Design and analysis of nozzles for pneumatic windshield wiper

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Abstract. Almost all the vehicles use mechanical wipers to clean the windscreen when rain or other elements such as dirt hit the surface of the windshield. This helps maintain visibility so the driver can see through the windshield. Also, mechanical wipers can damage the windscreen over time with friction and partially hinder the visibility as they only clear the screen partially. There are no alternative models currently available for solving the same problem. This paper proposes an air jet windshield wiper system consists of a high-speed air outlet mounted on the edge of the windshield through which a high-speed mass of air, called as air-beam, is released over the windshield. This can be achieved with the help of an air nozzle. The air-beam ejected by the outlet of the nozzle is designed to cover most of the surface of the windshield. The beam thickness is used to push rain drops over the windshield to the roof of the vehicle and beyond. In this paper, necessary calculations were done for selecting suitable nozzles for the project. To verify the results, FEM analysis and experimental analysis has been done.

Keywords: Windshield, Air jet wiper System, Nozzle

1. Introduction

A windshield wiper is a device which is used to eliminate rain, debris, snow from a vehicle's front windshield. For cars, trucks, buses, train locomotives, watercraft with a cabin, and some aircraft wipers are legal necessities. A wiper generally consists of a metal arm, one end pivots. The other end has a long rubber blade attached to it. The arm is powered by a motor, often an electric motor, although pneumatic power is also used for some vehicles[1-3]. The blade is swung back and forth over the glass, pushing water or any other obstructions from its surface[4]. The credit for inventing
the windshield wiper goes to an American inventor Mary Anderson (United States Patent No. 748,801, 1903)[5]. She invented the first operational wiper. In her patent, she termed wiper as a ‘window cleaning device.’ Before that, drivers used to get out of the car and clean the windshield manually. On vehicles made after 1969, the speed is usually adjustable, with several continuous speeds, and often intermittent settings. Most personal vehicles use two synchronized radial-type arms, while many commercial vehicles use one or more pantograph arms. The basic principle of the wiper has continued to this day.

Even after 115 years, nothing has changed. But it has been observed that the uneven wiping action results in streaking of water and reduced driver visibility. Especially during heavy rain and snowfall, the rate of cleaning of the windshield is slow, which reduces the visibility of the driver. As wipers have a direct impact on visibility, this is usually rather negative, and there are enough reasons to replace the principle.

So improvement is required of the conventional wiper to increase the visibility of the driver, to provide more efficient cleaning and eradicate the problems of the traditional wiper such as continuous replacement, scratches on the windshield, and also reduce the maintenance cost.

By looking for a solution to all these problems, a question is raised: Is there already enclosed means of transport with a windshield without wipers? Some scientists have already invented different methods for improving the visibility of the driver during using of the wiper. At 1989, A. Demir et al. investigated T100 Hema air Jet texturing nozzle with varying geometrical configurations [6]. They reported that the exit shape has virtually no effect on the airflow while other parameters contribute to the formation of the emerging jet which performs the texturing. An air wiper unit was patented (Japan Patent No. 5,419,005, 1995)[7] by Japan in 1995. It reported that the air wiper includes a first air ejection unit and a second air ejection unit. The first ejection unit gives out compressed air upwards near windscreen glass and along the outer surface of the windscreen glass to form an air curtain. The second air ejection unit is arranged. An air curtain is generated being spaced away from the windscreen glass more than the first that oscillates and forms a second air curtain through the oscillating movement. The second air ejection unit is formed of multiple nozzles, which forms the second air curtain. A warm air supplying device is arranged in front of and near the lower end of the windscreen glass to feed warm air upwards along the outer surface of the windscreen glass.

Ho-Young Kim [8] reported the study of the sliding velocity of Liquid Drops Down on an Inclined Solid Surface. High-velocity impact of a liquid droplet on a rigid surface. Haller Knezevic, 2002 [9] Was reported by Haller Knezevic. They simulated water droplets impacting at the surface at 500 m/s (1.5 Mach number), and found that the scattered water droplets had the velocity over 6000 m/s from the point of impact (18 Mach number). Alidoost Dafsari 2016 [10] experimented with the atomization and internal flow field mechanism of a hollow nozzle under different inlet pressures. Variations in the flow rate, spray cone angle, and radial spray density was also obtained under different working conditions. The results show that with the increase of inlet pressure, the growth of flow rate tends to be slower, and the airflow field in the nozzle swirl chamber is squeezed but with a more stable shape. Jagmit et al. investigated the effect of Nozzle Geometry on Critical-Subcritical Flow Transitions. They identified the optimum nozzle geometry that maximizes critical pressure ratio while minimizing pressure drop across the nozzle.

