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Technical Note

Dispersion in the near wake of idealized car model

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Abstract

The paper presents some recent experimental results concerning tracer gas diffusion within the near wake of a simplified model car. The model car is an Ahmed model (with a rear slant angle of 5°, 25° or 40°). Pollutant emission is simulated using heated air injected through a small pipe at one side of the model base. Fine cold wire thermometry is used to measure instantaneous temperature excess in the near wake. Characteristics of the mean and fluctuating temperature fields are presented for the near wake ($0 < x^* < 10$) where x^* is the distance x downstream from the model normalized by the model height H. Results are explained accounting for the velocity field.
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Keywords: Ahmed model; Separated turbulent flow; Dispersion; Passive scalar

1. Introduction

Recent interest in heat and mass transfer problems concerning environmental applications has increased the attention of researchers on the understanding of the transport of a passive contaminant in 3D separated turbulent flows. For an example, this situation occurs when exhaust gases are injected in the wake of a ground vehicle. Most of the studies devoted to turbulent diffusion of automobile exhaust gases have tackled this problem using a global approach [1]. The pollutant dispersion downwind of a vehicle model has been mainly studied by considering the far wake [2]. The influence of the near wake of a car or truck models on dispersion and chemical reactions of exhaust gases has been only recently investigated [3–5]. As mentioned by Baker [4], up to now little attention has been paid to connect the flow properties of the near wake with the dispersion of pollutants. In comparison, a lot of experimental and numerical work has been devoted to the aerodynamics of road vehicles in order to find out new solutions to reduce aerodynamic drag and limit fuel consumption. For that purpose, a large number of studies has been recently carried out to measure or simulate the complex three-dimensional velocity field in the wake of a ground vehicle. Most of these works have used the Ahmed model due to its geometric simplicity [6–12]. As shown in Fig. 1, the Ahmed model is a reference car model with a variable slant angle α controlling the near wake flow structure and the aerodynamic drag. In this paper, we present the results of an experimental study of the initial dispersion of a passive scalar injected through a small pipe at one side of an Ahmed model. Particular attention is paid to the influence of α on the dispersion of pollutants.

The outline of the paper is as follows: in Section 2 the experimental apparatus and experimental techniques are described, the experimental results concerning the temperature fields are presented in Section 3 and discussed in Section 4.

2. Experimental set-up

As shown in Fig. 1, the model car is an Ahmed model with a rear slant angle $\alpha = 5°$, $25°$ or $40°$ and with the following dimensions: length $L = 80$ mm, width $W = 30$ mm and height $H = 22$ mm. This model was mounted on the adiabatic flat plate of a two-dimensional wall jet (80 mm × 200 mm) and aligned with the exit velocity U_∞.

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Nomenclature

c_p	specific heat, J m^{-1} K^{-1}
d_s	exhaust pipe diameter, m
H	model height, m
L	model length, m
T	temperature excess with respect to ambient, K
P	electric power, W
U_∞	streamwise velocity, m s^{-1}
U_j	exhaust jet velocity, m s^{-1}
W	model width, m
x	streamwise coordinate, m
y	vertical coordinate, m
z	transverse coordinate, m

Greek symbols

α	rear slant angle, °
ρ	density, kg m^{-3}

Superscript

*	dimensionless

Other symbol

$\langle\rangle$	mean value

The wall jet was driven by a centrifugal fan allowing an exit velocity $U_\infty = 12.5$ m s^{-1}. The Reynolds number based on the free-stream velocity U_∞ and the length L of the model was 7×10^4. The origin of the reference system was located at the rear of the model. The x-axis was oriented in the direction of the main flow, the y-axis was vertical and the z-axis was perpendicular both to the model side wall and the main flow.

