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EXPERIMENTAL STUDY OF THE INTERACTION BETWEEN TWO VEHICLES: THE EFFECT OF THE INTER-VEHICLE DISTANCE ON THE RECIRCULATION ZONE

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ABSTRACT

Air quality is a key issue worldwide. Cars are a significant contributor to pollutant emissions. Ultrafine particles emitted from the tailpipe disperse in the wake of the vehicle. They can infiltrate the following vehicle exposing drivers and passengers to potential high concentrations of pollutants. Once released in the atmosphere, the particle dynamics is strongly affected by the flow topology in the near wake of the emitting vehicle, the recirculation region playing a key role. This has been demonstrated for a single vehicle. The present paper aims at extending this result to the interaction between two vehicles with different inter-vehicle distances. An experimental study was undertaken in the wind tunnel at ESTACA. Velocity measurements were conducted using a 2D LDV system. Reduced-scaled Ahmed bodies were used, the leading one having different rear slant angles (φ=0°, 25°, 35°). The inter-vehicle distance ranges from d=0.93h (h being the height of the vehicle) to d=5.56h. Mean and turbulent flow properties between vehicles were described. A detailed discussion is proposed regarding the effect of the rear slant angle of the leading vehicle on the wake flow. We show that d influences the size of the recirculation zone, which volume strongly influences particle dispersion. We identify a critical distance above which the leading vehicle has no more influence on the following one. In terms of application, this study can lead to a better understanding of how pollutants emanating from the tailpipe can disperse and infiltrate a following vehicle in real traffic conditions.

KEY WORDS: Ahmed body, inter-vehicle distance, recirculation region, wind tunnel, turbulence

1. INTRODUCTION

Transportation modes contribute to the worsening of air quality by emitting ultrafine particles (UFP) and gases such as NO_x and CO_2. Altogether, these pollutants have strong adverse health effects and participate in the global warming. When released from the tailpipes of automobiles, they can either disperse in the atmosphere or infiltrate the following vehicles. In urban environments, pedestrians and vehicle occupants are then exposed to high levels of pollution. This is especially noticeable in car cabins, which are a microenvironment. It has become crucial to get a better understanding of the dynamics of the pollutants when released in the surrounding air and to identify the governing parameters to prevent their infiltration in cars. In a recent study, Rodriguez [1] has conducted an intensive campaign to analyse the dispersion of UFP in the wake of a single vehicle. Using simplified car models (Ahmed bodies with different rear slant angles φ) at a reduced scale, he identified the volume of the recirculation region as well as the longitudinal vortices appearing for φ=25° as key factors influencing the dispersion of these UFP. In the present paper, using the same experimental facilities, we go further and work with two vehicles models. We aim at discussing the influence of the inter-vehicle distance on the recirculation region. Three situations were experienced corresponding to three rear slant angles (φ=0°,

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25° and 35°) for the leading vehicle, the following one being always the same (φ=0°). In the next part, the experimental facilities and measurement technique are presented. Then, the results are presented in terms of mean and turbulent velocity fields. In the last part, conclusions and future works are detailed.

