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Study of Air Flow through a Open Windows Bus Using OpenFOAM

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Abstract

Open window buses without air-conditioning are a major mode of urban and inter-city transport in most countries. High occupancy combined with hot and humid conditions makes travel in these buses quite uncomfortable. In this study air flow through a bus has been studied using openFOAM that could be the basis for low cost and eco friendly methods of increasing passenger comfort and possibly reduce drag. The aerodynamics of such a road vehicle has not been studied as previous investigations have been confined to vehicles with closed windows that present a smooth exterior to air flow. Here flow of air with open windows bus is studied at different operating speeds and results of drag force, lift force and power are compared with a close windows bus.

Keywords: openFOAM; Drag force; Lift force; Air –conditioning.

1. Introduction

The performance, handling, safety and comfort of an automobile are significantly affected by its aerodynamic properties. Low drag is important for good fuel economy and low emission. Increasing fuel prices and stringent regulations have made this long established relationship now widely acknowledged. But the other aspects of vehicle aerodynamics are no less important for the quality of an automobile, directional stability, wind noise stability, soiling of lights, windows and body, cooling of an engine, gearbox and brakes and finally heating, ventilating and air-conditioning of the passenger compartment. These all depend on the flow filled around and through the vehicle.

In terms of fluid dynamics, road vehicles are bluff bodies in very close proximity to the ground. Their external geometry is extremely complex. There are also internal ducts and recessed cavities and they communicate with the external flow. The flow over a vehicle is fully three-dimensional. Boundary layers are turbulent. Flow separation is common and may be followed by the reattachment. Large turbulent wakes are formed at the rear, and in many cases they interact with longitudinal vortices shade from the after body.

The bus is a major mode of public transport in most countries of the world, especially in urban areas. On per passenger per kilometre basis, the fuel economy is better and emissions are lower than either the automobile or motorized two-wheelers. Although viewed as essential, bus services and buses are generally looked down upon for a variety of reasons.

In this paper mainly concentration is given to numerical investigations carried out on flow of air on open window bus and comparing with closed window bus at speed range from 40km/hrs to 70 km/hrs. Here evaluation of coefficient of drag, coefficient of lift, drag force, lift force are done by OpenFOAM Software.

2. Methodology

The OpenFOAM (Open Field Operation and Manipulation) CFD toolbox is used to analyses the air flow through the geometries for both close and open window Bus. OpenFOAM has extensive range of features to solve anything complex fluid flow involving chemical reactions, turbulence, and heat transfer to solid dynamics and electromagnetics.

The Bus with various combination of close and open window is been modeled in Catia V5 R16 .Then The model is saved in .STL extension file. The domain is define in which Bus is to be placed. STL file is then linked to snappyHexMesh for generation of mesh. For the generation of initial flow we are using potentialFoam. By giving initial boundary conditions calculations are done by using simpleFoam and finally post processing is done by using ParaFoam.

The velocity and pressure distribution over the geometries are visualized and discussed.

3. Mathematical Formulation

3.1 Drag Force (F_D)

Aerodynamic drag force is the force acting on the vehicle body resisting its forward motion. This force is an important force to be considered while designing the external body of the vehicle, since it covers about 65% of the total force acting on the complete body. The drag coefficient is dimensionless quantity that describes vehicle aerodynamic resistance and is useful tool for comparing different vehicle shapes.The Aerodynamic drag force is calculated by the following formula:

$$F_D = \frac{1}{2}\rho V^2 C_D A \qquad (1)$$

where:

F_D=Drag Force
C_D =Drag Coefficient
A=Frontal Area Of The Vehicle
V=Wind Velocity
ρ=Air Density

Lift Force (F_L)

Lift force causes the vehicle to get lifted in air as applied in the positive direction, whereas it can result in excessive wheel down force if it is applied in negative direction. Engineers try to keep this value to a required limit to avoid excess down force or lift.