Pollutant emission was simulated using heated air injected at velocity U_j through a small pipe of diameter $d_s = 3.5$ mm located at one side of the model base as shown in Fig. 1 as usual for real cars. The exit of the heated jet is located at S: ($x^* = 0$; $y^* = 0.17$; $z^* = -0.3$). The velocity of this heated jet U_j was 8.50 m s^{-1}. The temperature difference between the potential core of this jet and the free stream was 20 °C and maintained constant owing to a feedback control system delivering a power P. Fine cold wire thermometry was used to measure instantaneous temperature excess in the near wake. For the present experiment, a single cold wire probe was used. The probe was traversed in the y-direction and the z-direction at each station. The cold wire was made of 0.7 μm diameter Wollaston (Pt–10%Rh) wire. It was operated with in-house constant-current (0.1 mA) circuit. The frequency response of this temperature probe was about 6 kHz. The analog signals were digitized at a sampling frequency of 20 kHz and stored on a Nicolet Vision recorder for subsequent processing.

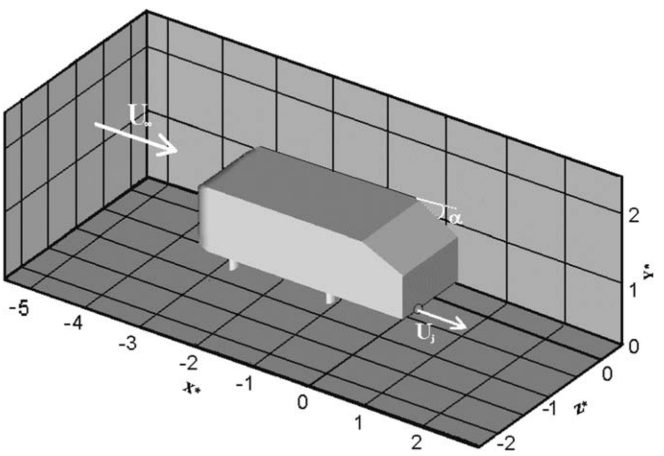


Fig. 1. Experimental set-up.

