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Flow Field Analysis inside Intake Nozzles of a Household Vacuum Cleaner

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Keywords : *Household Vacuum Cleaner, Intake Nozzle, Flow Visualization, PIV, Aerodynamic Power*

Abstract

The inside configuration of intake nozzle of vacuum cleaner greatly affects the dust-collection efficiency and acoustic-noise effect generated from flow separation interaction between high-speed flow and internal structure. In order to improve the performance of the vacuum cleaner, flow fields inside the intake nozzles were investigated using flow visualization and PIV (Particle Image Velocimetry) technique. The measurement to aerodynamic power, suction efficiency and noise level were also carried out. Valuable information was obtained from the experiments, revealing how to modify the intake nozzle. In this paper, the results of visualization, velocity distribution of flow fields, aerodynamic power, suction efficiency and noise level are discussed.

1. Instruction

The dust-collection ability is a very important factor of a vacuum cleaner. However, noise level is another criterion to judge the quality of a vacuum cleaner. Generally, the aero acoustic nise of a vacuum cleaner is caused by flow separation inside the device and vibration caused by unbalance rotating of devices. Several researches about vacuum cleaners have been reported by Bentouati *et al.* (1999), Omori *et al.* (1997), Sarbu *et al.* (1996). Most previous studies are mainly concerned about the methodology to improve the suction power and to control the acoustic noise emissions.

There is no literature to investigate the internal flow structure inside intake nozzle of a vacuum cleaner. It is desirable to study the noise, pressure and flow structure systematically to identify predominant noise generation mechanisms and to enhance the suction efficiency.

Experimental results obtained flow visualization and PIV measurement are discussed together with pressure and acoustic measurements. The main objective of this paper is to investigate the internal flow structure for improving the dust-collection efficiency and reducing acoustic-noise by modifying the intake nozzle of a household vacuum cleaner.

2. Experimental methods and apparatus

2.1 Proto-type of vacuum cleaner intake nozzle

Flow fields of a household vacuum cleaner intake nozzle, and two of its modification modes were. The profile of inside structure of original intake nozzle is shown in Fig.1. In order to improve its dust-absorption ability and acoustic character, the inside structure of the intake nozzle was modified. First, the bottom inclination angle from side trenches to center of original suction hole is about 6.8^0, the bottom of trenches was modified by reducing the depth of 0.8mm, so that the inclined angle decreased to 5^0 and avoid flow separation and duct induced aerodynamic noises, Second, the intake nozzle and the hand-hold suction pipe are linked by a rectangular connection chamber, the stream passing through this rectangular chamber will directly flow into circular suction pipe, this will cause sudden drop of suction power and increase flow-induced noise, in order to reduce these efficiency, a contraction nozzle was fixed inside the connection chamber, the rectangular nozzle entrance changes to circular exit ant the surface shape of the nozzle is changed gradually from concave to convex wall.

2.2 Experimental methods

As shown in Fig.2, the intake nozzle was placed on the bottom of a transparency experimental chamber with volume of 70x70x40 cm^3, the images of flow field in testing area were taken by CCD cameras from the beneath of chamber, but flow visualization experiment, there has no laser and synchronizing system.

The images of flow visualization were taken by a Weinberger high speed CCD camera, which has the maximum frame rate of 1000frames/sec and resolution of 512×512pixels^2. The test section was illuminated by 300watt Tungsten halogen lamp. The dusts are simulated by polystylene particles with diameter of 100μm-200μm. For each intake nozzle mode, the CCD camera captured the visualization images for 2 seconds with 500 frames/sec, the animate files of visualization show the variation of the flow fields clearly. In this paper, we extract 4 images from animate files of one intake nozzle mode so as to demonstrate the typical moments of flow field evolvement.

For PIV measurement, the laser light sheet illuminates the testing section from side of intake nozzle. The PIV system consists a dual-head Nd:YAG laser, a Kodak frame-straddling CCD camera with resolution of 1008×1018 pixel^2 and frame rate of 15fps, a frame grabber, a synchronizer . The time interval between two laser pulses was 18.0μs. The output energy of Nd:YAG laser is 25mJ with 10Hz repeating rate. Seeding particles were olive oil particle with average diameter of 10μm.

In order to compare the working efficiency of vacuum cleaner with different intake nozzles quantitatively, the aerodynamic power, suction efficiency and noise level(NL) are measured. The detailed descriptions to the testing

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methods to aerodynamic power and noise level measurement were introduced by Park, *et al*, 2002.