The formula usually used to define this force is written as:

$$F_L = \frac{1}{2}\rho V^2 C_L A \quad (2)$$

where:

F_L =Lift Force
C_L =Lift Coefficient
A=Frontal Area Of The Vehicle
V =Wind Velocity
ρ=Air Density

For aerodynamic simulations, it is important to obtain accurate results for the drag and lift values. In this section the drag and lift obtained by OpenFOAM are presented. The calculations are carried out for 200 iterations.

Case Details

In this section we are going to discuss the two cases .The cases discussed are as follow

1. Bus with close windows.
2. Bus with open windows.

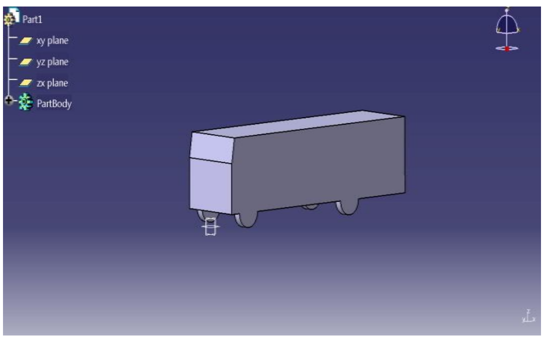

Fig. 1: Bus with all windows closed (case 1)

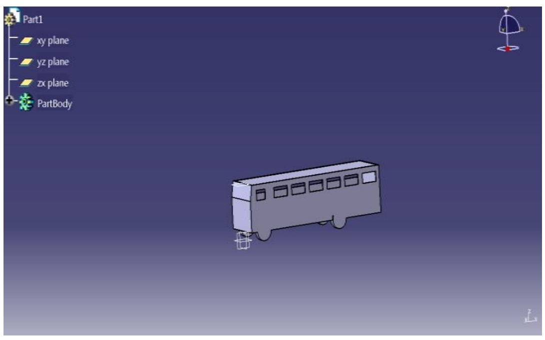

Fig. 2: Bus with all windows open (case 2)

Actual dimensions of Bus

Overall length of Bus-9.6m
Overall width of Bus–2.55m
Overall height of Bus–3.1m
Man clearance inside Bus–1.95m
Side windows dimension–0.55m×0.65m
Number of windows–14nos.

Computational set up

During this paper, different cases were considered in order to achieve the given goals. However, the simulation setup is the same for all the cases and hence the procedure is same for all cases. The first step required to begin a new simulation is to input the actual mesh into the file structure of OpenFOAM . The geometry is created in Catia V5 modeling software. It is then converted into the stereolithogrphy (STL) file.

Domain specifications

The computational domain is designed to lead to a free flow with neglectable blockage, which essentially means a box that consist of a inlet, a outlet, two sides, a roof and ground surface. When the geometry was defined in the creation of the computational mesh, all faces of the domain were assigned names. The names of the inlet and outlet planes (at x=0 and x=L) are front face and back face of domain as velocity inlet and pressure outlet respectively. The names of the planes at y=L, z=0, and z=L are outer wall as wall. The names of the model are bus as a wall.

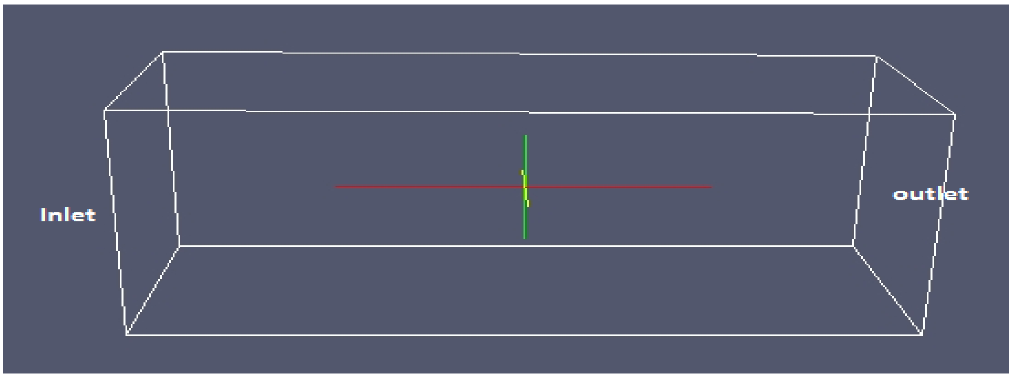

Fig. 3: Defining the Domain.