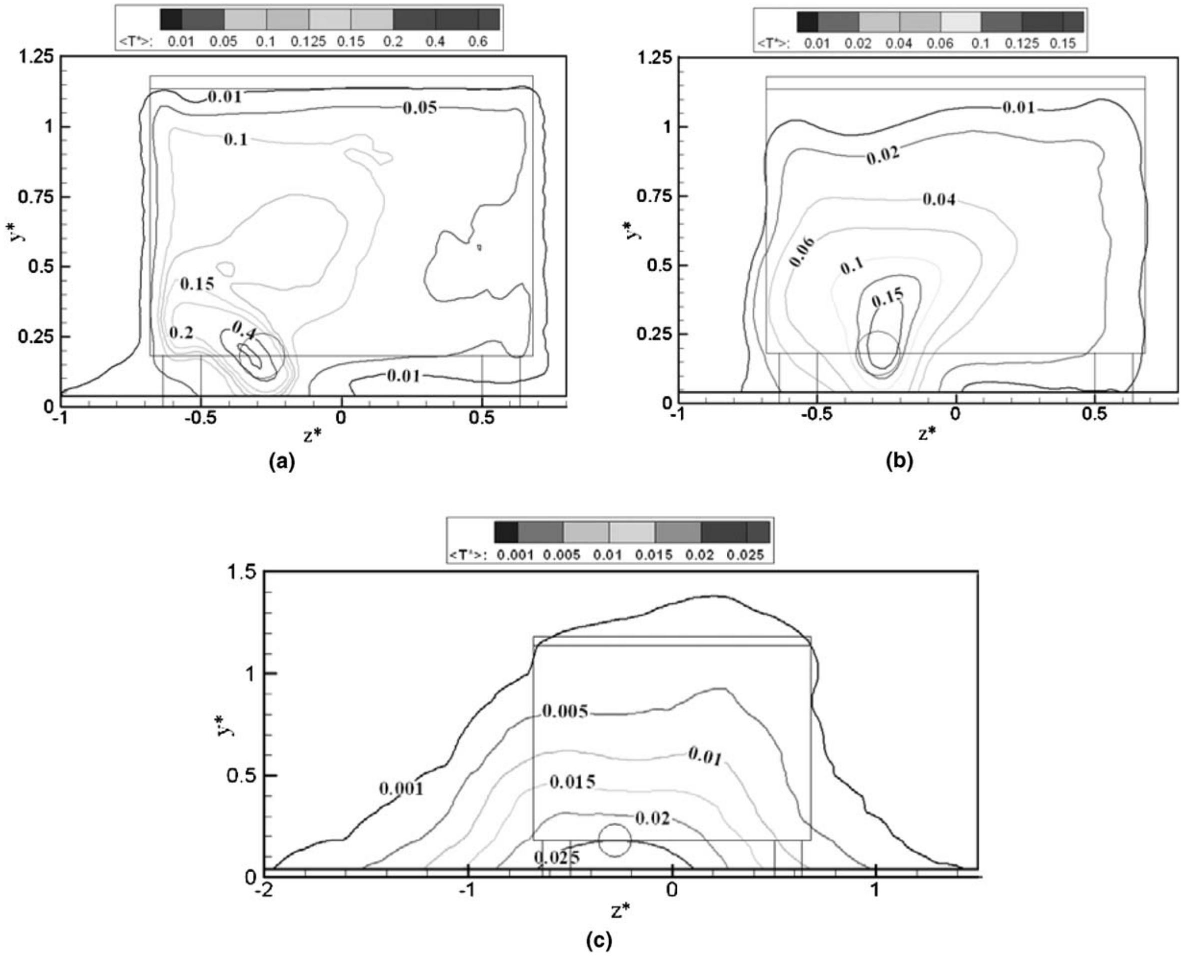
In our study, the asterisk always denotes normalization. The lengths are normalized by the height of the model H. The temperature excess is normalized by a reference temperature excess $\Delta T_{\text{ref}} = P/(\rho c_p \pi d_s^2/4)U_j$ corresponding to the initial temperature excess of the exhaust flow. As a result, the normalized mean temperature corresponds to the reciprocal of the dilution factor R increasing from the value 1 at the exhaust pipe up to ∞ in the far wake.

3. Experimental results

Characteristics of the mean temperature field have been measured successively for $\alpha = 5°$, $25°$ and $40°$. Cross-sectional maps (y–z planes) of mean temperature excess $\langle T^* \rangle$ measured at $x^* = -0.25$ and 0 (for $\alpha = 25°$ and $40°$) and $x^* = 0.25$, 1 and 5 (for $\alpha = 5°$, $25°$ and $40°$) are presented in Figs. 2a–c, 3a–e and 4a–e. Results show large differences between the three cases.

For $\alpha = 25°$ and $40°$, as shown in Figs. 3a,b, 4a and b, it is worth to note that a small amount of tracer gas is found into the region located just above the slant part of the model at $x^* = -0.25$ and 0. When $\alpha = 40°$, the heated fluid spreads out almost homogeneously in this zone. On the other hand, when $\alpha = 25°$, the fluid above the slant part is slightly heated and heated zones are mainly concentrated on the upper edge located on the injection side.

Downstream of the exhaust tail pipe, at $x^* = 0.25$ (Figs. 2a, 3c and 4c) results show that for the whole cases, heated fluid is trapped in the recirculation zone. Outside the recirculation zone, at $x^* = 1$ and 5 (Figs. 2b, c, 3d, 3e, 4d and e), the shape of the isotherms is more steady. When $\alpha = 5°$ and $40°$, the mean temperature fields $\langle T^* \rangle$ display similar behaviors and tend to be symmetric about the x–y plane coming through S. When $\alpha = 25°$, the mean temperature field $\langle T^* \rangle$ is symmetric about the x–y plane coming through the middle of the model. In the latter case, the isotherms



(a)

(b)

(c)

Fig. 2. Mean temperature excess $\alpha = 5°$. (a) $x^* = 0.25$, (b) $x^* = 1$, and (c) $x^* = 5$.

are strongly curved in the central zone and maximum values of $\langle T^* \rangle$ are found on the edges of the wake.

