigated the reduction of annoying sound radiated by handheld vacuum cleaners by varying the vacuum working fan blade. To probe the role of the connecting tube in noise production, Petrie and Huntley (1980) investigated the acoustic noise of a steady airflow in an internally corrugated duct. Sarbu and Kraft (1996) proposed that vacuum cleaner noise consists of three main components : airborne, structural and mechanical noises. Of these components, airborne acoustic noise caused by flow friction and velocity fluctuations is the most disturbing to the human ear.

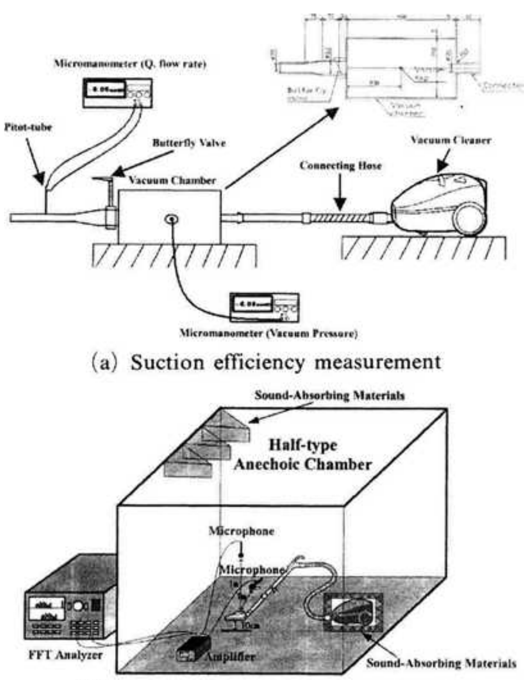
In spite of the importance of airborne noise, to our knowledge only a few experimental studies have been carried out to optimize the configuration of the suction nozzle through systematic study of the intake flow characteristics. In the present study, the internal configuration of a suction nozzle of a commercial vacuum cleaner was modified to experimentally investigate the effect of nozzle configuration on the suction power, suction pressure and aero-acoustic noise of the vacuum cleaner. The experiments were carried out systematically, following the standard test method for vacuum cleaners. The main objective of this study was to optimize the suction nozzle configuration so as to achieve enhanced suction efficiency and reduced airflow-induced noise.

2. Experimental Apparatus and Methods

The aerodynamic power and suction efficiency of the vacuum cleaner were measured using a vacuum chamber of dimensions 0.46 m wide × 0.46 m long × 0.25 m high. The chamber was designed according to the KS (Korean Standards) and JIS (Japanese Industrial Standards) standard test methods and regulations for vacuum cleaners. A schematic diagram of the suction efficiency measurement system is shown in Fig. 1 (a). The vacuum cleaner used in this study was a general-purpose commercial household appliance driven by a 1400 W electric motor, known as the Extron (LG model V-3913DV).

A butterfly valve of inner diameter 53 mm was installed in front of the chamber to control the airflow rate into the vacuum chamber. The dynamic pressure (h_d) at the center of the inlet duct and the suction pressure (h_s) at the vacuum chamber were measured with Pitot tubes. These pressures were used to calculate the aerodynamic power of the vacuum cleaner. Pressure signals were measured by two micro-manometers (FCO-012 and FCO-510) ; the butterfly valve was rotated in increments of 0.3° between pressure measurements. At each flow rate, 5000 pressure data were acquired at a sampling rate of 1 kHz.

Prior to data acquisition, the vacuum cleaner was operated for about thirty minutes to ensure a steady state flow condition. During the experiments, the temperature variation of the ambient air was maintained at less than 1℃. Aerodynamic suction power was measured as a function of in-coming airflow rate through the inlet duct by



(a) Suction efficiency measurement

(b) Sound pressure level measurement

Fig. 1 Schematic diagram of experimental set-up for the suction efficiency and sound pressure level measurements

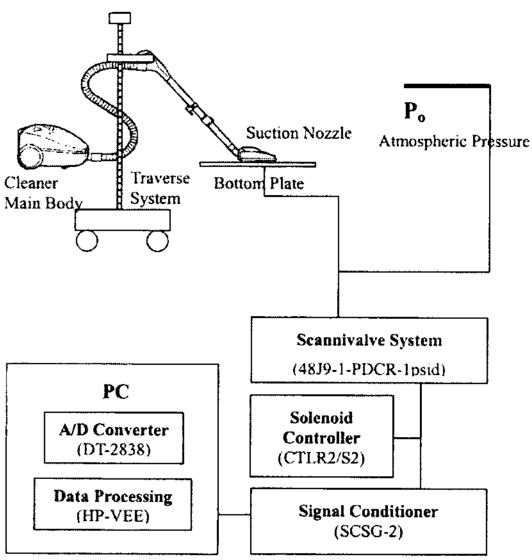
adjusting the butterfly valve gradually from a fully open to a closed state. The vacuum cleaner was driven at the maximum power mode. The suction efficiency ($\eta = AP_{MM}/AP_{MO}$) was defined as the ratio of the maximum air power of the tested suction nozzle (AP_{MM}) to the maximum air power without the suction nozzle (AP_{MO}).