3. Experimental results and discussion

3.1 Flow visualization of intake nozzle

The evolvement of flow field of intake nozzle with contraction chamber is shown in Fig.3(a)-(d).The vacuum cleaner worked with maximum suction power, it took about 340ms for the flow field to become stable from starting. The four instantaneous images of flow field are extracted from this duration, the time interval between sequent images is 60m. At beginning, the powerful flow moves downward from upper side of suction hole(refer the PIV result in section 3.2), it suppresses the upward moving flow from lower side of suction hole, the flow from two trenches impact in the center of the suction hole(T=100ms). Then the flow in vertical direction and flow from trenches are enhanced, some particles at lower side of suction hole near the trench are entrained by the flow from left trench and gradually form a small vortex(T=160ms), this flow phenomena lasts for quite a long time until T=220ms. Thought more and more particles are collected from lower side of suction hole, the center part of upward moving flow is still suppressed by the strong flow from upper side, this causes the generation of two symmetric vortices in the entrance of suction hole(T=280ms). Afterward the flows in vertical and horizontal directions reach a balance gradually.

3.2 Velocity fields of intake nozzles

The instantaneous velocity field of original intake nozzle is shown in Fig.4(a). The particles near upper and lower side of suction hole are sucked powerfully, but absorption ability in X direction is weak, the maximum flow velocity in Y direction measured by PIV technique is V_{max}=44.49m/s, and in X direction U_{max}=11.15m/s, the magnitude of maximum velocity in X direction is about 25% of that in Y direction. Because the velocity of the particles moving in Y direction is much higher than that in X direction, before particles at right and left sides of intake nozzle are sucked along the trench, a plenty of particles at lower and upper side of suction hole are absorbed into the suction hole. With the increasing strength of flow from trenches, the combined flows are sucked into the hole with an angle of 40^0 with respect of horizon. The flow from upper side of trench moves downward and smash with the upward moving flow and form strong turbulent movement, two symmetric vortices are generated and their rotating directions are different. Fig.4(b) shows the velocity field of intake nozzle with contraction nozzle. The flow moves mainly from upper side to lower side. The maximum velocity in Y direction drops to V_{max}=36.35m/s. But in X direction, the flow velocity increased to U_{max}=15.83m/s, the magnitude of U_{max} is about 44% of V_{max}, the ability of collecting dust at left and right side is improved in this case. Fig.4(c) shows the instantaneous velocity field of flow in intake nozzle with modified trench and contraction nozzle. The maximum velocity in X direction increased to U_{max}=20.32m/s, which is almost two times of U_{max} in original intake nozzle, the particles in X direction are sucked with great power, a plenty of particles swarm into the suction hole. On the contrary, the flow velocity drops to its lowest value in Y direction, the maximum velocity is V_{max}=25.08m/s. With the increase of suction power, the velocity of flow at lower side starts to increase and more particles entrained into the suction hole, the range of upward moving flow is wider than that of original intake nozzle, but the flow from upper side is very weak. The ratio between U_{max} and V_{max} is increased to 81%, the dust-collection ability in X and Y direction is comparable.

3.3 Aerodynamic power, suction efficiency

To evaluate the performance of the vacuum cleaner w ith different intake nozzle modes, the aerodynamic powe r of vacuum cleaner was measured.

Fig.5 shows the comparison of aerodynamic powers and suction efficiency of different intake nozzle modification. We can find that the vacuum cleaner without any intake nozzle has the maximum aerodynamic power, because the momentum loss is minimized in the system. The suction efficiency is 100%. The aerodynamic power and suction efficiency of original intake nozzle are similar to those of vacuum cleaner without intake nozzle. When the modified contraction chamber was applied, the aerodynamic power decreased remarkably and the suction efficiency has a small value of 90% compare with those of original intake nozzle. For the case of intake nozzle with contraction chamber and trenches height modified, the aerodynamic power lays between the values of original nozzle and nozzle with only contraction chamber modified, and the suction efficiency increased to 93%.

