Isı Bilimi ve Tekniği Dergisi, 36, 2, 103-109, 2016
J. of Thermal Science and Technology

ISSN 1300-3615

GEOMETRIC MODIFICATIONS TO MINIMIZE LIFT ACTING ON A SIMPLIFIED FRONT WINDSHIELD WIPER BLADE

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(Geliş Tarihi: 23.02.2016, Kabul Tarihi: 24.05.2016)

Abstract: In this numerical study, aerodynamic lift and drag forces acting on windshield wipers operating on a simplified front windshield of a car are investigated. Geometric modifications including spoiler curvature, total wiper height and connection between metal part and spoiler of the wiper are tested with the aim to reduce lift forces acting on the front windshield wiper blades at high speeds such as 240 km/h. The inference of the investigated geometric modifications is then proposed as a useful wiper prototype which can be applied to minimize lift forces at relatively high speeds.
Keywords: Wiper blade, Lift, Drag, Aerodynamics, Computational Fluid Dynamics (CFD).

BASİTLEŞTİRİLMİŞ BİR ÖN CAMDA SİLECEK GEOMETRİSİNE ETKİ EDEN KALDIRMA KUVVETLERİNİN AZALTILMASINA YÖNELİK GEOMETRİK DEĞİŞİKLİKLER

Özet: Bu sayısal çalışmada basitleştirilmiş bir araç ön cam geometrisinde sileceklere etkiyen aerodinamik direnç ve kaldırma kuvvetleri incelenmiştir. Sileceklere 240 km/h gibi yüksek hızlarda etkiyen kaldırma kuvvetini azaltmak için farklı rüzgârlık profilleri, silecek yüksekliği ve sileceğin rüzgârlık ile metal parçası arasında olan bağlantı şekilleri incelenmiştir. İncelenen geometrik özellikler daha sonra birleştirilerek yüksek hızlarda kaldırma kuvvetlerini azaltma bağlamında faydalı olabilecek yeni silecek geometrileri önerilmiştir.
Anahtar kelimeler: Silecek, Kaldırma, Direnç, Aerodinamik, Hesaplamalı Akışkanlar Dinamiği (HAD).

NOMENCLATURE

Latin:

A_p	projection area of the wiper [m^2]
C_D	drag coefficient [= $2F_{Drag}/\rho\, U^2_\infty A_p$]
C_L	lift coefficient [= $2F_{Lift}/\rho\, U^2_\infty A_p$]
C_i	model constants for i = 1, 1ε, 2, 3ε, μ
dt	time step [s]
F_{Drag}	aerodynamic drag force [N]
F_{Lift}	aerodynamic lift force [N]
F_X	aerodynamic force in x-direction [N]
F_Y	aerodynamic force in y-direction [N]
k	turbulence kinetic energy [m^2/s^2]
P_b	generation of turbulence kinetic energy due to mean velocity gradients
P_b	generation of turbulence kinetic energy due to buoyancy
p	pressure [N/m^2]
U_∞	uniform free stream velocity [m/s]
v	velocity [m/s]

Greek:

α	inclination angle of the windshield [°]
ε	dissipation of turbulent kinetic energy [m^2/s^3]
ρ	density [kg/m^3]
μ	dynamic viscosity [kg/ms]
μ_t	turbulent viscosity [= $\rho C_\mu k^2/\varepsilon$]

INTRODUCTION

Windshield wipers are developed to improve visibility during inclement weather and belong to standard safety equipment. A conventional wiping system of a vehicle consists of three components, namely motor and mechanism, wiper arm and wiper blade. The wiper arm transfers the movement to the wiper blade and cleaning is achieved by wiping water and dirt from the windscreen by a blade rubber. In order to wipe water and dirt from the windshield, the wiper blade should be forced onto the windshield with a specified force. The necessary down force is obtained by a spring mechanism within the arm. During the motion of the vehicle aerodynamic lift force opposite of the down force is acting on the wiper system. As the aerodynamic lift force increases, the necessary down force cannot be sustained to wipe the windshield. In order to minimize the aerodynamic lift force, various wiper geometries are proposed in this paper.