2. EXPERIMENTAL CONDITIONS AND MEASUREMENT TECHNIQUES

The experiments were conducted in the wind tunnel at ESTACA West Campus in Laval (France). It is an open circuit. The test section has a length L_{wt}=1 m, a width l_{wt}=0.3 m and a height h_{wt}=0.3 m. The maximum speed of the air flow is 40 m/s. The convergence ratio at the entrance is 1:16. The turbulence level for an empty test section is below 1% out of the boundary layer. Walls are made of transparent altuglass allowing the use of optical devices such as LDV for velocity measurements.
For the car models, we used simplified geometries known as Ahmed bodies [2]. The wake flow is governed by the rear slant angle φ. Indeed, the rounded front face of the model prevents flow detachment. In this region, the boundary layer develops in a less chaotic way. As a consequence, the influence of the front part of the model is weaker. Furthermore, the main structures developing in the wake of the Ahmed bodies are similar to those appearing in the wake of real square-back and fastback cars (these models being predominant in the vehicle fleet). Lastly, the effects of singularities such as mirrors are neglected with Ahmed bodies.
During the experiments, two models are placed in the test section. The leading vehicle (LV) had different rear slant angles φ (φ=0°, 25° and 35°) while φ is always 0° for the following one (FV). All car models were 0.196 m in length (L), 0,054 m in height (h) and 0.073 m in width (l). The aspect ratio AR defined as $AR=(h*l)/(l_{wt}*h_{wt})$ was 4.8%. Thus, no wall effect were considered. The position of the LV was always at 3.9h from the test section entrance. Additional information regarding the experimental setup are given by Shen [3].
To assess the effect of the distance between the two vehicles (d) on the recirculation region, six configurations were studies: d/h=0.93, 1.85, 2.78, 3.70, 4.63 and 5.56, d being the distance between the rear face of the LV and the front of the FV. Ahmed bodies were aligned on the centreline of the test section. x, y and z refer to the horizontal, transversal and vertical directions, respectively. The origin was taken on the rear face of the leading vehicle, centreline of the channel at the bottom of the vehicle (Fig 1). Four stilts per vehicle were used to fix them on the bottom of the test section. Their height was h_s=15 mm and their diameter was d_s=5 mm. The dimensionless ground clearance (h_s/h) was 0.28. The inflow velocity U_0 was chosen according to a kinetic similitude assuming a vehicle in an urban environment (U_0=14 m/s). Based on the height of the vehicle, the Reynolds number was approximately 49 500 [1].
The velocity fields were measured using a 2D LDV system mounted on a 3D displacement table. This system was computer-controlled. The software for the data acquisition was provided by DANTEC (BSA Flow). Optical characteristics of the system are detailed in [1]. According to a preliminary calibration, acquisition lasts 90 sec and a maximum of 5000 samples were recorded. Measurements were made at the centreline of the test section (y=0). In the vertical direction, the step between two measuring points was always 5 mm while it was either 10 mm or 20 mm in the horizontal direction depending on the distance d between the two vehicles. The acquisition mode is defined as IR (Individual Realization). Data analysis was made according to the ITTT method developed by Rodriguez et al. [4]. Figure 1 presents the experimental setup. The LV is the black one. On the bottom right of the figure, the LASER probe is visible. The two red dots above the following vehicle correspond to two LASER beams for the measurement of the horizontal component (U) of the velocity.
Results are divided in two parts corresponding to the mean and turbulent flows. They are given as dimensionless values, the reference length and velocity being h and U_0, respectively.

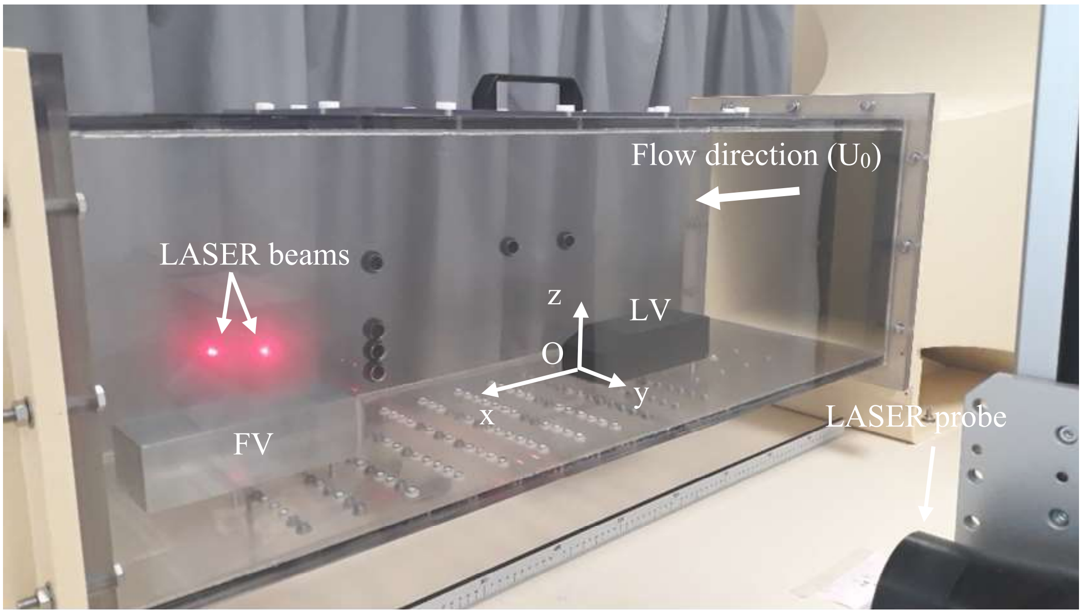

Fig. 1 Experimental set up (LV: Leading Vehicle; FV: Following Vehicle)