The airflow-induced sound pressure level (SPL) of each suction nozzle was measured in a half-type anechoic chamber of dimensions 2 m wide×2 m long×2 m high. Following the KS (Korean Standards) standard test regulations for vacuum cleaners, the suction nozzle was installed 10 cm above the bottom surface in the central region of the anechoic room as shown in Fig. 1 (b). In general, the vacuum working fan airflow at stall increases the broadband noise level approximately 6 to 8 dB over the broadband noise radiated by the electric motor alone (Brungart et al., 1999). Therefore, the main body of the vacuum cleaner was enclosed with sound-absorbing materials to minimize noise from the electric motor and fan.

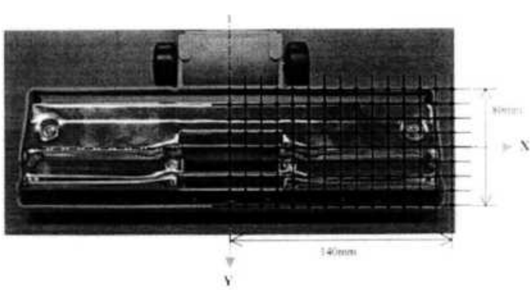
Two microphones (B&K-4192) were directed towards the sound source, one 1 m above the suction nozzle and the other 1 m to the right-hand side of the nozzle (see Fig. 1(b)). These are pressure-field type microphones and have a frequency range from 3.15 Hz to 20 kHz. They can be used for sound measurements requiring random-incidence response or in acoustic couplers in general. The acoustic signals from the two microphones were digitized at a sampling rate of 50 Hz using a high-precision Dynamic Signal Analyzer (SR-785). The measured pressure data were represented as the sound pressure level (SPL) in decibels (dB). The power spectra of the radiated sound signals were measured in a one-third octave band within the audio frequency in the range from 50 to 20,000 Hz. In addition, the noise levels (NL), linear and A-weighted sound pressure levels, were measured using a microphone sound level meter. The total noise level (TNL) of the vacuum cleaner suction nozzle was represented as the average of the noise levels measured from the upper and side microphones.

To measure the suction pressure on the ground surface beneath the suction nozzle, 135 pressure taps were installed at 10 mm intervals on the flat bottom plate. In consideration of the symmetry of the nozzle, the spatial distribution of the suction pressure was measured only over half of the area beneath the suction nozzle. Figs. 2(a) and (b) show schematics of the suction pressure measurement system and the pressure-tap positions on the flat bottom plate respectively.

The pressure taps were connected to the Scannivalve system (48J9-1) by vinyl tubes of inner diameter 0.8 mm. Each pressure tap was selected by a solenoid controller (CTLR2/S2) and the analog voltage output from the pressure transducer (PDCR22-1psid) was digitized by a high-precision A/D converter (DT-2838). The handle of vacuum cleaner was fixed at a traverse system to situate the suction nozzle fully contact the flat plate with upright posture.



(a) Pressure measurement system



(b) Pressure tap positions

Fig. 2 Schematics of suction pressure measurement system and pressure tap positions on a flat bottom plate

The frequency response of the pressure transducer employed in the experiments was about 330 μs. At each pressure tap, 16,000 pressure data were acquired at a sampling rate of 1 kHz and statistically averaged to obtain mean and rms pressure data. The suction pressure (P_s) was expressed as the pressure difference between the surface pressure on the bottom flat plate (P) and the ambient atmospheric pressure (P_o) as follows :