Mesh

Mesh is created using snappyhexmesh, OpenFOAM's native meshing tool. Utility snappyHexMesh is used to create high quality hex dominant meshes based on arbitrary geometry. It is controlled by parameters in the le snappyHexMeshDict. It can be executed in parallel. It preserves the feature edges, addition of wall layers. Details of mesh size is given in the following table 5.1

Table 1: Details of mesh size.

No. of Points	No. of Cells	No. of Faces	No. of Internal Faces
2185655	1986273	6157320	5963048

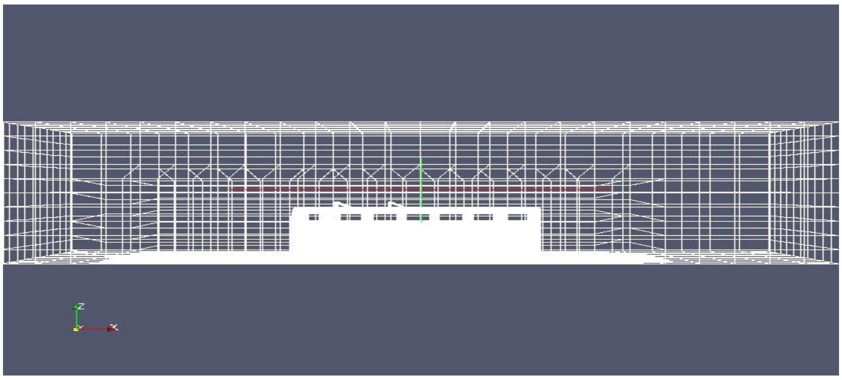

Fig. 4: Side view after meshing.

Boundary conditions

The tests were taken at different operating speed range such as 40km/hr, 45km/hr, 50km/hr, 55km/hr, 60km/hr, 65km/hr, 70km/hr. That means each geometry of Bus can pass through these speed range. For example consider case 1 when it pass through 40km/hr, velocity of the inlet boundary condition is set with value 40km/hr (11.11m/s) with temperature of 300K (26.85^{0}C). The outlet boundary condition is set to pressure outlet with gauge pressure of 0 pa. The density of the air is set as 1.125kg/m^3 and the viscosity of the air is 1.7894×10^{-5} kg/(ms).

Turbulence Modeling

All of the simulations took turbulence into account with the k ωSST turbulence model. This model was used for its ω proven reliability in separation zones and its ability to blend a good freestream model to a good boundary layer model.

Turbulence Intensity

The turbulence intensity, *I*, is defined as the ratio of the root-mean-square of the velocity fluctuations, u`, to the mean free stream velocity, u.

$$I = \frac{u'}{u}. \tag{3}$$

For internal flows the value of turbulence intensity can be fairly high with values ranging from 1%-10% being appropriate at the inlet. The turbulence intensity at the core of a fully developed duct flow can be estimated as:

$$I = 0.16Re^{-1/8} \tag{4}$$

For external flows the value of turbulent intensity at the freestream can be as low as 0.05% depending on the flow characteristics. We are considering turbulence intensity as 0.02%.

About Turbulence Length Scale

The turbulence length scale, *l*, is a physical quantity which represents the size of the large eddies in turbulent flows. Empirical relationship between the physical size of the obstruction (or characteristic length), *L*, and the size of the eddy, *l*, can be used to get an approximate length scale.

$$l = 0.07L \tag{5}$$

Turbulent Kinetic Energy(K) and Specific Dissipation Rate (ω)

Required Turbulent Kinetic Energy(K) and Specific Dissipation Rate (ω) can br find out from the following equations and table no.2 gives the (K) and (ω) for our selected operating speed range.

$$\text{Turbulent Kinetic Energy(K)} = \frac{3}{2}(UI)^2 \tag{6}$$

$$\text{Specific Dissipation Rate } (\omega) = \frac{K^{1/2}}{C\mu^{1/4} \times l} \tag{7}$$

Table 2: values of K and ω

Sr. No.	Speed in km/hr	Speed in m/sec	K	ω
1	40	11.11	0.074	0.258
2	45	12.5	0.0938	0.2908
3	50	13.89	0.1157	0.3231
4	55	15.27	0.1400	0.3554
5	60	16.67	0.1667	0.3878
6	65	18.05	0.1955	0.4199
7	70	19.44	0.4523	0.4523
8	80	22.22	0.2962	0.5169

4. Result and Discussion

In this section we are going to discuss following things...