Considering the noise level is another important index to evaluate the quality of a vacuum cleaner, though the modification to the intake nozzle causes decreasing of aerodynamic power and suction efficiency, the acoustic characteristic is improved. Table 1. shows the noise levels of different intake nozzle modification. For the contraction chamber and trenches height modified intake nozzle, the value was reduced 3.338dB compared with that of original intake nozzle and less than the NL reduction of intake nozzle with contraction chamber, but it has better suction efficiency and aerodynamic power, so with contraction chamber and trenches modified intake nozzle can be considered as a optimized design from view point of suction efficiency and noise level.

4. Conclusion

Flow fields inside the intake nozzles of a commercial vacuum cleaner intake nozzle were investigated using flow visualization and PIV technique together with aerodynamic power, suction efficiency and noise level measurement. The modification of the intake nozzle inside structure decreased the suction power compared with the original intake nozzle, but the acoustic characteristic of the vacuum cleaner was improved significantly. When both modifications of trenches height increasing and smooth contraction chamber are applied simultaneously, the vacuum cleaner shows good performance in consideration of dust-collection ability and acoustic noise reduction.

Acknowledgements

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Table 1. Noise level reduction of modified intake nozzles

Suction nozzle modification	NL (dB)	NL Reduction (dB)
Original nozzle	72.175	0
Chamber contraction	67.812	-4.363
Trench height + chamber contraction	68.837	-3.338

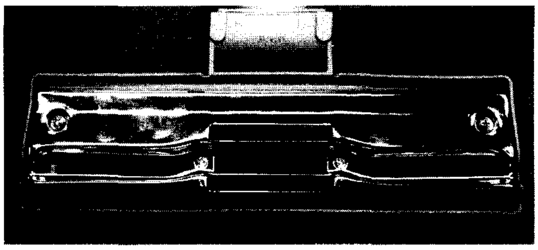


Fig.1 Bottom structure of the original intake nozzle

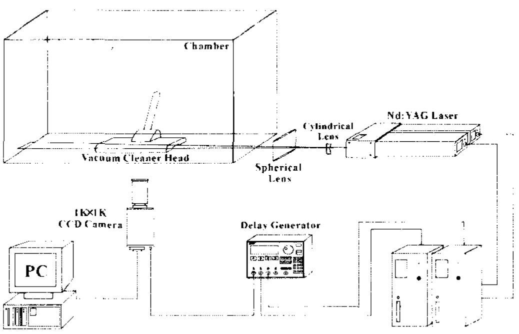
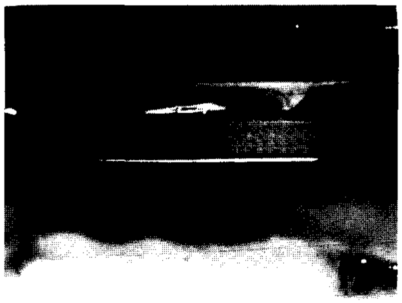
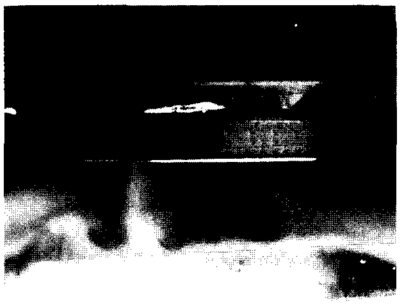


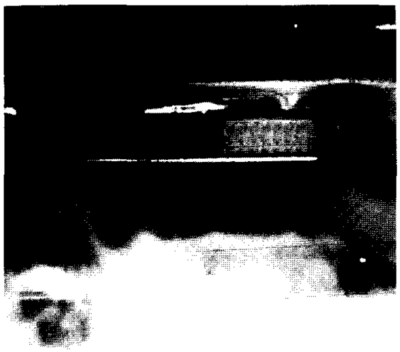
Fig.2 Schematic diagram of experimental set-up for PIV measurement and flow visualization