$$P_s = |P - P_o| \quad (1)$$

3. Results and Discussions

3.1 Suction nozzle modification

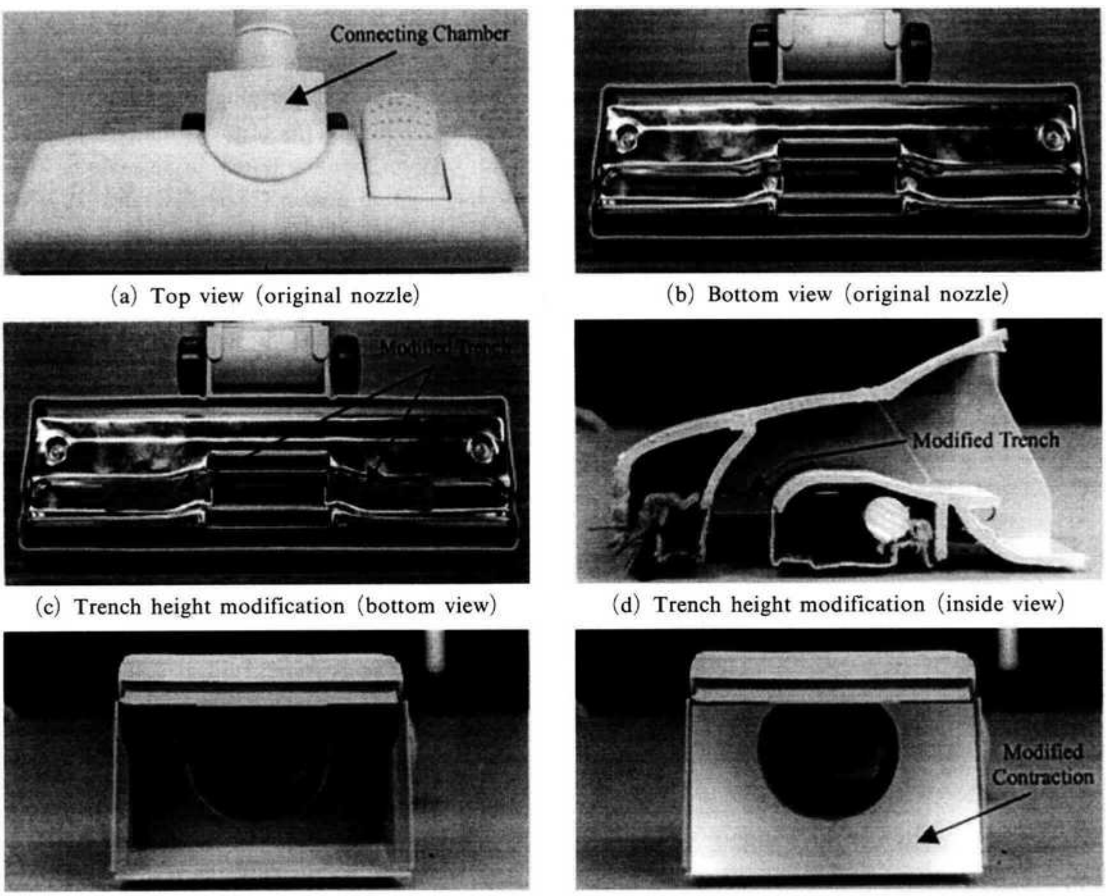
Figure 3 shows the original suction nozzle and modified airflow paths of the commercial household vacuum cleaner tested in this study. The original suction nozzle (Figs. 3(a) and (b)) has been widely used for cleaning carpet and laminated floor surfaces. The airflow channel is narrow and deep to give enhanced dust-absorption capability in a compact shape.

The trench bottom of the original suction nozzle is sloped such that the trench deepens with going towards the main rectangular suction hole located at the nozzle center. The inclination angle of the trench bottom of the original suction nozzle is about 6.8°. It is known that the flow separation on a flat surface of a diffuser does not occur when the inclination angle is less than about 5°. This flow separation usually induces aerodynamic noise and makes the flow structure more complicated (Rae and Pope, 1984).

First, we investigated the effect of trench height variations (Δt) on the aerodynamic power, sound pressure level and suction pressure characteristics. To increase the trench height of the suction nozzle, a series of flexible plastic strips of thickness 200 μm was stacked up to the desired thickness. The trench height variation (Δt) is defined as the depth of the plastic strips added to the trench. The depth of trench bottom of original nozzle at the central suction hole is 14.2 mm. Four trench height modifications were tested (Δt=0.4, 0.8, 1.2, and 1.6 mm). The bottom and inside views of the modified trench positions are shown in Figs. 3(c) and (d).

The handheld suction pipe and the suction nozzle are linked through a rectangular connecting chamber, as shown in Figs. 3(a) and (e). The flow enters this chamber through an entrance of rectangular cross section and exits through a circular pipe of smaller cross section. The sudden contraction from the rectangular chamber to the circular pipe causes flow separation at the downstream pipe and causes the flow to have the vena contracta. In addition, a separated shear layer is formed in front of the sudden contraction in the rectangular reservoir. The flow separation and vortex formation due to the sudden contraction from the rectangular reservoir to the circular pipe cause friction losses and an increased pressure drop (White, 1986).

In consideration of this fluid loss, we modified the sudden contraction into a smoothly converging nozzle to reduce the sudden pressure drop and large flow-induced noise around the throat of the connecting chamber. To create the modified suction nozzle, the cross section of the flow path was gradually changed from rectangular to circular by filling the corners of the chamber with putty as shown in Fig. 3(f). Thus, the nozzle surface was gradually changed from a concave



(a) Top view (original nozzle)
(b) Bottom view (original nozzle)
(c) Trench height modification (bottom view)
(d) Trench height modification (inside view)
(e) Connecting chamber (original, rectangular)
(f) Chamber contraction modification

Fig. 3 Photographs of original suction nozzle and modified suction nozzles shape at the inlet to a convex configuration at the exit to fill-in the region of separation bubbles. The contraction ratio CR (rectangular duct area/circular pipe area) of the converging nozzle was about 2.8.

Finally, we simultaneously applied both of the modifications (trench height adjustment and converging nozzle) to the original suction nozzle to optimize the suction nozzle design. For these modified suction nozzles, the aerodynamic power, sound pressure level and suction pressure distributions were measured.

3.2 Suction power

To evaluate the vacuum cleaner performance, we measured the aerodynamic power of the vacuum cleaner. The aerodynamic power (AP) for a vacuum cleaner is defined as the net time rate of work done by the vacuum cleaner while expending energy to produce the suction air under a specified air resistance condition, expressed in watts. Therefore, the aerodynamic power of a vacuum cleaner is calculated as follows :

$$AP=0.1633\times Q\times h_s \qquad (2)$$

where AP is the aerodynamic power in watts (W), Q is the flow rate (m^3/min), and h_s is the suction pressure represented in absolute vacuum pressure (mmH_2O). The constant 0.1633 is used to maintain consistency in unit conversions.