Clarke and Lumley (1960) studied problems associated with windshield wipers and observed wiping quality first on a flat plate and then on a vehicle up to a speed of 140 km/h experimentally. It is stated that wiping performance is reduced with increasing speed and they suggested the use of an airfoil to establish wiping performance.
Dawley (1965), investigated aerodynamic effects on automotive components experimentally including windshield wiper with the aim to drop aerodynamic forces acting on the wiper blade. They equipped the wiper with an airfoil and investigated the effect of airfoil's angle on lift forces. With increasing angle of incidence of the airfoil, lift forces can be reduced significantly to negative numbers.

Jallet et al., (2001) carried out numerical and experimental studies for conventional type of wiper blades with and without a spoiler and found satisfactory agreement between numerical and experimental results. They used a flat plate in their simulations for a free stream velocity of 144 km/h. They found out a total 4.4 N of lift force for wiper blade without a spoiler and observed that with a spoiler the lift force could be reduced to -4 N. They used k-ε turbulence model in their studies where they validated their results with experiments.

Billot et al., (2001) continued the former study of (Jallet et al., 2001) and investigated wiper system at mid wipe position on a car geometry numerically. They used conventional type wiper blade with and without a spoiler and tested new flat blade wiper. According to their work wiper blade without a spoiler has 9.8 N uplift force, one with the spoiler has 7.4 N uplift force and the new blade design has 4.9 N uplift force.

Gaylard et al., (2006) worked on conventional wiper blades and investigated flow properties and vortex structures at different wiping angles of a sport-utility-vehicle for a speed of 130 km/h. They carried out both numerical simulations to identify λ_2 iso-surfaces and experiments to capture flow structures on the windshield by flow visualizations.

Yang et al., (2011) investigated conventional wiper blades on a vehicle numerically. They investigated the variation of lift and drag forces at three different vehicle speeds 30, 50, 70 km/h and seven wiping angles varying between 0° and 90°. They found that the aerodynamic forces reach a peak at 30° on the driver side and 15° on the passenger side.

Lee et al., (2011) carried out numerical studies on new flat blade wipers on a vehicle. They investigated lift and drag forces for four different wiping angles at two different vehicle speeds 170 and 200 km/h and obtained consistent results concerning aerodynamic forces on driver and passenger side found by Yang et al.

In this numerical study modified wiper blade geometries are developed with the aim to reduce aerodynamic lift forces to improve wiping quality.

GEOMETRY AND BOUNDARY CONDITIONS

The 3D computational domain consists of the wiper blade, windshield and the hood of the car. The flow domain around the wiper blade is simplified to be able to compare different modifications and reduce computational cost. Only wiper blade is taken into account and the car geometry is assumed to be slightly curved surfaces representing the windshield and the hood of the car. Since aerodynamic forces acting on the wiper blade are of main interest, mesh is clustered in the vicinity of the wiper blade consisting of quadrilateral cells. Windshield has an inclination angle of approximately α = 35° with the horizontal plane. The angle between the windshield and hood of the car is approximately 158°. Wiper blade is positioned sufficiently far (415 mm) from the velocity-inlet surface and enough distance is given downstream of the wiper blade.

Figure 1 shows the simplified flow geometry and imposed boundary conditions. The vertical surface upstream of the wiper blade is prescribed with velocity inlet boundary condition (uniform free stream velocity of 240 km/h) and the upper surface of the domain and the vertical surface opposite to the inlet have pressure outlet boundary conditions. The remaining vertical surfaces on the right and left sides of the wiper blade are defined with symmetry boundary condition.