Longitudinal variations of the maximum values of temperature excess $\langle T^* \rangle_{\max}$ and temperature intensity $I_{T'\max} = \langle T^{*\prime 2} \rangle_{\max}^{1/2} / \langle T^* \rangle_{\max}$ are plotted in Figs. 5 and 6 respectively. Fig. 5 shows that the strongest decrease of $\langle T^* \rangle_{\max}$ is found for $\alpha = 25°$. Longitudinal variations of $I_{T'\max}$ display similar behaviors for $\alpha = 5°$ and 25°, both reaching a clear maximum (0.36 for $\alpha = 5°$ and 0.48 for $\alpha = 25°$), before settling down to a nearly constant value (0.22 for $\alpha = 5°$ and 0.26 for $\alpha = 25°$). For the case $\alpha = 25°$, the maximum value of $I_{T'\max}$ is attained at a smaller value of x^*. These results suggest that the mixing between the heated jet air and the cold free stream air occurs nearer the model for $\alpha = 25°$ than for $\alpha = 5°$.

4. Discussion

Results concerning the temperature fields have to be related to the complex velocity field observed in the wake of this model. As shown in previous studies [6,12], the structure of the velocity field in the wake of the Ahmed model is 2D for $\alpha = 5°$ and 40° whatever the Reynolds number and 3D for $\alpha = 25°$ when $Re_L < 2.7 \times 10^4$. The structure of the flow field is 3D for $\alpha = 25°$ when $Re_L > 2.7 \times 10^4$. Comparison of experiments performed over the Reynolds number range 7×10^4–3×10^6 have shown that the characteristics of the near wake, for an example the initial recirculation zone length, are found slightly dependent on the Reynolds number Re_L [13].

These facts explain the important differences found on the thermal fields between the cases $\alpha = 5°$ and 40° and the case $\alpha = 25°$. The temperature fields obtained for $\alpha = 5°$ and 40° revealed the two-dimensional nature of the near wake while for $\alpha = 25°$ the temperature field displays the three-dimensional structure of the wake of the model. Furthermore, the scalar fields are dependent on the two main regions downstream of the model: the recirculation zone and the wake zone.

In the first zone, flow separation occurs from the lower edge of the slanted wall for $\alpha = 5°$ and 25° or from the upper edge for $\alpha = 40°$. In fact in the scenario proposed by Ahmed et al. [6] for $\alpha = 25°$, the flow detaches along the upper part of the slant on a small distance and then reattaches at the bottom edge of the slanted surface. It results that for all cases a part of the heated fluid released from the exhaust is drawn in the recirculation zone by the lower anti-clockwise internal vortex. The other part is

