параметричні дослідження енергетичних характеристик модельного вітроагрегату, виявлено вплив на них кількості лопатей та їх геометричої досконалості. Теоретичні та практичні дослідження, що були виконані у роботі, дозволяють використовувати отримані дані у подальших розрахунках вітроагрегатів указаного типу, проводити порівняння різних методів розрахунку, вдосконалювати їх, тощо.

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# NUMERICAL SIMULATION OF UNSTEADY THREE-DIMENSIONAL DETACHED FLOW AROUND THE REFERENCE AHMED CAR MODEL

**Для численного моделирования обтекания воздухом упрощенной модели автомобиля типа Ahmed Car применены осредненные по Рейнольдсу уравнения Навье-Стокса вязкой несжимаемой жидкости. При замыкании системы уравнений использовалась модель турбулентности SST (Shear Stress Transport). Численное решение исходной системы уравнений получено методом контрольных объемов. Численная методика реализована в программно-методическом обеспечении, написанном на языке Fortran. Расчетная область вокруг корпуса Ahmed Car разделена на контрольные объемы неструктурированной гексаэдрической сеткой, состоящей из 3.5 миллионов ячеек. Проведены расчеты двух вариантов эталонной геометрии – с углом заднего скоса 25° и 35°. Число Рейнольдса, рассчитанное по длине корпуса, равнялось 2.6 млн. Выполнена визуализация результатов расчетов, их анализ и сравнение с работами других авторов. Представлены распределения модуля скорости, давления и линии тока в плоскости симметрии Ahmed Car, распределения векторов скорости в поперечном сечении за корпусом Ahmed Car, а также распределение коэффициента давления и коэффициента трения по**

**поверхности корпуса. Выполнена трехмерная визуализация области возвратного течения за задней поверхностью корпуса и вихревого следа, полученного поверхностью постоянного значения инварианта скорости Q. Для сравнения приведены результаты работ других авторов: распределения модуля скорости в продольном сечении и распределение давления по корпусу Ahmed Car из работы Banga S., распределения векторов скорости в поперечном сечении за корпусом Ahmed Car из работ Minguez M. и Lienhart H.. Результаты моделирования полностью воспроизводят все известные особенности структуры потока при обтекании корпуса Ahmed Car. Получены аэродинамические характеристики Ahmed Car. Коэффициент лобового сопротивления составил 0.255 и 0.268 для угла заднего скоса 25*°* и 35*°* соответственно, что хорошо согласуется с результатами других численных и экспериментальных исследований. Полученные результаты говорят о практической применимости выбранного метода и разработанного программно-методического обеспечения для задач аэродинамики наземных транспортных средств.**

**Ключевые слова:** аэродинамика, транспорт, эталонная модель Ahmed Car, численное моделирование, уравнения Навье-Стокса, модель турбулентности SST, метод контрольных объемов.

**Для чисельного моделювання обтікання повітрям спрощеної моделі автомобіля типу Ahmed Car застосовано осереднені за Рейнольдсом рівняння Нав'є-Стокса в'язкої нестисливої рідини. При замиканні системи рівнянь використовувалася модель турбулентності SST (Shear Stress Transport). Числовий розв'язок вихідної системи рівнянь отримано методом контрольних об'ємів. Числова методика реалізована в програмно-методичному забезпеченні, написаному на мові Fortran. Розрахункова область навколо корпусу Ahmed Car розділена на контрольні об'єми неструктурованою гексаедричною сіткою, що складається з 3.5 мільйонів комірок. Проведено розрахунки двох варіантів еталонної геометрії – з кутом заднього скосу 25*°* і 35*°*. Число Рейнольдса, розраховане по довжині корпусу, дорівнювало 2.6 млн. Виконано візуалізацію результатів розрахунків, їх аналіз і порівняння з роботами інших авторів. Наведено розподіли модуля швидкості, тиску та ліній течії в площині симетрії Ahmed Car, розподіли векторів швидкості в поперечному перерізі за корпусом Ahmed Car, а також розподіл коефіцієнта тиску і коефіцієнта тертя по поверхні корпусу. Виконано тривимірну візуалізацію області зворотної течії за задньою поверхнею корпусу і вихрового сліду, отриманого поверхнею постійного значення інваріанта швидкості Q. Для порівняння наведено результати робіт інших авторів: розподіл модуля швидкості в поздовжньому перетині і розподіл тиску по корпусу Ahmed Car з роботи Banga S., розподіл векторів швидкості в поперечному перетині за корпусом Ahmed Car з робіт Minguez M. і Lienhart H. Результати моделювання повністю відтворюють всі відомі особливості структури течії при обтіканні корпусу Ahmed Car. Розраховано аеродинамічні характеристики Ahmed Car. Коефіцієнт лобового опору склав 0.255 і 0.268 для кута заднього скосу 25*°* і 35*°* відповідно, що добре узгоджується з результатами інших чисельних і експериментальних досліджень. Отримані результати говорять про практичну застосовність обраного методу і розробленого програмно-методичного забезпечення для задач аеродинаміки наземних транспортних засобів.**