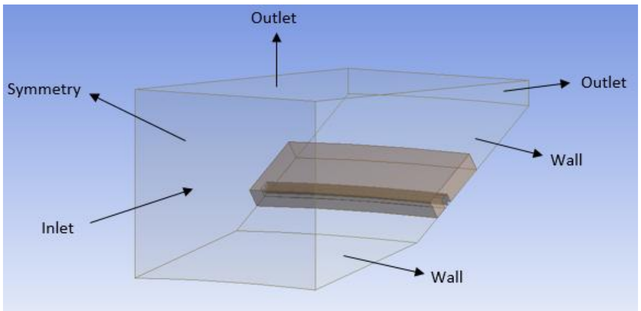

Figure 1. Geometry and imposed boundary conditions

Mesh Independence

To obtain reliable numerical results, several meshes with different number of elements are tested to show mesh-independence. Thus, the computed vertical (F_Y) and horizontal forces (F_X) and their resultant drag and lift forces are calculated for various mesh sizes as indicated in Table 1. After extensive grid checks have been performed for five different dense meshes, it is shown that a mesh with around 13.8 million elements is sufficient to obtain robust numerical results. The mesh is shown in Figure 2 where it is densely clustered in the vicinity of the wiper blade both in upstream and downstream directions. As a result, the flow structures and flow separation zones past the wiper can be modeled precisely and the consequent forces can be calculated correctly. Outer parts of the mesh consist of coarser elements to save computational time.

Table 1. Mesh independence results for 240 km/h

Mesh Size [millions]	F_X [N]	F_Y [N]	F_{Drag} [N]	F_{Lift} [N]	C_D	C_L
5.3	32.4	30.3	43.97	5.92	2.16	0.291
7.7	34.1	29.1	44.64	3.96	2.20	0.195
10.2	32.9	30.6	44.58	5.92	2.19	0.291
13.8	35.0	28.9	45.27	3.34	2.23	0.164
16	35.6	28.7	45.64	2.83	2.25	0.139

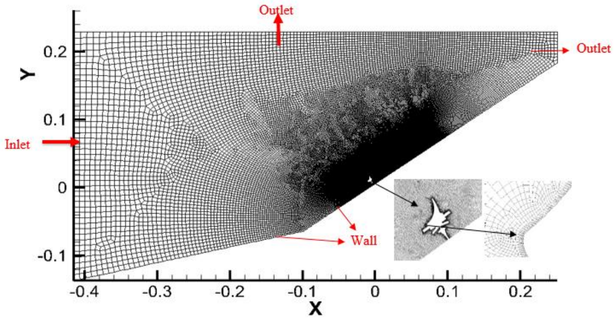

Figure 2. Selected mesh with nearly 13.8 million elements

NUMERİCAL MODEL

The flow over a windshield wiper and spoiler is simulated by a commercial flow solver (ANSYS-Fluent). The flow is simulated by the finite-volume based, incompressible, turbulent, steady flow solver. The flow is assumed to be still incompressible as the highest local Mach number is around 0.2, thus compressibility effects are ignored. In the numerical study by Jallet et al., (2001) k-ε turbulence model is used and it is shown that this turbulence model is capable of modelling the flow around wiper blades successfully.

SIMPLE algorithm is preferred with second order upwind schemes for momentum, turbulence kinetic energy and turbulence kinetic energy dissipation equations. The turbulent length scale is assumed to be the height of the spoiler which is 0.016 m for the original case.

Turbulence intensity is set to be 3%. The working fluid is air with constant thermo-physical properties where the density is ρ =1.225 kg/m^3 and the dynamic viscosity is μ =1.79x10^{-5} kg/ms.