From Bernoulli's equation and momentum conservation law, the airflow rate (Q) can be expressed as follows :

$$Q=A\times V=A\times\sqrt{2g/\gamma}\times\sqrt{h_d}=0.19\sqrt{h_d} \qquad (3)$$

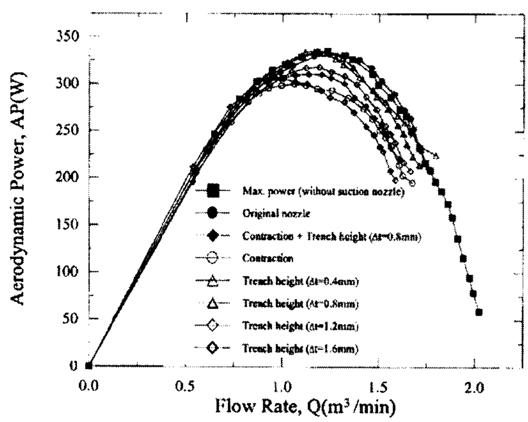
where A is the cross-sectional area (m^2) of the pipe, V is the airflow velocity (m/s), g is the gravitational acceleration, γ is the specific weight of air, and h_d is the dynamic head of the air stream in millimeters of water.

By substituting Eq. (3) into Eq. (2) and using conversion factors, we can finally evaluate the aerodynamic power of a vacuum cleaner.

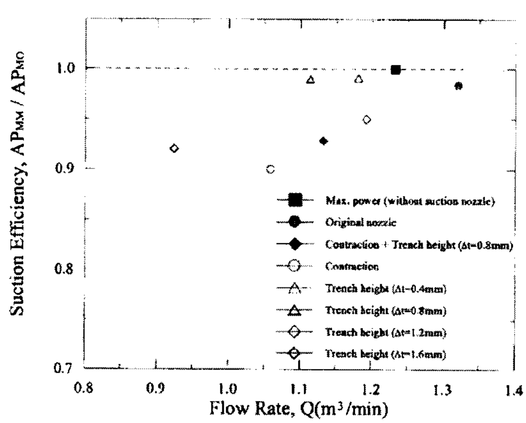
$$\begin{aligned}AP&=0.1633\times Q\times h_s\\&=3.1027\times10^{-2}\times\sqrt{h_d}\times h_s\end{aligned} \qquad (4)$$

From this equation, we can calculate the aerodynamic power by measuring the suction pressure (h_s) and dynamic pressure (h_d) of the air stream with a Pitot tube. The suction efficiency of a suction nozzle is calculated by comparing the maximum aerodynamic power with that of the main vacuum cleaner without the suction nozzle. To determine the best estimate of air power of the vacuum cleaner model, the corrected airflow concerning many operating modes such as stall should be precisely considered. However, the airflow rate was fixed at discrete value for comparison and not considered as an independent variable in the present study.

Figure 4 shows the effect of suction nozzle modification on the aerodynamic power and suction



(a) Aerodynamic power



(b) Suction efficiency

Fig. 4 Aerodynamic power and suction efficiency for modified suction nozzles over an artificial lawn

Table 1 Comparison of maximum aerodynamic power and suction efficiency for modified suction nozzles installed over an artificial lawn

Suction Nozzle Modification	Aerodynamic power AP_{MM} (W)	Flow rate Q (m^3/mm)	Suction efficiency AP_{MM}/AP_{MO}
Max. air power (without nozzle, AP_{MO})	334.5	1.232	1.0(100%)
Original	331.6	1.244	0.98(98%)
Trench height (Δt=0.4 mm)	334.3	1.180	0.99(99%)
Trench height (Δt=0.8 mm)	334.4	1.180	0.99(99%)
Trench height (Δt=1.2 mm)	317.9	1.120	0.95(95%)
Trench height (Δt=1.6 mm)	307.9	0.924	0.92(92%)
Chamber contraction	300.0	1.059	0.90(90%)
Trench height (Δt=0.8 mm) +Chamber contraction	310.6	1.132	0.93(93%)

efficiency of the vacuum cleaner installed over an artificial lawn, which was used to simulate the surface condition of carpet. The air power and suction efficiency were compared with varying the height of the bottom trench and the connecting chamber configuration.

The aerodynamic power of the vacuum cleaner has a parabolic distribution as a function of airflow rate, as shown in Fig. 4(a). As the airflow rate increases, the dynamic pressure increases and the suction pressure (h_s) is reduced. Since the air power is a product of airflow rate and dynamic pressure, it increases up to the maximum at small flow rate and then decreases on further increase of the airflow rate.

In general, the maximum power of a vacuum cleaner is obtained when no suction nozzle is installed in front of the main vacuum chamber because momentum loss is minimized in that system. The maximum power without any suction nozzle was AP_{MO}=334.5 W at the flow rate of Q=1.23 m^3/min.