1) Case 1 Bus with all windows closed is taken in consideration and tested at operating speed 60km/hr .There pressure contour, velocity contour, vector plot , front view, side view, and top view are pressure variation is observed.
2) Case 2 Bus with all windows open is taken in consideration and tested at operating speed 60km/hr. There pressure contour, velocity contour, vector plot , front view, side view, and top view are pressure variation is observed.

Case 1 Bus with all windows closed
Consider at speed of 60Km/hrs

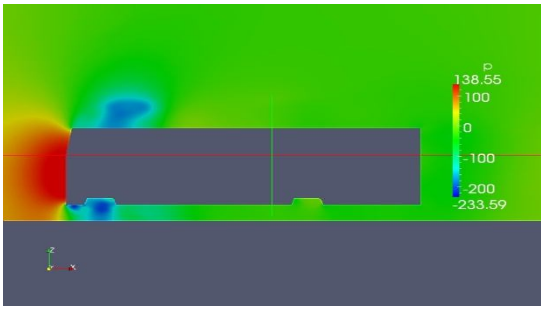

Fig. 6: Pressure Contour

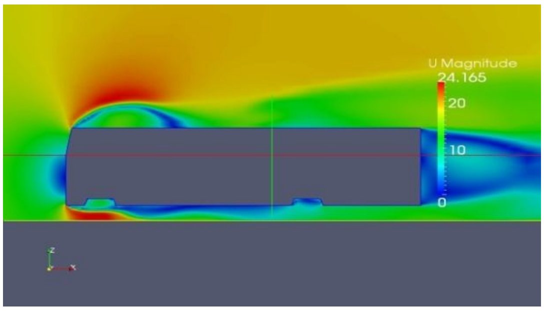

Fig. 7: Velocity Contour

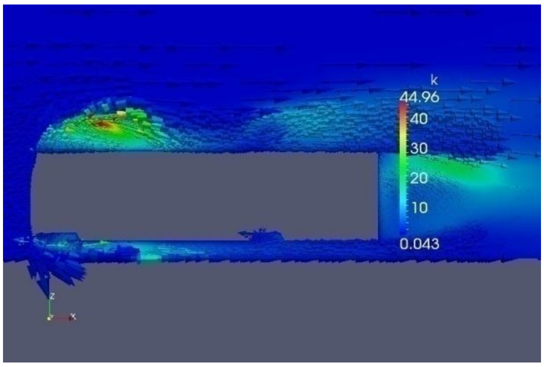

Fig. 8: Vector Plot For K.E.