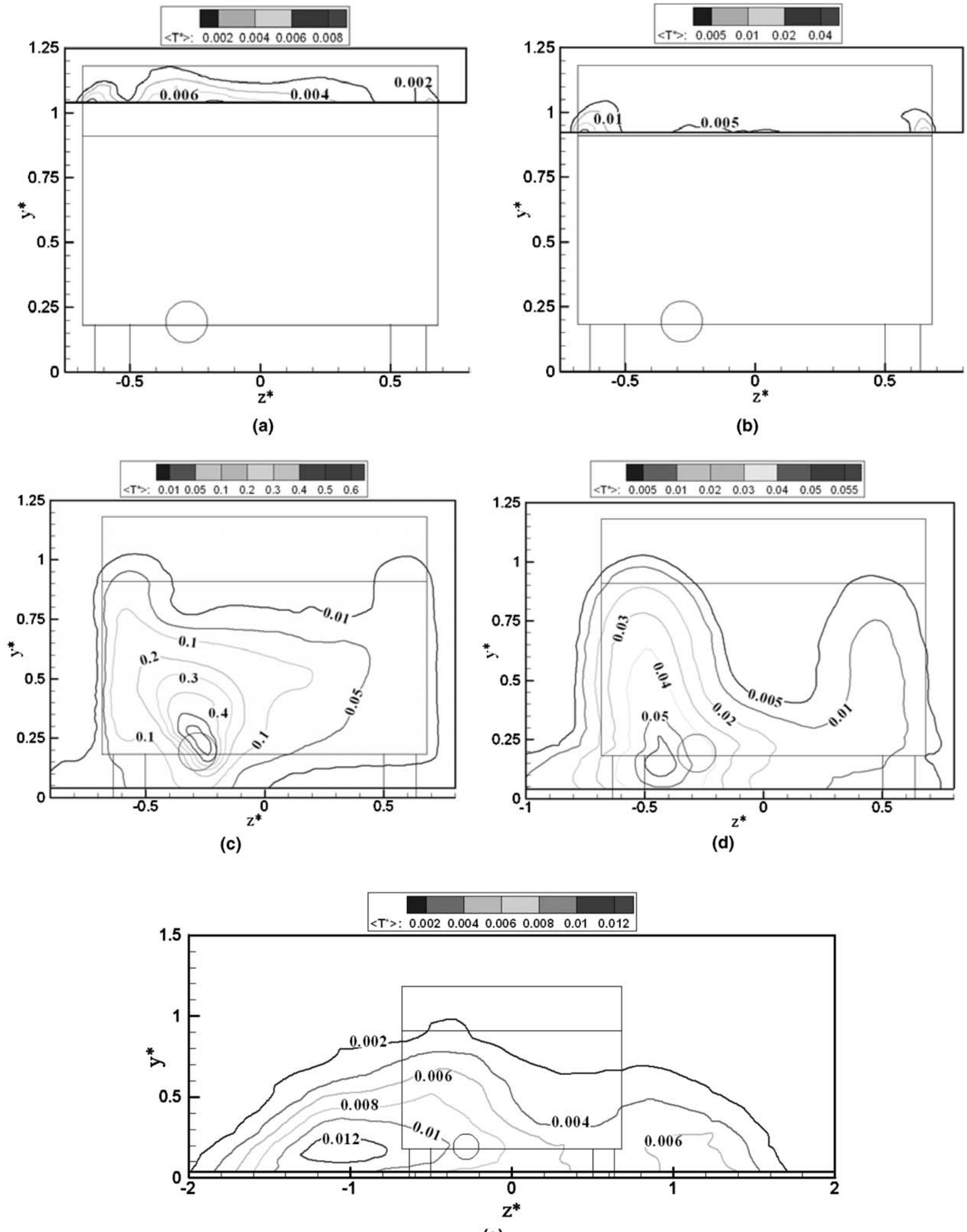


Fig. 3. Mean temperature excess $\alpha = 25°$. (a) $x^* = -0.25$, (b) $x^* = 0$, (c) $x^* = 0.25$, (d) $x^* = 1$, and (e) $x^* = 5$.

drawn straight into the wake. Then, the heated fluid recirculates back towards the base of the model and a part is trapped in the upper internal vortex. This explains the presence of heated fluid found on the opposite side of the model base for $\alpha = 5°$ and above the slanted wall for $\alpha = 40°$. This scenario proposed by Richards et al. [3] to analyze the initial behavior of exhaust gases in the near wake flow of the MIRA fastback reference model is in agreement with our measurements. For $\alpha = 25°$, the small amount of heated fluid observed above the slanted wall leads us to suppose