The aerodynamic power increases as the trench height variation is increased and has the maximum value at the height increase of Δt=0.8 mm. Thereafter, it decreases again. The critical trench height seems to be closely related to the flow separation induced on the surface of the diffusing channel ; this will be discussed in greater detail in Section 3.3. The relative suction efficiency (AP_{MM}/AP_{MO}) was about 0.99 (99%) at the trench height increase of Δt=0.8 mm, as shown in Fig. 4(b).

When the modification of the connecting chamber is applied, the aerodynamic power decreases substantially and the relative suction efficiency has a small value of 0.90 (90%) compared with that of original suction nozzle. This indicates that the modified connecting chamber still acts to some extent as a sudden contraction due to the small streamwise length of the contraction, even though the modifications to the chamber reduce the upstream separation bubbles.

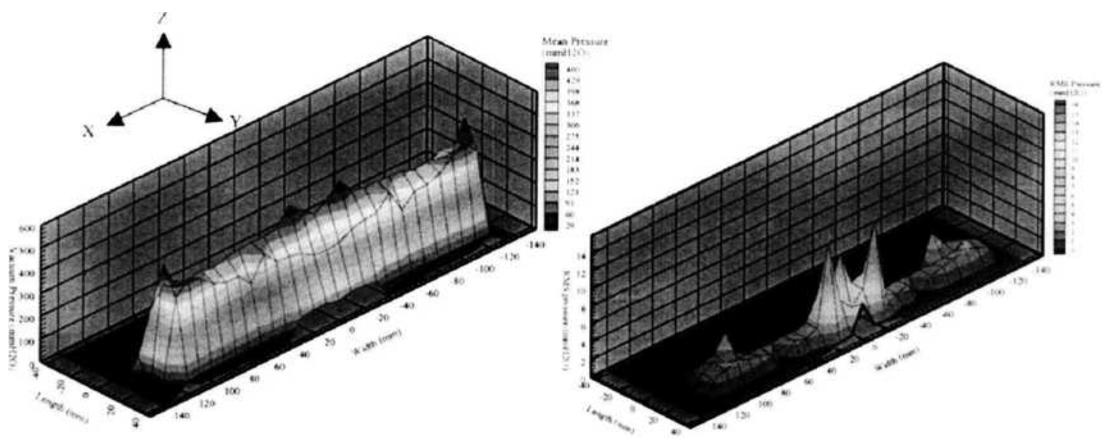
When the two modifications (trench height increase of Δt=0.8 mm and converging nozzle) were simultaneously applied to the original suction nozzle, the aerodynamic power of the resulting system lay between the values obtained when the modifications were applied independently. The relative suction efficiency increased to 93% on application of a trench height increase of Δt=0.8 mm and the converging connecting chamber. The aerodynamic power and suction efficiency for all modifications tested in this study are summarized in Table 1.

3.3 Suction pressure

Figure 5 shows the spatial distributions of the mean pressure and rms pressure fluctuations acting on a flat plate located beneath the original suction nozzle. For the case of the original suction nozzle, the mean suction pressure is highest along the suction airflow trench and is nearly uniform along the trench. From the viewpoint of dust-sucking ability, this suction pressure distribution should give effective efficiency due to the high values of the mean suction pressure.

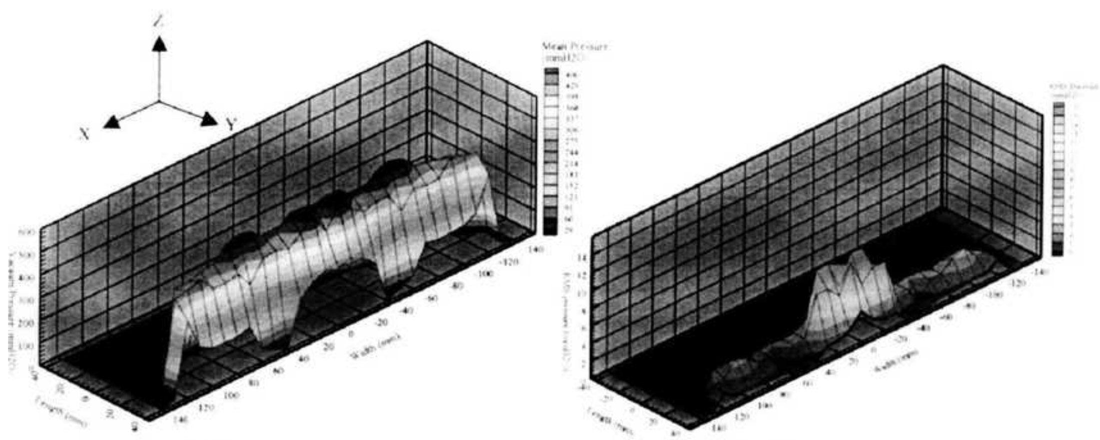
The pressure fluctuations for the original suction nozzle, however, display several peaks around the central suction hole as shown in Fig. 5(b). These sharp and large pressure fluctuations induced by the flow separation lead to an increase in the aero-acoustic noise produced by the suction nozzle.