Governing Equations

The governing equations for the problem are incompressible steady continuity and Navier-Stokes equations given in Equations (1) and (2) respectively. According to the turbulence model, transport of turbulent kinetic energy (k) and transport of turbulent kinetic energy dissipation (ε) are given in Equations (3) and (4) respectively where the model constants for the Realizable k-ε turbulence model are indicated in Eq. (5).

$$\nabla(\vec{v}) = 0 \qquad (1)$$

$$\nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \rho \vec{g} + \nabla \cdot \left[\mu \left(\nabla \vec{v} + \nabla \vec{v}^T \right) \right] \qquad (2)$$

$$\frac{\partial}{\partial x_j}\left(\rho k u_j\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\varepsilon - Y_M + S_k \qquad (3)$$

$$\frac{\partial}{\partial x_j}\left(\rho \varepsilon u_j\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k} C_{3\varepsilon} P_b + S_\varepsilon \qquad (4)$$

$$C_1 = \max\left[0.43, \frac{\eta}{\eta + 5}\right], \eta = S\frac{k}{\varepsilon}$$
$$S = \sqrt{2S_{ij}S_{ij}}, \; S_{ij} = \frac{1}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) \qquad (5)$$
$$C_{1\varepsilon} = 1.44; \; C_2 = 1.9$$

NUMERICAL RESULTS

Calculation of Aerodynamic Forces

Forces acting on a wiper geometry are shown in Figure 3. As given in Equation (6) aerodynamic lift and drag forces acting on the wiper and spoiler are resultant forces obtained from numerically calculated horizontal and vertical forces F_X and F_Y, thus depending on the inclination angle of the windshield (α) corresponding lift and drag coefficients can be calculated. These coefficients are obtained using uniform free stream velocity of the fluid (U_∞) and the projection area of the wiper.

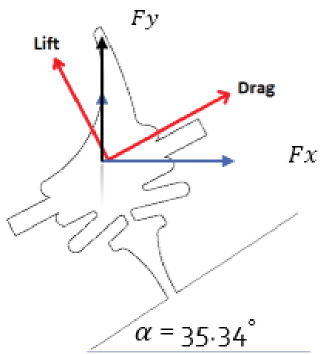

Figure 3. Aerodynamic forces acting on windshield wiper

$$F_{Lift} = F_Y \cos\alpha - F_X \sin\alpha$$
$$F_{Drag} = F_Y \sin\alpha + F_X \cos\alpha \quad (6)$$

Geometric Modifications

Basic geometric features of the wiper including the 'spoiler curvature', 'height of the spoiler' and the 'connection between the metal part and the spoiler of the wiper' are tried to be modified with the aim to reduce aerodynamic lift forces acting on the wiper and spoiler. The goal here is to increase the total pressure force above the spoiler and achieve the maximum pressure in a more desired position.

The modification of the wiper and spoiler is symbolized by Wiper_A_B_C where A denotes the spoiler curvature change, B denotes the height of the spoiler and C denotes the connection type of the metal part of the wiper with the spoiler respectively. Number '1' in this notation identifies the corresponding geometric feature of the original wiper to be optimized.

Effect of spoiler curvature on drag and lift forces

Numerical modelling of the external flow over the windshield wiper and spoiler reveals that there is a positive pressure field upstream of the wiper and negative pressure field downstream of the wiper. On the other hand, the flow separation zone on the spoiler influences the pressure distribution on the spoiler. This physical phenomenon leads to the thought that a certain geometric modification of the spoiler curvature will assist to reduce the separation zone and alter the effect of the pressure forces acting on the wiper. As a result, nine different spoiler curvatures are suggested (the first seven given in Figure 4) and their influence on aerodynamic forces is tabulated in Table 2. The modified wiper profile provides either increased or decreased lift forces compared to the original case where the drag forces remain almost the same. An intermediate modification of the spoiler curvature among those, number 4 is a useful design which reduces the lift force of the original case by almost one third.