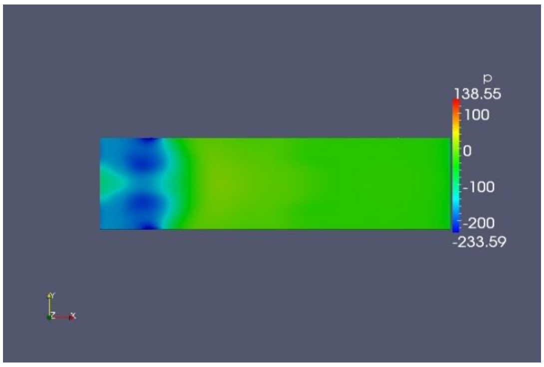

Fig. 9: Top view Pressure Variation

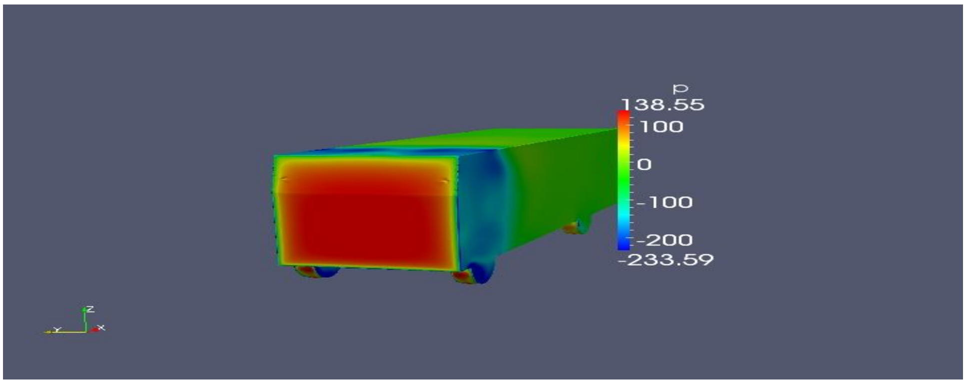

Fig. 10: Front Side Pressure Variation.

Observations of various contours

Pressure contour-It is obvious from all the pressure contours that there is a higher pressure concentration on the front of the bus. Particularly, the air slows down when it approaches the front of the bus and results in that more air molecules are accumulated into a smaller space. Once the air stagnates in front of the bus, it seeks a lower pressure area, such as the sides and top of the bus.

Velocity contour-We can conclude from all the velocity contours that air velocity is decreasing as it is approaching the front of the bus. then air velocity increases away from the bus front.

Vector plot for K.E. The red vectors has maximum kinetic energy while blue vectors has minimum. As the speed increase the magnitude of K.E also increases and intensity of Turbulence is also increases at top of Bus.

Bus Body pressure variation-From the front ,side and top view we can easily observe pressure variation, the pressure is maximum at the front and minimum in side and top of car.

