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Effect of rear slant angle on flow structures, and pollutant dispersion and concentration fields in the wake of the studied model vehicle

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A B S T R A C T

Experimental investigations of the interaction effect of rear slant angle (i.e., $\alpha = 25°$ and $60°$) and heated air exhaust jet condition (i.e., U_j and T_j) on flow structures, and pollutant (i.e., scalar) dispersion and concentration fields in the near-wake region of two simplified scale-model vehicles at Reynolds number $Re_h = 5.8 \times 10^4$ were performed in a closed-circuit wind tunnel using laser Doppler anemometry (LDA) and the cold wire thermometry. The results show that the behaviors of flow structures and pollutant dispersion in the near-wake region of the studied model vehicles are highly dependent on the interaction effect of U_j/U_∞ and α. For the low value of U_j/U_∞ (i.e., the driving mode from 30 km h^{-1} to 70 km h^{-1}), the wake structure of the two studied model vehicles is almost similar to the case without introducing the vehicular exhaust jet flow, $U_j/U_\infty = 0$, but the scalar concentration is neither sent straight to the wake region nor trapped by the recirculation zone. For higher value of U_j/U_∞ (i.e., the driving mode of 10 km h^{-1}), the jet flow perturbation along the central plane of the vehicular exhaust tailpipe causes the disappearance of the lower vortex in the recirculation zone for the studied model vehicle **A** ($\alpha = 25°$) while it causes the stretching of the recirculation zone for the studied model vehicle **B** ($\alpha = 60°$). The contaminant is mainly straight trajectory along its jet exhaust flow axis. Outside the recirculation zone, the flow field becomes symmetrical and its flow structure depends only on the rear slant angle of the studied model vehicle. The scalar concentration field of the studied model vehicle **B** is characterized by a two-dimensional flow structure whatever the studied driving modes are. The distribution of the mean normalized temperature excess field (i.e., scalar concentration field) conforms to the velocity vector field for both studied model vehicles. For the studied model vehicle **A**, the scalar concentration is drawn to the edge of the trailing vortex at the vehicular exhaust jet side. This phenomenon causes a significant reduction of the scalar concentration level whatever the studied driving modes are.

1. Introduction

Motor vehicle emissions are the major source of air pollution in most urban cities [1]. The exhaust pollutant dispersion from motor vehicles is of particular interest with respect to the improvement of air quality in urban cities. It causes serious impact on urban air quality and public health. Over the decade, the major attention of researchers has mainly been focused on a global approach by the modelling of vehicular exhaust emissions in urban areas such as urban street canyon or near a roadway [2–5]. Pollutant concentration measurements on particle and gaseous emissions have also been performed within a busy urban street canyon [6] and from on-road motor vehicles [7,8].

On the contrary, much less attention has been paid to the studied pollutant in the near-wake region of a ground vehicle. It is vital that the flow structures and pollutant dispersion in the near-wake region of a ground vehicle, and its response to the wind speed and direction be known for short time and distance scales. In general, the interaction between the vehicle wake and vehicular exhaust jet plume dominate the pollutant dispersion which appears by a more or less fast dilution of gaseous/particle emissions in the surrounding medium. These studies not only include the effects of turbulence diffusion, vortex recirculation, heat transfer, dilution and species transport, but also microphysico-chemical processes such as coagulation and chemical reactions [9–14]. This type of pollutant dispersion behaviour not only has direct impact on human health, particularly on the drivers, bicyclists, pedestrians, people working nearby and vehicle passengers [15–17], but also constitutes a major fraction of the total pollutant dispersion [18].

Among these few studies which have tackled scalar dispersion in the vehicle wake, Chan et al. [15] developed a two-dimensional pollutant dispersion numerical model based on the joint-scalar PDF approach and a k–ε turbulence model to simulate the initial

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Nomenclature

B width of a real on-road vehicle, m
D diameter of a real on-road vehicle exhaust tailpipe, m
H height of a real on-road vehicle, m
I_{ii} turbulent intensity in i component
I_{uvw} total turbulence intensity
$I_{T'_{max}}$ normalized temperature intensity, $I_{T'_{max}} = \sqrt{\overline{T'^{*2}_{max}}}/\overline{T'_{max}}$
L length of a real on-road vehicle, m
Re_j vehicular exhaust jet Reynolds number in Eq. (1)
Re_h Reynolds number, $Re_h = U_\infty h/\nu$
St_p Stokes number, $St_p = \tau_p/\tau_u$
T_j initial temperature excess difference from an exhaust jet, K
T_∞ or T ambient temperature or temperature excess with respect to ambient, K
$\overline{T^*}$ normalized mean temperature excess, $\overline{T^*} = \overline{T}/T_j$
$\sqrt{\overline{T'^{*2}_{max}}}$ normalized maximum standard deviation of the temperature, $\sqrt{\overline{T'^{*2}_{max}}} = \sqrt{\overline{T'^2_{max}}}/T_j$
U streamwise velocity in x direction, m s^{-1}
U_j vehicular exhaust jet exit velocity, m s^{-1} in Eq. (2)
$U_{\text{real vehicle}}$ on-road real vehicle speed, m s^{-1}
U_∞ free stream velocity, m s^{-1}
$\overline{U^*}$ normalized streamwise velocity, $\overline{U^*} = \overline{U}/U_\infty$
$\dot{m}_{j(\text{real vehicle})}$ mass flow rate of a vehicular exhaust gas jet from a real on-road vehicle, $\dot{m}_{j(\text{real vehicle})} = \rho_{\text{exhaust gas}} U_{j(\text{real vehicle})}\left(\frac{\pi D^2}{4}\right)$, kg s^{-1}
$\dot{m}_{j(\text{model vehicle})}$ mass flow rate of a vehicular exhaust hot air jet from a scale-model vehicle, $\dot{m}_{j(\text{model vehicle})} = \rho_{\text{hot air}} U_{j(\text{model vehicle})}\left(\frac{\pi d^2}{4}\right)$, kg s^{-1}
$\dot{m}_{\text{real vehicle}}$ mass flow rate of a real on-road vehicle, $\dot{m}_{\text{real vehicle}} = \rho_{\text{ambient air}} U_{\text{real vehicle}}(\text{BH})_{\text{real vehicle}}$, kg s^{-1}
$\dot{m}_{\text{model vehicle}}$ mass flow rate of a scale-model vehicle, $\dot{m}_{\text{model vehicle}} = \rho_{\text{ambient air}} U_\infty (\text{bh})_{\text{model vehicle}}$, kg s^{-1}
b width of a scale-model vehicle, m
d diameter of a scale-model vehicle exhaust tailpipe, m
h height of a scale-model vehicle, m
l length of a scale-model vehicle, m
u relative to the streamwise velocity
v relative to the transversal velocity
w relative to the spanwise velocity
x streamwise coordinate, m
y transverse coordinate, m
z spanwise coordinate, m