After studying the literature mentioned above, it can be concluded that scientists are trying to replace the windshield wipers in the car by an air jet. The jet of air should be strong enough and aligned with the glass to deflect the raindrops that come into contact with the windshield.

2. Design Of Wiping System

This system is designed here for trucks and trailers because, in trucks, compressed air is readily available, used in the braking system. A fraction of this air will be used for operating the pneumatic windshield wiper.
As the air-beam blows over the surface of the windshield, it carries away elements deposited on the windshield with it. If the device is activated during rainfall, it can carry droplets of rain away from the windshield.

With appropriate airspeed and air volume, the device can ensure a completely dry windshield even during rainfall. This can allow a tremendous increase in visibility for the driver and occupants of the vehicle. Essential components of wiping systems are compressed air, pressure regulator, pneumatic pipes, and nozzles.

The air jet windshield wiper system consists of a high-speed air outlet mounted on the car at the windshield through which a high-speed mass of air, henceforth an air-beam, is released over the windshield. The air-beam is characterized by the velocity of its flow, its direction of motion and its shape. The velocity of the air-beam is substantially the average velocity of the air particles in the beam. Similarly, the direction of the air-beam is the direction in which the majority of the air particles in the air-beam are traveling.

Air from the reservoir is passed through a valve to start/stop the system. In the stop position, the valve is closed, and no air is passed ahead. When the valve is open, the air enters the piping and enters into the nozzle. In the nozzle, the pressure energy from the incoming air is converted into kinetic energy, which enables air beam impinging on the windscreen at higher kinetic energy. The air discharged from the nozzle at high velocity will be used for wiping the water droplets from the windshield.

For calculation of the mass of raindrop, raindrops are considered as a sphere. The maximum diameter of a raindrop is 5 mm [11]. If the raindrop gets any larger than 5 mm, it usually splits into two separate drops. Small raindrops are more spherical than larger ones [12]. The frictional drag from the air makes the more massive drops to have a hamburger bun shape. The volume of a small raindrop can be approximated by using the sphere formula [13].

\[
m = \frac{4}{3} \pi r^3
\]

where, \(m\) = mass of the rain droplet, \(\rho\) = density of water, \(r\) = radius of rainwater droplet

According to Spilhaus [14], \(V_t\) = Terminal Velocity (The constant speed that a freely falling object eventually reaches when the resistance of the medium through which it is falling prevents further acceleration) is 9 m/sec.

![Fig. 1 Resultant Vector](image1)

![Fig. 2 Windshield diagram](image2)

\[V_t = \text{Velocity of car,}\]

Relative Velocity (\(v_r\))

\[= \sqrt{V_t^2 + V_c^2}\]

The momentum of a single raindrop is calculated by Eq. (3)

\[p = m \times v_t\]

From the rainfall intensity surveyed at various locations in the country, the mean number of raindrops that fall on the windshield can be estimated to be 500 [15] and 1 mm of rainfall equals
to 1 liter of water on 1 m$^2$ area in an hour [16-20]. Fig 2 shows dimensions of a flat windshield (Consider windshield of Maruti 800 car, and slanted angle of 5°), area 0.749 m$^2$ [21-22]. For deflecting rainwater, the mass flow rate of air should be higher than the mass flow rate of water ($\dot{m}_{\text{air}} > \dot{m}_{\text{water}}$).

For calculating the outlet velocity at the end of the nozzle, the momentum energy is equated with the kinetic energy of the steady flow of water

$$p \times a = \frac{1}{2} \times \dot{m} \times v^2 \quad (4)$$

With the help of the above formulae, the velocity of raindrop and angle of raindrop has been calculated. Fig 3 and Fig 4 represents the same.

![Fig. 3. The velocity of raindrop vs. speed of the car](image)
![Fig. 4. The angle of raindrops vs. speed of the car](image)

After developing the CAD model in CATIA, ANSYS FLUENT software was used for analyzing the nozzles, which were eventually finalized. The purpose of using this software was to test the flow and outlet velocity of the nozzle.