Case 2 Bus with all windows Open
Consider at speed of 60Km/hrs

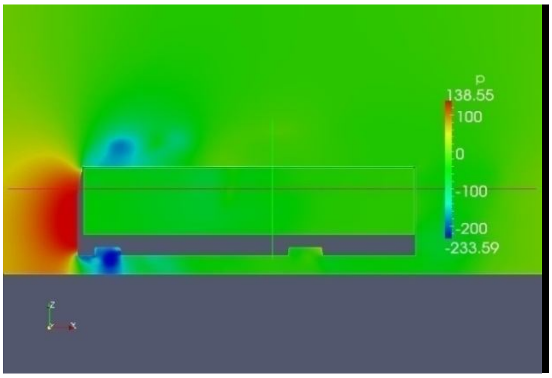

Fig. 11: Pressure Contour

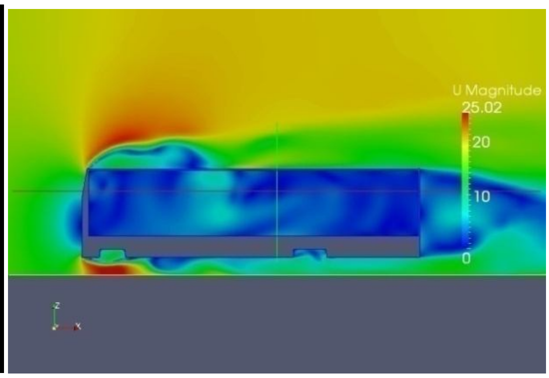

Fig. 12: Velocity Contour

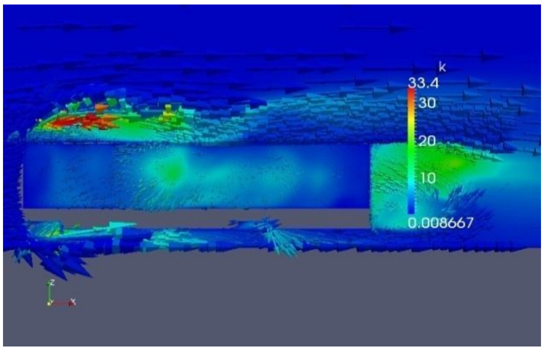

Fig. 13: Side view Vector plot for KE

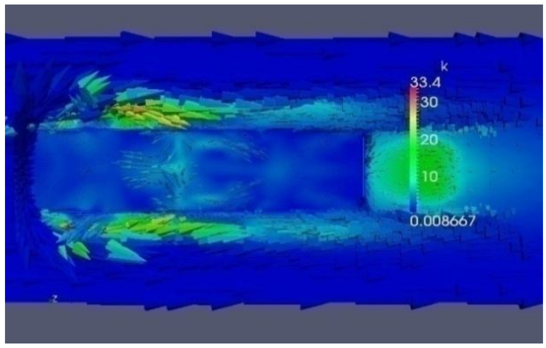

Fig. 14: Top View Vector plot For KE

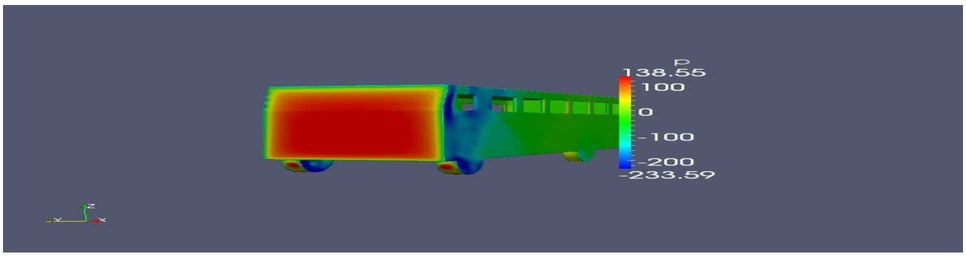

Fig. 15: Top view Pressure Variation.

Observations of various contours

Pressure contour-It is obvious from all the pressure contours that there is a higher pressure concentration on the front of the bus. Particularly, the air slows down when it approaches the front of the bus and results in that more air molecules are accumulated into a smaller space. Once the air stagnates in front of the bus, it seeks a lower pressure area, such as the sides and top of the bus. The pressure for open window bus is less as compare to close window bus.

Velocity contour-We can conclude from all the velocity contours that air velocity is decreasing as it is approaching the front of the bus. then air velocity increases away from the bus front.

Table 3: Comparison of Coefficient of Drag and Coefficient of lift for Case 1 and Case 2

Speed	CD Close	CD Open	CL close	CL Open
40	0.9997	1.1475	0.2326	0.2981
45	1.0004	1.1399	0.2326	0.2984
50	0.9998	1.1364	0.2331	0.298
55	0.9995	1.1362	0.2324	0.2973
60	0.9993	1.1369	0.2321	0.2966
65	0.9998	1.1318	0.2283	0.2951
70	0.999	1.1318	0.2299	0.2952

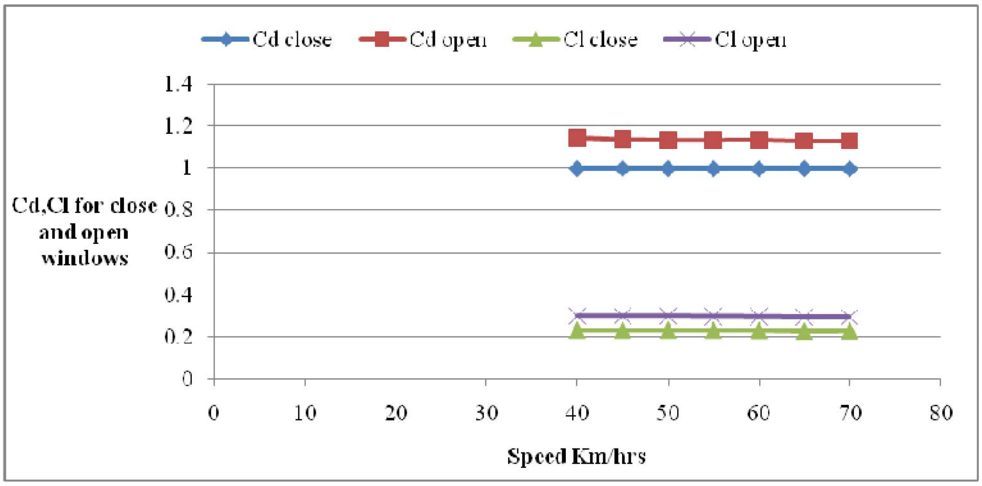

Fig. 16: Comparison of Coefficient of Drag and Coefficient of lift for Case 1 and Case 2