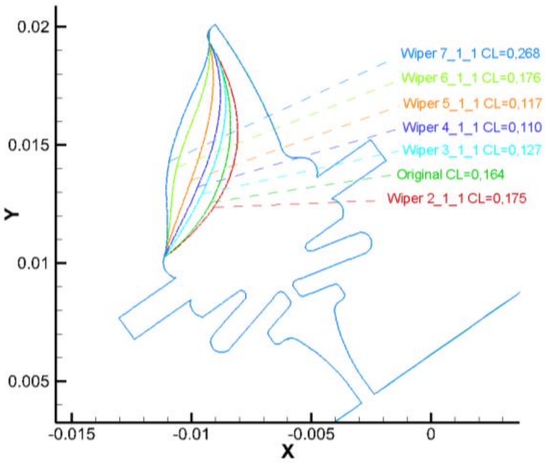

Figure 4. Modifications of the spoiler profile

Table 2. Numerical results for various spoiler curvature

Model	F_X [N]	F_Y [N]	F_{Drag} [N]	F_{Lift} [N]	C_D	C_L
Original	35	28.9	45.27	3.34	2.23	0.164
2_1_1	34.9	29.1	45.34	3.56	2.23	0.175
3_1_1	35.8	28.6	45.76	2.59	2.25	0.127
4_1_1	36.2	28.4	45.93	2.25	2.26	0.110
5_1_1	35.7	28.2	45.46	2.37	2.24	0.117
6_1_1	34.0	28.5	44.16	3.57	2.17	0.176
7_1_1	31.7	29.2	42.74	5.44	2.10	0.268
8_1_1	31.6	29.0	42.53	5.33	2.09	0.262

Based on the results tabulated in Table 2, a further design is proposed (see Fig. 5) where the spoiler is slightly swept back (case Wiper_9_1_1) which increases the frontal surface of the spoiler leading to a considerable reduced lift force according. Although there is no evident difference between pressure distributions of the cases Wiper_4_1_1 and Wiper_9_1_1, the increased frontal area plays an important role in reducing the lift forces as tabulated in Table 3.

Figure 6 indicates pressure and velocity distributions for the original case and proposed designs with best aerodynamic performances concerning reduced lift forces. The spoiler curvature is very effective in reducing the flow separation zone past the spoiler and as displayed in Fig.6. The proposed spoiler curvatures prevent the formation of a big vortex and smoothens the flow structure.

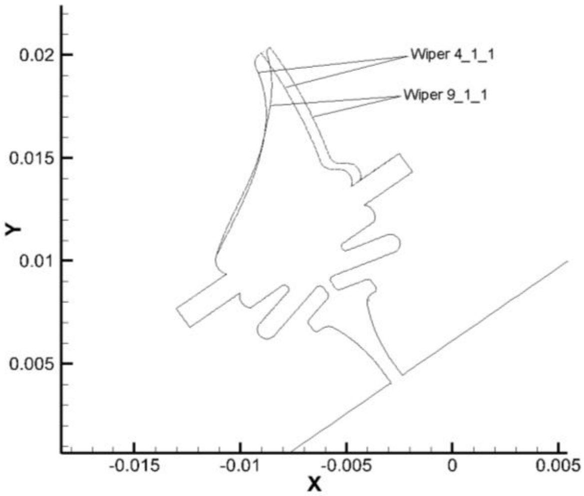

Figure 5. Proposed spoiler profiles with best performances

Table 3. Comparison of numerical results for the best spoiler profiles

Model	F_X [N]	F_Y [N]	F_{Drag} [N]	F_{Lift} [N]	C_D	C_L
Original	35	28.91	45.27	3.34	2.23	0.164
4_1_1	36.2	28.4	45.93	2.25	2.26	0.110
9_1_1	37.4	27.1	46.18	0.52	2.27	0.025