Figure 6 shows the suction pressure distributions when the trench height around the central suction hole of suction nozzle is increased by $\Delta t = 0.8$ mm. When the trench height is increased by $\Delta t = 0.8$ mm, the inclination angle of trench bottom surface decreases from 6.8° to 6.0°. Since an inclination angle of 6.0° on a diffuser duct corresponds to an equivalent cone angle of 5°, the flow separation from the trench surface is suppressed and the flow-induced noise decreases as a consequence (Rae and Pope, 1984). Although the trench height variation lowers the flow separation from the surface by the analogy of bottom plate pressure, there may be some difference from the pressure distribution on the trench surface.



(a) Mean pressure (b) Rms pressure

Fig. 5 Suction pressure distribution for the original suction nozzle



(a) Mean pressure (b) Rms pressure

Fig. 6 Suction pressure distribution for the modified suction nozzle with trench height ($\Delta t = 0.8$ mm)

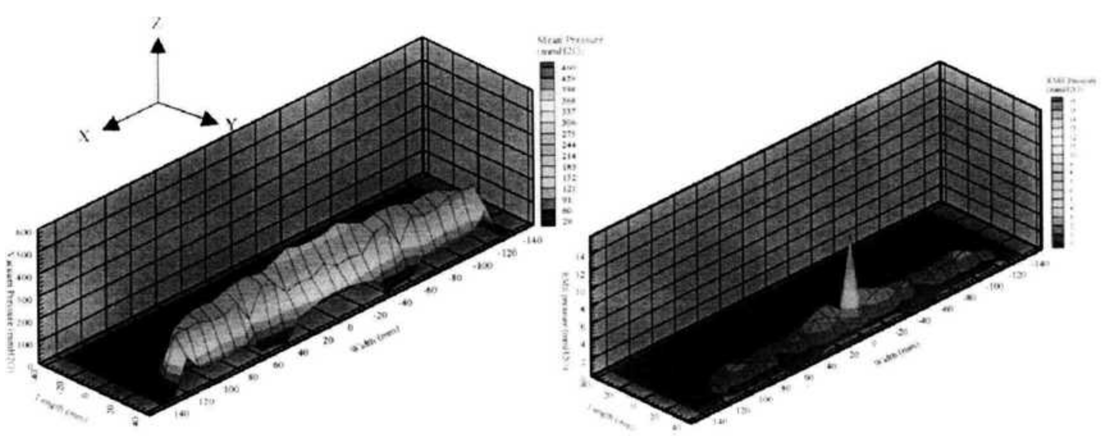
In comparison to the original suction nozzle, the nozzle with the trench height increased to $\Delta t = 0.8$ mm shows substantially higher mean suction pressures in the center of the airflow trench region around the central suction hole, as shown in Fig. 6(a). The mean pressure in the front face of the nozzle (positive Y-axis) is also increased due to the increase in gap flow entrained through the gap space between the suction nozzle and bottom plate. This indicates that the modification of the trench height enhances the suction pressure largely in the central region of suction nozzle at the expense of suction power at the two side ends of the bottom trench. This leads to an increase in the suction efficiency of the vacuum cleaner.

From the rms pressure distribution of the nozzle with the trench height increased to $\Delta t = 0.8$ mm (Fig. 6(b)), we can see that the sharp peaks at the central suction hole observed for the original nozzle disappear due to the decrease of the bottom inclination angle. This indicates that the decreased inclination angle causes a reduction in the flow separation occurring at the throat of the central suction hole. However, the pressure fluctuations around the central suction hole still have high values since the mean suction pressure is greatly increased in this region. In addition, the overall pressure fluctuations along the suction trench are slightly lower for the modified nozzle, especially at the two ends. Collectively, the results indicate that the nozzle with the modified trench produces slightly less aero-acoustic noise than the original suction nozzle.

Figure 7 shows the suction pressure distributions for the nozzle in which the connecting chamber has been modified to a converging nozzle shape. The mean suction pressure is reduced to a surprising extent, as shown in Fig. 7 (a). On average, the mean pressure is reduced about 65% in comparison to the original suction nozzle. This indicates that the suction efficiency of the modified nozzle is relatively low compared with the other suction nozzles tested in this study.

In general, a converging nozzle with a contraction ratio (CR) larger than 6 is used to increase airflow speed and to improve flow quality (Rae and Pope, 1984). However, in the present work an adequate airflow acceleration cannot be obtained because the contraction ratio employed is about CR=2.8. This seems to arise from the fact that, due to the space limitations imposed by the dimensions of the connecting chamber, the length of the contraction nozzle is less than the size of the recirculation bubble located at the upstream corner. For this reason, the airflow is instead guided to have a large vena contracta in the connecting tube after passing the converging contraction.

In contrast, modification of the connecting chamber such that its cross-section decreased



(a) Mean pressure (b) Rms pressure

Fig. 7 Suction pressure distribution for connecting chamber modification smoothly between the inlet and exit led to an improvement in the flow quality. Pressure fluctuations are substantially decreased (see Fig. 7 (b)), the only exception being the large pressure fluctuations at the center of suction hole. This indicates that the flow-induced aero-acoustic noise is substantially reduced when the connecting chamber is modified to have a converging contraction.