![Fig. 5: Long Jet Nozzle](image)
![Fig. 6: Cone Jet Nozzle](image)

Fig. 5 represents the streamline model of the long jet nozzle where inlet pressure is kept 2 bar and outlet pressure at 1 bar. The outlet velocity obtained from the analysis was 231 m/s. The velocity is high, and the flow also has a descent spread angle. Fig. 6, shows the analysis of the cone-jet nozzle for the same operating conditions. It can be seen that it has the highest velocity of 267 m/s. Fig. 7 represents the streamline model of the flat jet nozzle for the same operating conditions. The outlet velocity obtained is 136 m/s, which is less than the long jet and cone nozzle.
3. Experimental Setup:

The purpose of this testing is to check the area covered by the nozzle and check the actual results. To begin with the experiment, first, collect some sand in a bowl. Check for any impurities in the sand particles. With the help of a sieve spread the sand on a flat surface and make sure it is evenly distributed. Meanwhile, turn on the compressor, let the pressure build-up to 4 bar. Place the nozzle in a position as shown in Fig. 13. Check all the fitting in pipes. Make sure there is no loose-fitting, as it will create pressure loss. After everything is checked, turn on the knob. The compressed air will flow through the nozzle and erode the sand. Take a long ruler and a protractor. Measure the range of a nozzle with the help of a long ruler and a protractor. The displacement is the distance between the nozzle and the farthest point of sand eroded. The angle is the area it covers discharging from the nozzle outlet.

The spray pattern of the long jet nozzle has a well-defined spray pattern with a spray angle of 60° and has an effective range of around 600 mm, which is shown in the given Fig. 8. The flat jet nozzle has an undefined and irregular spray pattern with a spray angle of around 90° but has a very low effective range measuring roughly 300mm. Graphs are shown (Fig 11 and 12) are based on experimental results drawn. It shows the nozzle displacement and sprays angle of the long jet nozzle (blue) and flat jet nozzle (brown).
Different arrangements of nozzles were tried to get the best results. Some of the arrangements are shown below. In the given Fig 11, six nozzles were arranged on the windshield. High-pressure air from the compressor is passed through the pneumatic pipes and is equally distributed among the six nozzles. During this arrangement, the area covered is more, but the outlet velocity is reduced due to the pressure drop, which shows this arrangement insufficient. In the given Fig. 13, 14, two different nozzles were arranged on the windshield (long jet and cone nozzle). This arrangement was efficient in cleaning the nozzle, but the area covered was less. Among the two, the long jet nozzle was more efficient.

4. Results
For the cleaning of the windshield, four nozzles were tested. All the tests done give the following results.

**Flat Jet nozzle:**
The outlet velocity of this nozzle is 136 m/s, but the spray angle is 90°. The distance covered by this nozzle is around 300 mm, which is less compared to other nozzles. This is due to the widespread angle of this nozzle. As the need for the project is for high velocity, so choosing this nozzle is not a good option.

**Long Jet nozzle:**
The outlet velocity of this nozzle is 231 m/s. The distance covered is up to 600mm and the spray angle is 60°. The results obtained by calculating exit pressure, exit velocity, and spray pattern of different nozzle manually and on Ansys shows that Long Jet Nozzle is suitable for the system. The spray angle problem can be encountered by mounting a rotating mechanism for this system.

**Cone nozzle:**
The outlet velocity of this nozzle is 267 m/s. The distance covered is almost the same as the long jet nozzle and even the spray angle is the same. This nozzle can also be used for the system but the main drawback is that they are heavy than the long jet nozzle. Lighter nozzles are more comfortable.
to arrange on the windshield.
Theoretical results were different from the actual result considering pipe loss, pressure drop, friction losses, and other external forces were not considered. The air pressure decreased when using 5/6 nozzles but was considerably enough while working with two nozzles.
Truck minimum compressor pressure is 5 bar and this system is made for all the conditions. This system pressure is also kept up to 5 bar to check if it can work under all the conditions. The results obtained by this pressure were sufficient to wipe off the windshield.

5. Conclusion
This paper presents an alternative method to clean the windshield of an automobile. It uses compressed air at

A certain pressure and velocity to wipe out the raindrops and other particles from the windshield. From the above results, it can be inferred that the pneumatic wiper system is cost-effective, needs less maintenance compared to the traditional method of cleaning the windshield with wipers. The pressurized air could not cover some parts of the windshield area. But this problem can be fixed in the future by designing custom nozzles. Overall, this system is feasible as per assumptions and calculations. Further, this system can also be used in conjunction with the newly developed nanotechnology-based water-repellant coatings, which will significantly increase the effectiveness of the system.