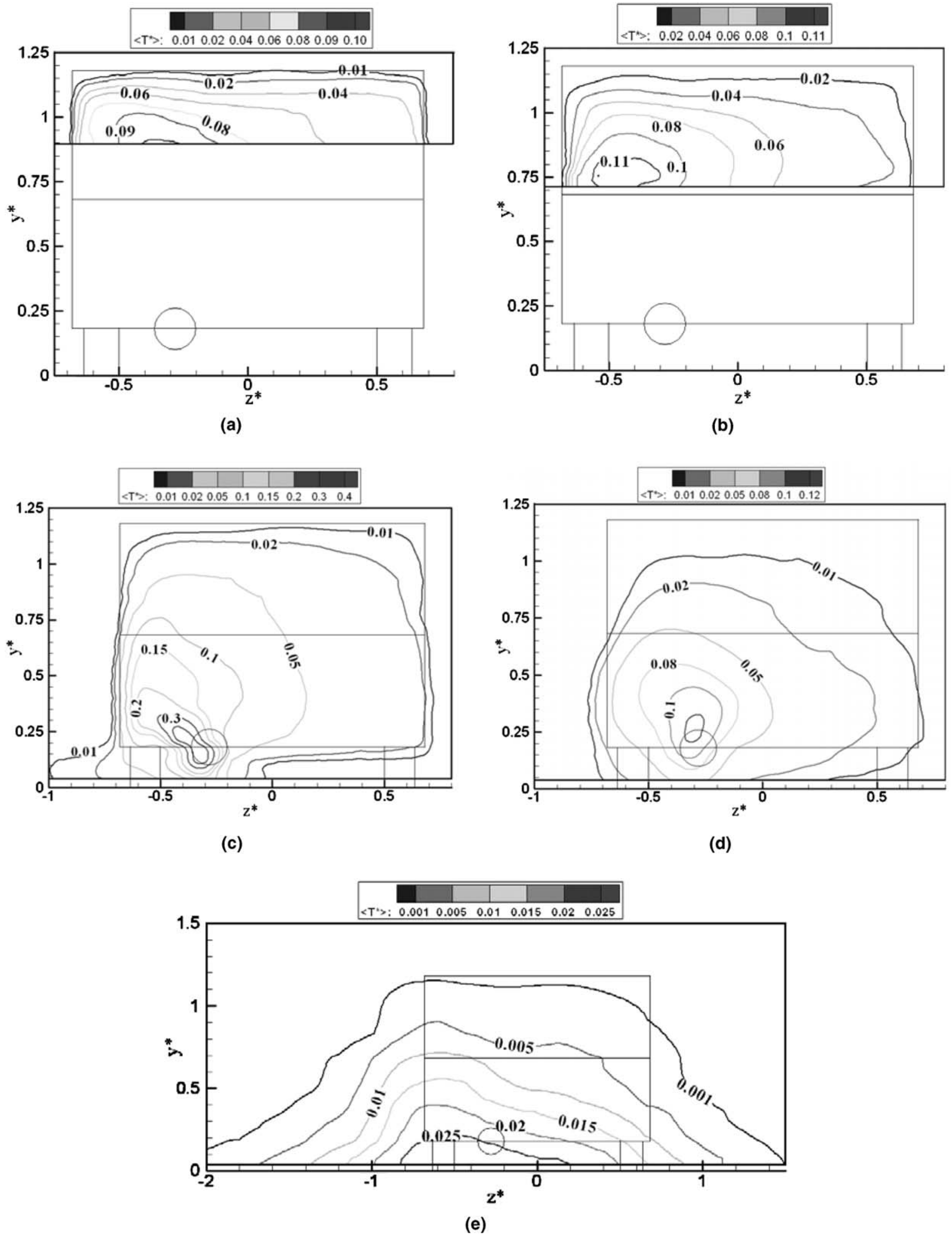


Fig. 4. Mean temperature excess $\alpha = 40°$. (a) $x^* = -0.25$, (b) $x^* = 0$, (c) $x^* = 0.25$, (d) $x^* = 1$, and (e) $x^* = 5$.

that if the flow occasionally reattaches near the bottom end of the sloping line it also frequently becomes separated over the whole of the rear end. This behavior is in agreement with the results of the large eddy simulations of an Ahmed reference model with $\alpha = 28°$ realized by Howard and Pourquie [10].