Figure 8 shows the spatial distributions of the mean pressure and pressure fluctuations for a nozzle in which the two modifications (trench height increase and converging contraction) are applied simultaneously. In this case, the merits of each modification are combined and complement each other. In this nozzle, the increase in mean suction pressure due to the increase of the trench height is offset by a decrease due to the connecting chamber contraction. In addition, the average mean pressure and suction efficiency are increased, with enhanced gap flow through the front bottom gap of the suction nozzle.

On the contrary, the pressure fluctuations observed for the trench height modified nozzle (Fig. 6(b)) are substantially attenuated by the modification of the connecting chamber, with the exception of the region near the central suction hole. This indicates that, in comparison to the nozzle in which only the trench height is modified, the flow quality in the nozzle with both types of modification is improved due to smoothing of the streamlines inside the suction nozzle.

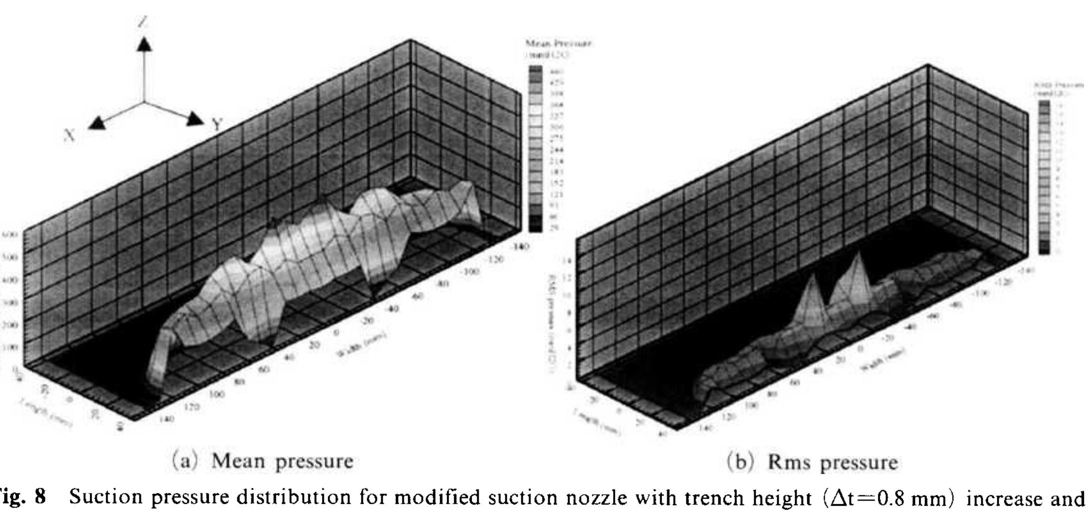
Consequently, when the two modifications are applied together, the suction nozzle characteristics involve a trade-off between suction power and acoustic noise. In a general sense, this combination has the potential to be an effective method for increasing the mean suction pressure and reducing the aero-acoustic noise from the suction nozzle.

3.4 Sound pressure level

Figure 9 shows the sound pressure level (SPL) distribution and noise level (NL) at 10 cm above a flat bottom plate for several suction nozzle designs. The A-weighted total noise level (NL) measured by each microphone is shown on the right side of each plot as an isolated solid bar.

The original suction nozzle has a typical higher value in the frequency band ranging from 500 to 1000 Hz, as shown in Fig. 9(a). This frequency band is closely related to the predominant aero-acoustic noises of the vacuum cleaner suction nozzle. The SPL measured by the side microphone is slightly higher than that measured at the upper location.

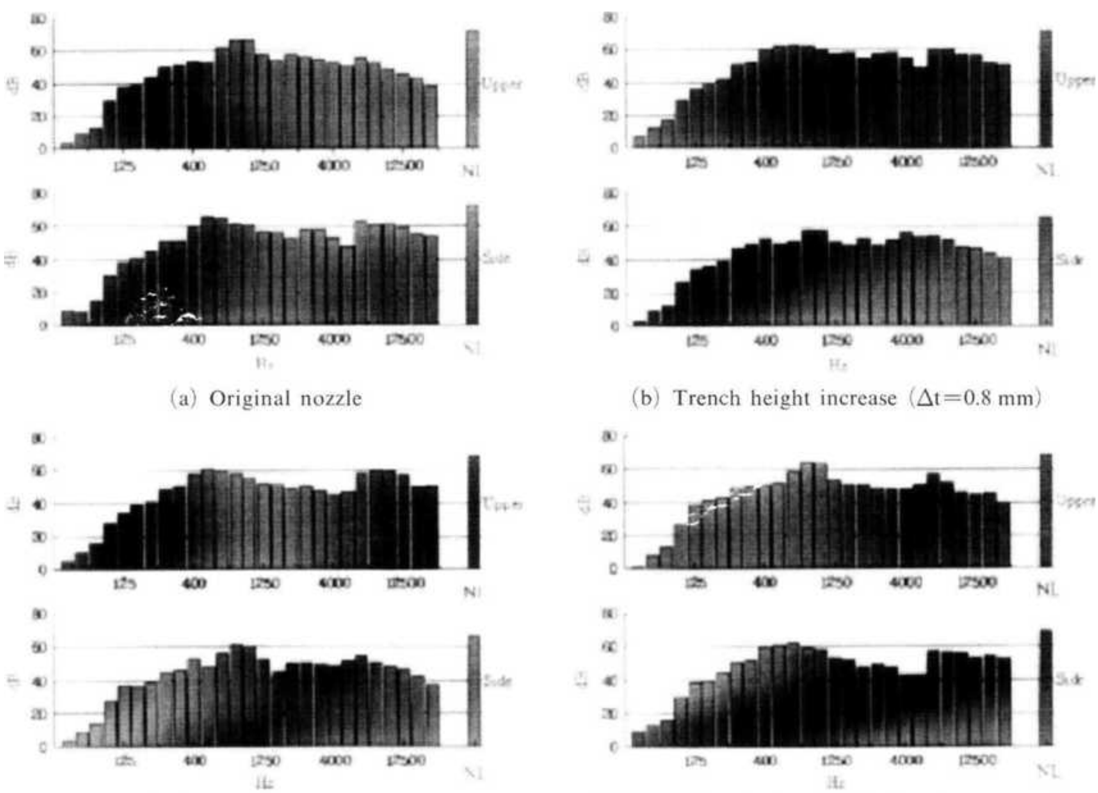
In contrast to the original nozzle, all of the