Vector plot for K.E. The red vectors has maximum kinetic energy while blue vectors has minimum. As the speed increase the magnitude of K.E also increases and intensity of Turbulence is also increases at top of Bus. From side view vector plot magnitude of K.E for open window bus is less compared to close window bus. From top view vector plot magnitude of K.E is more than side view vector plot which indicates that air try to enter through the windows present at front and proceed to the downstream.

Bus Body pressure variation-From the front ,side and top view we can easily observe pressure variation, the pressure is maximum at the front and minimum in side and top of car.

Table 4: Comparision of Drag force for Case 1 and Case 2

Speed Km/hrs	Drag Force N close	Drag Force N open
40	548.67	629.79
45	695.04	791.96
50	855.23	972.08
55	1036.29	1178.02
60	1234.78	1404.81
65	1448.41	1639.63
70	1678.72	1901.88

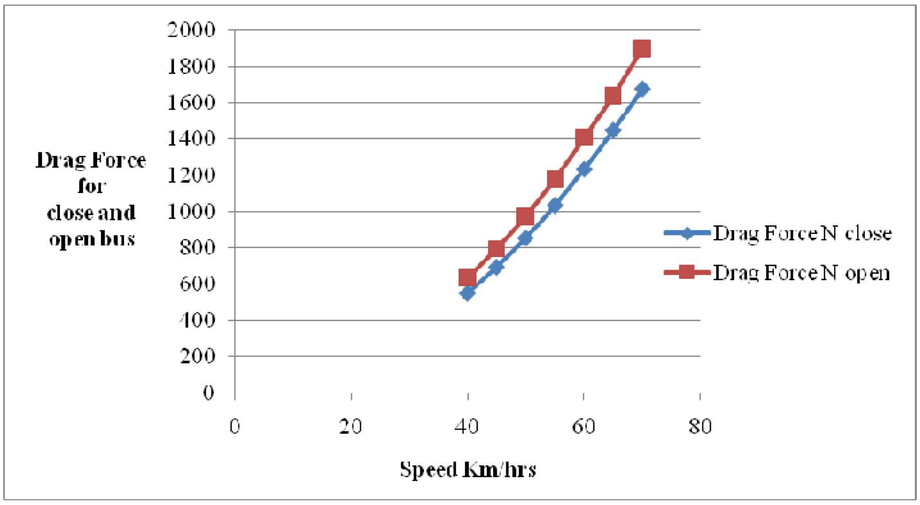

Fig. 17: Comparison of Drag Force for Case 1 and Case 2

From the above graphs it is concluded that Magnitude of Coefficient of Drag for close window is less than magnitude of Coefficient of Drag for open window Bus. Coefficient of Drag for close window remain constant while Coefficient of Drag for open window Bus decreases and remain constant after certain speed. Magnitude of Coefficient of Lift for close window is less than magnitude of Coefficient of Lift for open window Bus and fluctuate with speed. For close Bus it will be necessary to install Air conditioner unit for passenger comfort which will again leads to more fuel consumption. So it is better to have open windows Bus in city for low operating speed rather than close bus with air conditioner.

5. Conclusion

The studies show that flow inside a bus with open windows is complex. The size and nature of the recirculation regions on the side and top are different. For close Bus it will be necessary to install Air conditioner unit for passenger comfort which will again leads to more fuel consumption. So it is better to have open windows Bus in city for low operating speed rather than close bus with air conditioner. This study forms a basis for further investigations on the effects of roof and side vents, fans and blowers, window design and setting changes, thermal effects, and passenger loading, as well as less expensive methods for air conditioning. The study can also be extended to road dust entrainment and fire safety of such buses.

6. Conflicts of interests

The authors hereby declare that there is no issue of any type of conflict of interests in any manner.

7. Acknowledgment

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