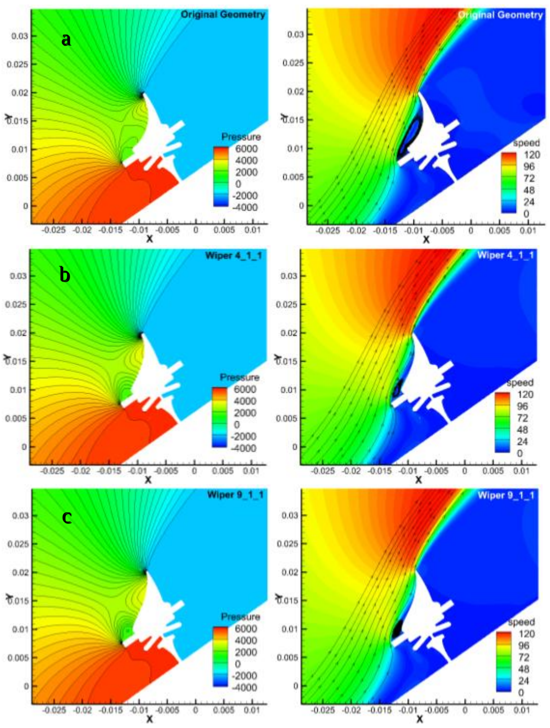

Figure 6. 1/2 sectional view of pressure contours in [Pa] (left column) and speed contours in [m/s] with streamlines (right column) for suggested profiles (a) Original, (b) Wiper 4_1_1, (c) Wiper 9_1_1

Effect of wiper height on drag and lift forces

An alternative way to decrease the lift forces drastically, is changing the height of the total wiper as can be seen in Figure 7. Four geometric modifications are suggested where elongating the wiper height assists to decrease the lift force even to negative numbers since the down force dominates over the lift force. As a result, shortening the wiper height increases the lift force as tabulated in Table 4. It should be mentioned that with an elongated spoiler, lower lift forces can be achieved where drag forces increase. With the elongation of the spoiler, the pressure above the spoiler increases considerably while the flow structures remain almost the same for all cases.

Effect of connection type on drag and lift forces

A new approximation in preventing the vortex structure occurring between the metal part of the wiper and spoiler is changing the connection type between them. Three connection types are suggested as given in Figure 8. All of the modifications are found to be useful in preventing the vortex structure between the metal part and the spoiler. However, modification Wiper_1_1_3 is the most effective case since it not only prevents the vortex occurring on the connection location but it also eliminates the main vortex structure on the top of the spoiler. As a result, this modification provides negative lift forces as tabulated in Table 5.

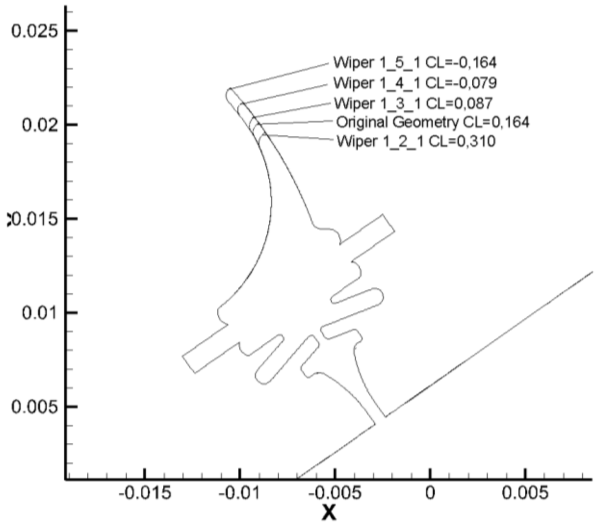

Figure 7. Modifications of the spoiler-heights

Table 4. Comparison of numerical results for various wiper heights

Model	Height [mm]	F_X [N]	F_Y [N]	F_{Drag} [N]	F_{Lift} [N]	C_D	C_L
1_2_1	16.0	30.4	29.0	41.6	6.08	2.13	0.310
Original	16.6	35	28.9	45.3	3.34	2.23	0.164
1_3_1	17.0	37.7	28.9	47.5	1.82	2.28	0.087
1_4_1	18.0	45.0	29.7	53.9	-1.75	2.45	-0.079
1_5_1	19.0	50.2	30.9	58.8	-3.82	2.53	-0.164