3. RESULTS

3.1 Mean flow

Figure 2 presents the velocity vector fields coupled with the magnitude of the velocity for the six inter-vehicle distances, the LV being the squared back model (φ=0°). The black line corresponds to the boundary of the recirculation region. From the top to the bottom, D=d/h=5.56, 4.63, 3.70, 2.78, 1.85 and 0.93. The same results were obtained for the two other configurations (LV being φ=25° and 35°). For all experimental conditions, the length of the recirculation region (L_r) was determined as well as the positions of the centres of the upper and lower vortices, which develop in the close wake. For D>2.78, L_r/h remains almost constant when the LV has a rear slant angle of 0° and 35°. Its length is in agreement with the result provided by [1] and [4] for a single vehicle. When the rear slant angle is 25°, L_r/h is stable when D>1.85. This is explained by the attachment of the flow on the slant in this latter case. The presence of the FV is depicted on Figure 2 by the blue areas on the right part of the figure. A flow separation occurs in front of the FV characterized by a decrease in the velocity magnitude. This is also shown from the streamlines. For the LV with a rear slant angle φ=35°, we showed that the centres of the upper and lower vortices were much more stables compared to the two other experimental conditions and quite similar to those obtained for a single vehicle [1]. By looking at the horizontal (respectively vertical) velocity fields, a symmetric (respectively antisymmetric) shape with respect to Z=0.5 is noticed when the square back model is the LV. A strong downwash effect is observed when the LV has a rear slant angle of 25°, which is associated with the shortest recirculation length (L_r/h~0.55 to 0.6 when D≥1.85). When the LV has φ=35°, an intermediate situation is obtained (L_r/h~1.10 when D≥2.78).

It is worthwhile to note that, for the largest inter-vehicle distance (D=5.56), our results were compared to [1], [4], [5] and [6] showing strong agreements for both mean and turbulent values. This confirmed that our experimental setup and data analysis techniques were robust. It means also that our experiments were also repeatable.