Greek symbols
α rear slant angle of scale-model vehicle, °
ρ density, kg m^{-3}
τ_p particle response time, s
τ_u turbulent time scale of the fluid flow, s
ν kinematic viscosity of fluid, m^2 s^{-1}

Other symbols
$*$ dimensionless
$\overline{A}$ mean value of the variable A
rms root mean square

dispersion process of nitrogen oxides, temperature and flow velocity distributions. Wang et al. [17] developed a three-dimensional numerical model based on the Reynolds-averaged Navier-Stokes equations coupled with a k–ε turbulence model to simulate the initial dispersion process of carbon monoxide distributions from a vehicular exhaust plume. This numerical model was validated for the measured data obtained from two types of diesel-fuelled vehicles under both high and low idling conditions. Richards et al. [19] studied numerically and experimentally the influence of the near-wake on pollutant dispersion downstream a fastback model. The numerical simulations of the near-wake flow field and gaseous dispersion were performed using k-ε models. Recently, Dong and Chan [20] and Chan et al. [21] have investigated comprehensively the three-dimensional flow structures and pollutant dispersion (i.e., scalar transport) in the near-wake region of a light-duty diesel vehicle for different rear slant angles (i.e., $\alpha = 25°$ and 60°), stationary (i.e., low and high idling modes) and moving (i.e., vehicle speed mode) vehicle conditions, and ambient wind conditions (i.e., wind speed and direction) within the urban road microenvironment using the large eddy simulation (LES) approach. Gosse et al. [16,22] have studied experimentally the passive scalar diffusion within the near-wake of an Ahmed model [23] (with a rear slant angle of 5°, 25° or 40°) in using heated air injected through a small pipe on one side of the model base. The cold wire thermometry measurements showed that the thermal field is strongly influenced by the rear slant angle. Kanda et al. [24] have recently investigated the dispersion behavior of exhaust gas from a reduced-scale model vehicle (i.e., a passenger car and a small-size truck). The results obtained by the flame ionization detector indicated the two vehicles promoted dispersion in the horizontal and the vertical direction, respectively. The wake field was analyzed by particle image velocimetry (PIV), and the distribution of the mean and the fluctuation flow fields was found to conform with the concentration field of the exhaust gas. However, these recent research works have only studied constant vehicular exhaust jet exit velocity from the vehicle(s) while the actual vehicular exhaust jet exit velocity depends on the real-world on-road vehicle engine/driving condition.

The aim of this paper is intended to study experimentally the interaction effect of vehicular exhaust jet exit condition and the rear slant angle on the flow structures, and pollutant (i.e., scalar) dispersion and concentration fields in the near-wake region of two simplified scale-model vehicles for different rear slant angles (i.e., $\alpha = 25°$ or 60°) and heated air exhaust jet conditions (i.e., U_j and T_j) at Reynolds number $Re_h = 5.8 \times 10^4$.

2. Experimental set-up

Experiments were carried out in a closed circuit wind tunnel with a 2.4-m-long square test section (0.6 m × 0.6 m). The flow uniformity in the test section was about 0.1% and the streamwise turbulence intensity was less than 0.4% in the absence of the studied model vehicle. Two simplified scale-model vehicles **A** and **B** of a rear slant angle for $\alpha = 25°$ and 60°, respectively were used for the present study as shown in Fig. 1 [20,21]. The wake structure of the studied model vehicle **A** ($\alpha = 25°$) is characterized by a three-dimensional flow which is induced by a pair of trailing vortices. The wake structure is much wider than the studied model vehicle **B** ($\alpha = 60°$). Hence, a smaller scale-model vehicle **A** was designed but keeping the same scale-model vehicle ratio in order to minimize the blockage effect of wind tunnel confinement as shown in Fig. 1. Hence, the heights, h, and widths, b of the two studied model vehicles **A** and **B** used were 0.081 and 0.108 m, and 0.09 and 0.12 m, respectively.

The origin of the reference system was located at the rear of the studied model vehicle as shown in Fig. 2b. The x-axis is oriented in