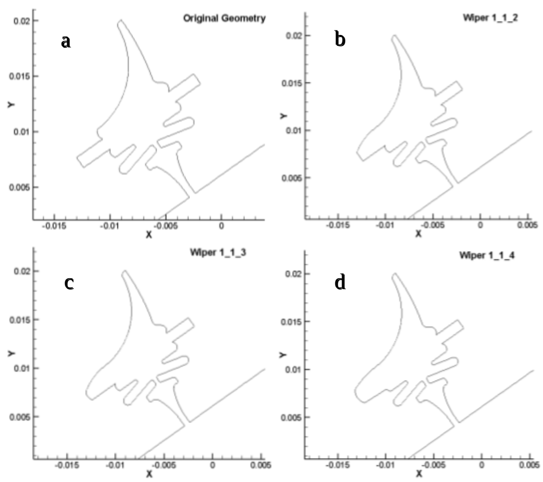

Figure 8. Geometries used in connection type modifications (a) Original, (b) Wiper 1_1_2, (c) Wiper 1_1_3, (d) Wiper 1_1_4

Table 5. Comparison of numerical results for various connection types

Model	F_X [N]	F_Y [N]	F_{Drag} [N]	F_{Lift} [N]	C_D	C_L
Original	35.0	28.91	45.27	3.34	2.23	0.164
1_1_2	38.0	27.5	46.92	0.46	2.31	0.022
1_1_3	40.0	26.7	48.02	-1.35	2.36	-0.067
1_1_4	38.4	27.4	47.17	0.14	2.32	0.007

Figure 9a and b show pressure and velocity distributions for the original and suggested connection types respectively. It can be seen in Fig.9b that both vortex structures on the connection and on the spoiler are eliminated in the new design. If the frontal connection between the wiper and the spoiler with sharp corners of the original case just near the stagnation point is rounded and transformed into a blunt body as suggested in modification three (Wiper_1_1_3), the stagnation point can be shifted further downstream and a smooth flow structure can be created.

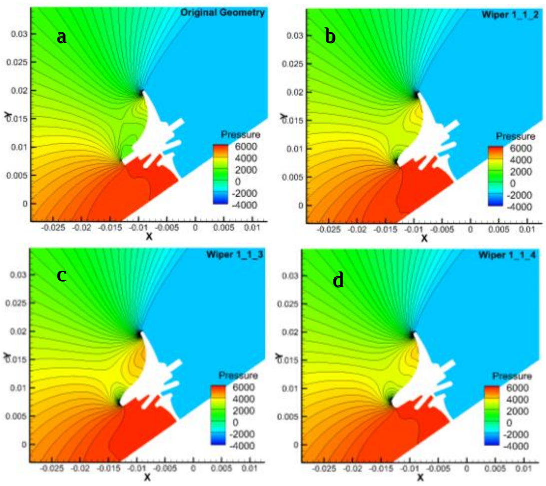

Figure 9a. 1/2 sectional view of pressure contours in [Pa] for suggested profiles (a) Original, (b) Wiper 1_1_2 (c) Wiper 1_1_3 and (d) Wiper 1_1_4

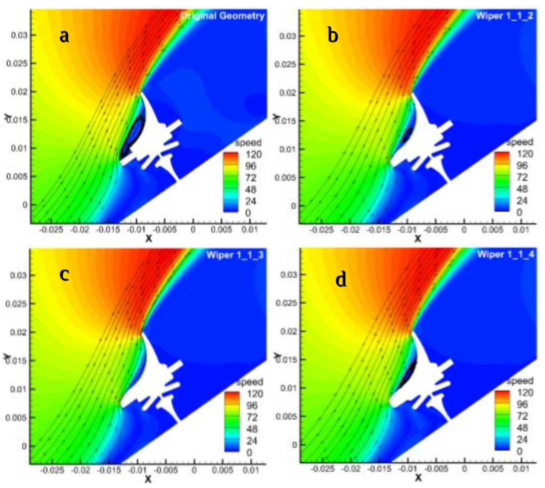

Figure 9b. 1/2 sectional view of speed contours in [m/s] for suggested profiles (a) Original, (b) Wiper 1_1_2 (c) Wiper 1_1_3 and (d) Wiper 1_1_4

Proposed Models

Based on previous numerical results, most effective cases are selected and instrumentally combined to increase down force acting on the wiper at a vehicle speed of 240 km/h.