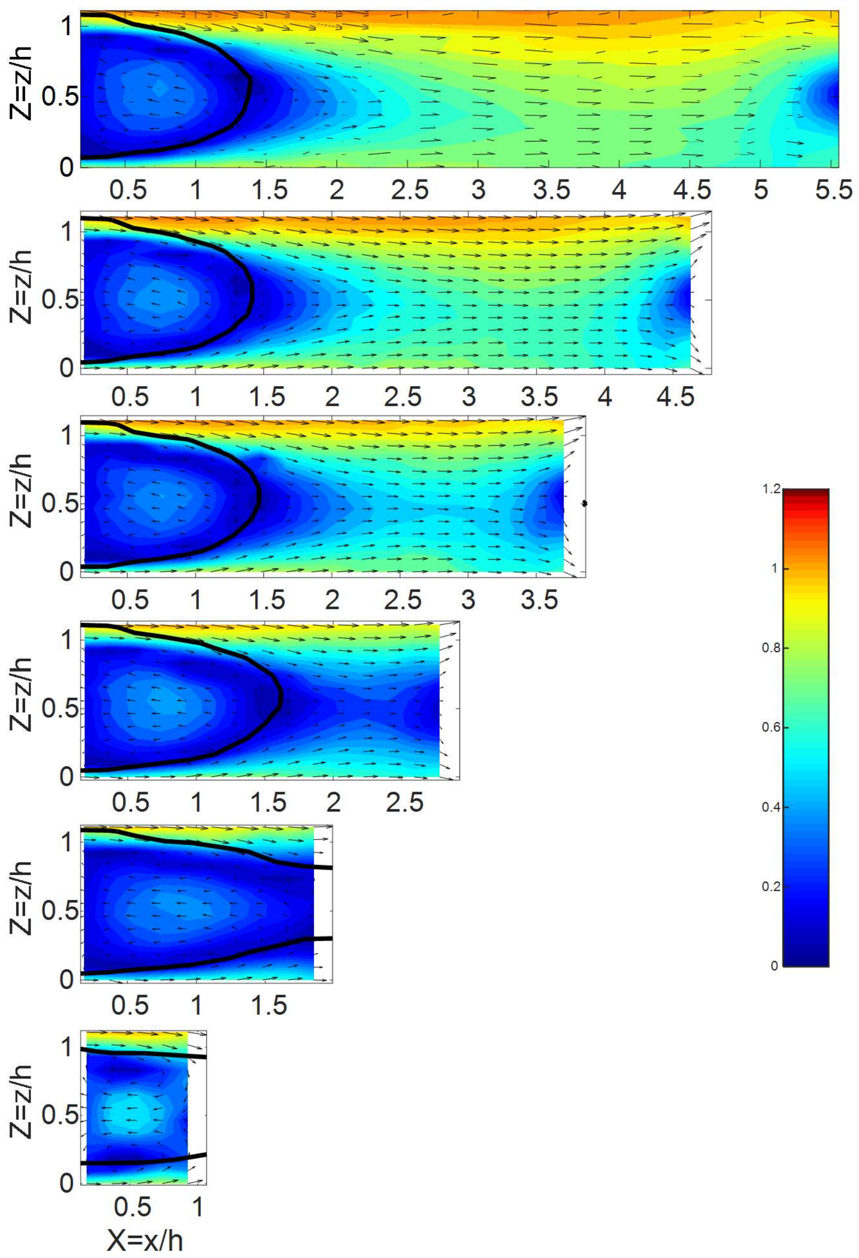

Fig. 2 Velocity magnitude and velocity vectors for φ=0° for the 6 inter-vehicle distances D

3.2 Turbulent fluctuations

For the turbulent part of the flow, different behaviors were depicted depending on the rear slant angle of the leading vehicle. When the rear slant angle of the LV is φ=0°, the streamwise turbulent intensity (I_x) is almost symmetric with respect to Z=0.5 for all D even if the highest levels are preferably found in the upper shear layer (~28% vs ~24%) and around the boundary of the recirculation region. When φ=25° and 35° for the LV, there is no more symmetry. Overall, the highest levels are measured in the lower shear layer (~25/30% vs ~12/18%) close to the bottom of the wind tunnel. In terms of dimensionless turbulent kinetic energy (TKE), the field is symmetric when φ=0° (for the LV) and D=0.93 with highest values of ~6/7% for X~0.5-0.6. For other D, the highest turbulent activity is found in the upper shear layer (~6%) at X~1. For φ=25° and 35° (LV), peaks are located in the lower shear layer (~5 to 10% at X~0.5) while it does not exceed 4% in the upper shear layer. Regarding the dimensionless Reynolds shear stresses (RSS), positive (respectively negative) values are found in the lower (respectively upper) part of the flow. For φ=0° (LV), the 2D map is almost symmetric with respect to Z=0. Nevertheless, magnitude were larger in the upper part of the wake flow (~0.03 to ~0.04) compared to the lower part (~0.02). For D=0.93, magnitudes are comparable (~0.03). For φ=25° and 35° (LV), negative dimensionless Reynolds shear stresses are observed in the major part of the wake flow (~-0.02 to -0.01) while positive values were larger in magnitude (~0.02 to 0.04) but spread over a smaller area.

4. CONCLUSION AND FUTURE WORKS

Following the previous work of Rodriguez [1] with a single vehicle, we present an experimental study on the interaction of two simplified car models (Ahmed bodies). We considered the flow topology in the wake of the leading vehicle. The influence of the inter vehicle distance is analyzed for three different rear slant angles of the leading vehicle (φ=0°, 25° and 35°). Critical distances were determined based on the recirculation length above which the influence of the second vehicle becomes less significant. This preliminary work will serve as a starting point for new study aiming at characterizing the dispersion of particles in the wake of a leading vehicle when interacting with a second one. Indeed, [1] identified the size of the recirculation region as a key parameter affecting UPF dispersion. Applications are related to air quality issues in transportation systems such as infiltration of UFP in car cabins.

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