The system can be made compact without compromising the performance to be used in cars, which may replace the present wiper system completely. It can have different speed settings which can be set according to the rain intensity. The above system can be automated, and it can be automatically switched ON, on detecting rain and stops when the rain stops. This will reduce manual intervention.
Rain sensors, along with 555 timers and the transistor, can be used to switch on the compressor. The rain sensor will detect the rain, and this signal will be processed by 555 timers and take the desired action. Rain sensor works on the principle of using water for completing its circuit, so when rain falls on it, its circuit gets completed and sends out the signal to 555 timer IC.

References

[1] Yang, Z. G., X. M. Ju and Q. L. Li. Numerical Analysis on Aerodynamic Forces on Wiper System. Proceedings of the Sixth International Conference on Fluid Mechanics, AIP Proceedings 1376, 213-217 2011.
[2] Lee, S. H. and et al. Numerical Study on the Aerodynamic Lift on the Windshield Wiper of High-Speed Passenger Vehicles, In The Proceedings of Asian Symposium on Computational Heat Transfer and Fluid Flow 3, 185-190 2009.
[3] Clarke, J. and R. Lumley Problems Associated with Windscreen Wiping. SAE Technical Paper. 1960.
[4] Gaylard A. P., A. C. Wilson and G. S. J. Bambrook. A Quasi-Unsteady Description of Windscreen Wiper Induced Flow Structures. In 6th MIRA International Vehicle Aerodynamics Conference. 2006.
[5] Anderson, M. United States Patent No. 748,801, 10th November 1903.
[6] A Demir. A Study of Air-Jet Texturing Nozzles: The Effects of Nozzle Configuration on the Air Flow. Journal of Engineering for Industry, 112(1), 97-104, May 1989.
[7] Mori, T. Japan Patent No. 5,419,005 May 30, 1995.
[8] Ho-Young Kim, H. J. (, December 10). Sliding of Liquid Drops Down an Inclined Solid Surface. Journal of Colloid and Interface Science, 372-380, 2002.
[9] Haller Knezevic, Y. V. A Computational Study of High-Speed Liquid Droplet Impact. Journal of Applied Physics, 92(5), 2821-28, September 2002.
[10] Alidoost Dafsari, R. &. An Experimental Study on Flow and Spray Characteristics of Pressure Swirl Nozzle with Variation of Swirl Chamber Length. Proceedings of the Autumn Conference of Korea Society of Automotive Engineers, 118-123, 2016.

[11] Cobert, J. H. Physical Geography Manual. U.S.: Kendall Hunt, 2003.

[12] Jallet, S. and et al. Numerical Simulation of Wiper System Aerodynamic Behavior. SAE Technical Paper. 2001

[13] Jeong, J. and F. Hussain On the identification of a vortex. Journal of Fluid Mechanics 285, 69-94. 1995

[14] Spilhaus, A. (1947, November 29). Raindrop Size, Shape, and Falling Speed. Journal of Meteorology, 5, 108-110.

[15] V. Sasi Kumar, S. S. Drop size distribution of rainfall of different intensitie — Indian Journal of Radio and Space Physics, 32, 217-220, 2003.

[16] Brouwer, C. Introduction to Irrigation. Rome: Food and Agriculture Organization of the United Nations, 1985.

[17] Billot, P., S. Jallet and F. Marmonier Simulation of Aerodynamic Uplift Consequences on Pressure Repartition - Application on an Innovative Wiper Blade Design. SAE Technical 01-1043. 2001

[18] Cadirci, S., S. E. Ak, B. Selenbas and H. Gunes Geometric Modifications to Minimize Lift Acting on a Simplified Front Windshield Wiper Blade. Journal of Thermal Science and Technology 36(2), 103-109, 2016

[19] Cadirci, S. and et al. Numerical Investigation of Turbulent Flow over a Windscreen Wiper Blade. In ASMEInternational Mechanical Engineering Congress and Exposition. 2016

[20] Dawley, M. Aerodynamic Effects on Automotive Components. SAE Technical Paper. 1965

[21] Jagmit Singh, L. E. Effect of nozzle geometry on critical-subcritical flow transitions. Heliyon, 5(2), 1-19, February 2019.

[22] R.Saidur, N. R. A review on compressed-air energy use and energy savings. Renewable and Sustainable Energy, 14(4), 1135-1153, May 2010.