In the second zone, the heated fluid is transported by a relatively more simple flow. In this wake region, experimental

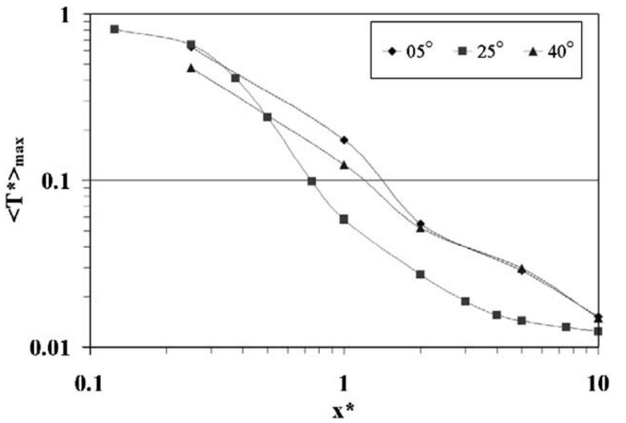


Fig. 5. Longitudinal variation of the maximum values of temperature excess $\langle T^{*}\rangle_{\max}$ for the three selected angles ($\alpha = 5°$, 25° and 40°).

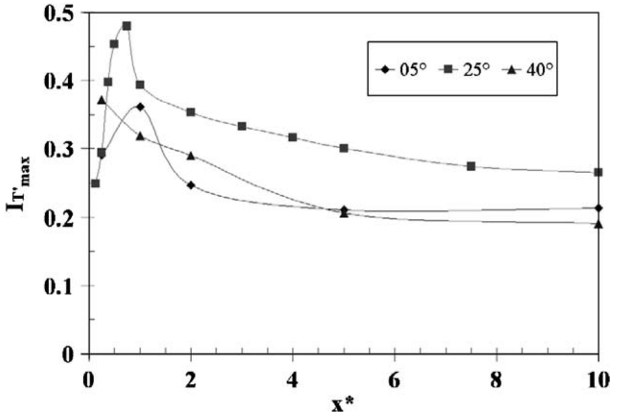


Fig. 6. Longitudinal variation of the maximum values of temperature intensity $I_{T'_{\max}} = \langle T^{*\prime 2}\rangle^{1/2}_{\max}/\langle T^{*}\rangle_{\max}$ for the three selected angles ($\alpha = 5°$, 25° and 40°).

results obtained for $\alpha = 5°$ and 40° are similar. This is mainly due to the two-dimensionality of the flow. For the case $\alpha = 25°$, the influence of the two longitudinal vortices, produced at the edges of the rear part of the model, on the scalar field is predominant. The main effect of these vortices is to bring ambient air into the wake reducing the temperature excess near the centreline. This result is in agreement with the findings of Eskridge and Rao [2] for the far wake.

5. Conclusion

We have studied experimentally the dispersion of heat injected in the near wake of a simplified model car. This model is an Ahmed model with a rear slant angle α of 5°, 25° or 40°. Results show that the thermal fields are strongly dependent on α in relation with the corresponding flow fields.

For distances lower than the recirculation length, contaminant is found both for $\alpha = 25°$ and 40°, in the lower and upper internal recirculation zones and above the slant wall.

For higher distances, experimental results obtained for $\alpha = 5°$ and 40° show that temperature fields are 2D and similar. For $\alpha = 25°$, the presence of a vortex pair induced by the model concentrates the thermal field on the two wake edges and lowers the temperature level along the model axis.

Acknowledgement

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