(a) Mean pressure (b) Rms pressure

Fig. 8 Suction pressure distribution for modified suction nozzle with trench height ($\Delta t = 0.8$ mm) increase and connecting chamber modification modified suction nozzles exhibit two frequency bands with higher value generating the dominant aero-acoustic noise as shown in Figs. 9(b) ~ (d). The first higher value occurs over the frequency band between 500 and 1000 Hz (Brungart et al., 1999). In the strict sense, however, the harmonics of noise spectrum are not observed peculiarly, since the aerodynamic noise spectrum shows slightly broadband distribution related to the turbulence at the suction nozzle. The second higher value, which acts as an additional noise source, occurs over the frequency band of 6300 to 10,000 Hz. Although all of the modified suction nozzles considered here exhibit two frequency bands with higher value, the magnitude of the noise level is relatively low and the total noise level is lower than that of the original suction nozzle. In particular, the connecting chamber modification (Fig. 9 (c)) shows a large reduction in the SPL at the two frequency bands with higher value.

Table 2 summarizes the aero-acoustic noise level (NL) and the attenuation of the total noise level (TNL) in decibels for three suction nozzle modifications. The total noise level of the vacuum cleaner suction nozzle was represented as the average of the noise levels measured from the upper and side microphones. In general, the A-weighted acoustic power levels of vacuum cleaners were known to be 59 to 103 dB with the average at 83 dB. Therefore, it was aimed to reduce the sound power level below the average value of 70 dB with suction nozzle alone in the present study (Kodera et al., 1998). When the rectangular connecting chamber is changed into a converging contraction nozzle, the maximum TNL reduction is about 4.363 dB compared with the TNL of the original suction nozzle. In addition, when the two modifications are com-



(a) Original nozzle

(b) Trench height increase (Δt=0.8 mm)

(c) Chamber contraction

(d) Trench height increase + Chamber contraction

Fig. 9 Comparison of sound pressure level for modified suction nozzles installed at 10 cm above the bottom plate (A-weighted)

Table 2 Comparison of sound pressure level of modified suction nozzles

Suction Nozzle Modification	NL_{upper} (dB)	NL_{side} (dB)	TNL (dB)	TNL Reuction (dB)
Original	71.641	72.709	72.175	0
Trench height (Δt=0.8 mm)	71.322	70.571	70.946	−1.229
Chamber contraction	68.969	66.655	67.812	−4.363
Trench height+ Chamber contraction	68.658	69.016	68.837	−3.338

bined, the TNL is reduced to 3.338 dB due to the mutual effects of the two modifications.

4. Conclusions

The effects of suction nozzle design on the aerodynamic power, suction pressure and aero-acoustic noise of a vacuum cleaner were investigated experimentally. The original suction nozzle of a commercial vacuum cleaner was modified by varying the bottom height of the airflow trench and the inner structure of the connecting chamber.

The aerodynamic power and mean suction pressure increased substantially when the trench height was increased to Δt=0.8 mm. These improvements in power and suction resulted from the suppression of flow separation on the surface of the suction airflow trench. However, this modification led to only a relatively small reduction in the noise level.

Flow quality was greatly improved by changing the rectangular connecting chamber into a converging contraction shape. This modification of the connecting chamber greatly decreased the pressure fluctuations that cause aero-acoustic noises, leading to an attenuation of the total noise level of more than 4 dB. However, modification of the chamber weakened the aerodynamic power performance.

When both modifications (trench height increase and connecting chamber contraction) were applied simultaneously, the aerodynamic power, suction pressure and aero-acoustic noise level were in between the corresponding values observed for nozzles in which the modifications were applied independently. Compared with the characteristics of the original suction nozzle, the combined modification reduces the aero-acoustic noise level by 3.34 dB and decreases the suction efficiency to about 93%. From a practical viewpoint, the combined modification has the potential to be an effective method, especially in situations where noise reduction is important.

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