The geometric modification concerning spoiler height revealed that the total spoiler height of 19 mm (Wiper_1_5-1) is effective in reducing lift force, however there was a big flow separation zone on the spoiler in this case, thus this design should be improved by increasing the spoiler curvature radius as in modification Wiper_2_5_1. In addition to this improvement, the blunt connection type (Wiper_1_1_3) is combined and the final model (Wiper_2_5_3) is created as shown in Figure 10. As Table 6 indicates, the down forces can be increased considerably by applying model 2_5_3.

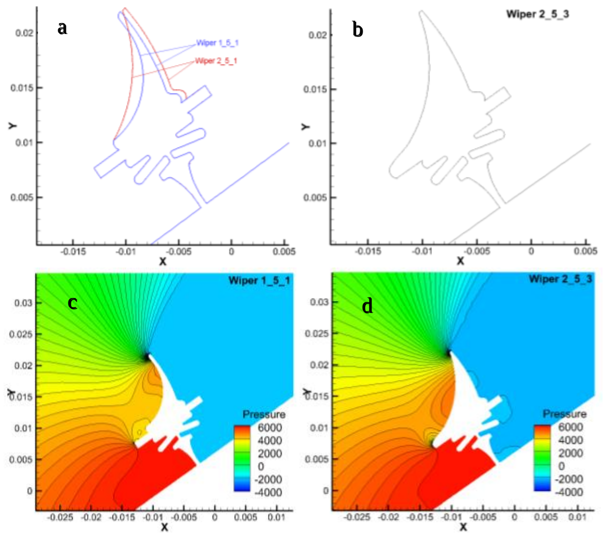

Figure 10. Proposed models: (a) improving profile of Wiper 1_5_1, (b) final model Wiper 2_5_3, (c) 1/2 sectional view of pressure contours in [Pa] for Wiper 1_5_1, (d) 1/2 sectional view of pressure contours in [Pa] for Wiper 2_5_3.

Table 6. Comparison of numerical results for proposed models with wiper height of 19 mm

Model	F_X [N]	F_Y [N]	F_{Drag} [N]	F_{Lift} [N]	C_D	C_L
1_5_1	50.2	30.9	58.77	-3.82	2.53	-0.164
2_5_1	51.4	29.6	59.04	-5.54	2.54	-0.238
2_5_3	53.6	28.8	60.36	-7.56	2.60	-0.325

CONCLUSION

In this numerical study, aerodynamic lift and drag forces acting on front windshield wiper blades are investigated by a finite-volume based, steady, turbulent flow solver (ANSYS-Fluent). To decrease aerodynamic lift forces, various wiper and spoiler geometries are suggested. The first modification which is changing the spoiler curvature assists to reduce or even prevent vortex structures on the spoiler. This modification results in increased pressure distribution along the spoiler and decreased lift forces for most cases. Second modification is changing the total wiper height. With the increase of the wiper height, aerodynamic lift forces can be decreased and as a result sufficient down force can be achieved to press the wiper onto the windshield. Third modification is changing the connection between metal part and the spoiler where just one of these modifications is capable of causing effective down force. Finally, most useful modifications are then combined with the aim to achieve relatively high down forces at high speeds.

ACKNOWLEDGEMENT

The authors are indebted to Ministry of Science, Industry and Technology of Turkey and Teklas Kaucuk A.S. for financial support through the project 0278-STZ-2013-2.

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