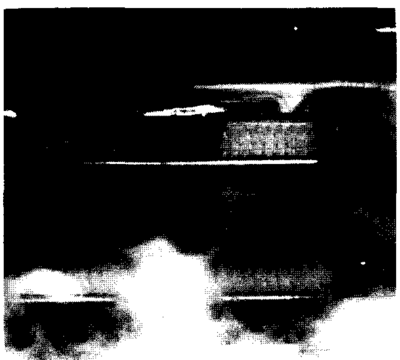
(a) T=100ms



(b) T=160ms

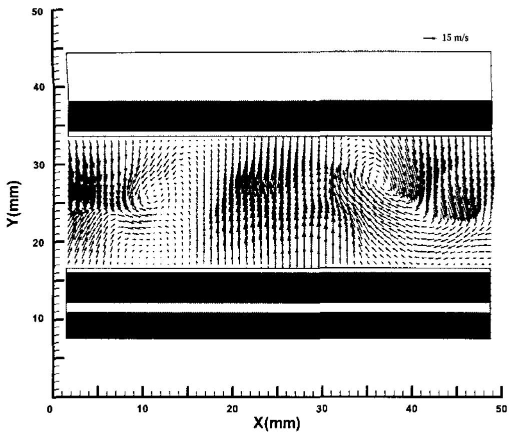


(c) T=220ms

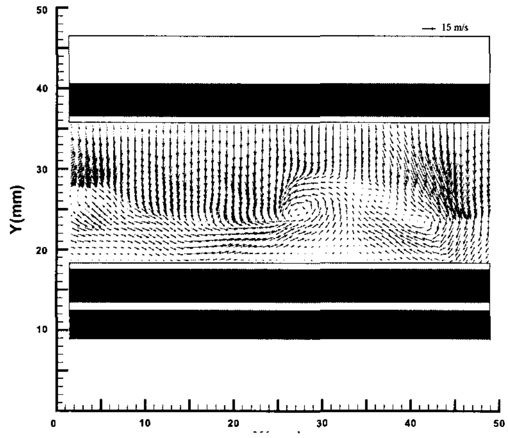


(d) T=280ms

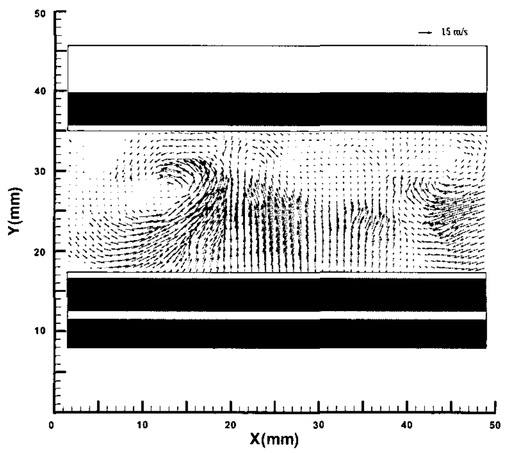
Fig.3 Flow field evolution at intake nozzle with contraction chamber



(a) Original NZ-21 intake nozzle

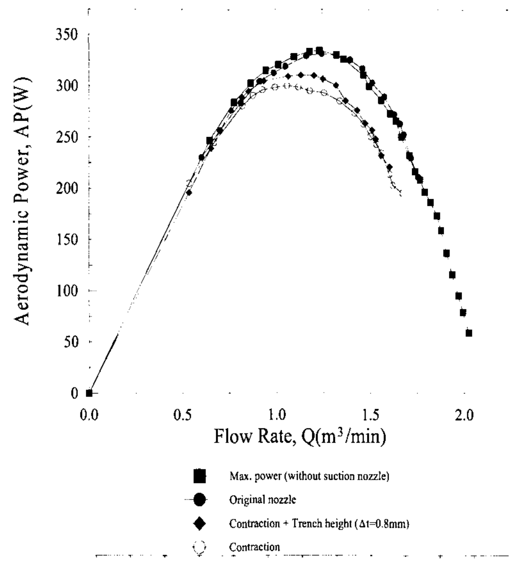


(b) Intake nozzle with contraction chamber



(c) Intake nozzle with contraction chamber and trenches height increase

Fig. 4 Instantaneous velocity fields



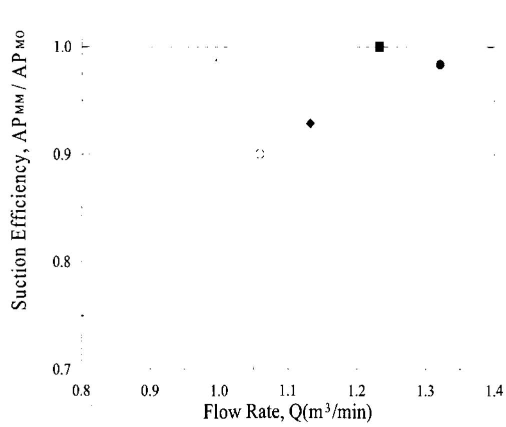


Fig.5 Aerodynamic power and suction efficiency