**Ключові слова:** аеродинаміка, транспорт, еталонна модель Ahmed Car, чисельне моделювання, рівняння Нав'є-Стокса, модель турбулентності SST, метод контрольних об'ємів.

**For the numerical simulation of the flow around simplified Ahmed Car type vehicle the Reynolds averaged Navier-Stokes equations of a viscous incompressible fluid were applied. To close the system of equations, the Shear Stress Transport (SST) turbulence model was used. The numerical solution of the governing equations was obtained by the control volume method. The numerical technique is implemented in program-methodical ware, written in the Fortran language. The computational domain around the Ahmed Car body is divided into control volumes by an unstructured hexahedral mesh consisting of 3.5 million cells. Calculations of two variants of the reference geometry - with the rear slant angle of 25° and 35° were carried out. The Reynolds number based on model length was equal to 2.6 million. The calculation results were visualized, analyzed and compared with results of other authors. The distributions of the velocity modulus, the pressure and the streamlines in the Ahmed Car symmetry plane, the distribution of the pressure and friction coefficients along the model surface, the distribution of the velocity vector in the cross section behind the Ahmed Car body were represented. The visualization of the return-flow region behind the rear surface of the model and the trailing vortex obtained by the isosurface of the velocity invariant Q was performed. For comparison, the results of other authors are presented: the velocity distribution in the longitudinal section and the**

**pressure distribution along the Ahmed Car from the work of Banga S., the distribution of the velocity vectors in the cross section behind the Ahmed Car body from the works of Minguez M. and Lienhart H. The simulation results completely reproduce all known features of the flow structure around the Ahmed Car body. The aerodynamic characteristics of Ahmed Car were obtained. The drag coefficient was 0.255 and 0.268 for the rear slant angle of 25° and 35° respectively, which agrees well with the results of other numerical and experimental studies. The obtained results indicate the practical applicability of the chosen method and the developed program-methodical ware for the tasks of the ground vehicle aerodynamics.**

**Key words:** CFD, numerical simulation, transport vehicle, reference Ahmed Car, RANS, SST turbulence model, control volume method.

**Introduction.** Modern humanity in many spheres of life relies on vehicles of different types. The main one is ground transport - cars, trucks, trains, etc. Over time, increasing production capacity and customer requirements leads to the need of improving transport parameters - speed, economy, cargo capacity / passenger capacity, environmental friendliness and safety.

Increasing the speed and economy of vehicles makes increased requirements for the vehicles aerodynamics, which make a significant contribution to the movement resistance at medium and high speeds. Today, many methods are used to improve the transport aerodynamics. The main ones are full-scale experiments, model experiments and numerical simulation. The latter method was rapidly developed due to the rapid improvement of computer technology over the past 30 years.

A lot of researchers dedicated their scientific and engineering works to the purpose of the aerodynamic processes studies and improvement of vehicle aerodynamics. Often, to facilitate the modeling of a particular geometry, it has to be simplified. Thus, thanks to the experimental work of Ahmed S.R. [4 – 6], a universal simplified model of the bluff vehicle occurred and was used by researchers from all over the world to test their distributed techniques in the applied car aerodynamics problem. The proposed simplified geometry – the Ahmed Car consists of a rectangular body with a rounded front part and a slant of the rear upper corner with a variable angle (fig. 1). The body is located at a short distance from a large plane – an imitation of the roadway. In the experiments the flow velocity was equal to 60 m/s and the Reynolds number was over 1.5 million, calculated by the model length.

Since the first time Ahmed S.R. publicated his studies [4 – 6], many other authors have performed a lot of experimental and computational studies of aerodynamics of the reference Ahmend Car model.

H. Lienhart and S. Becker [9] carried out detailed LDA measurements in a low speed wind tunnel at a speed of 40 m/s for the rear slant angles of 25° and 35°.

P. Drage et al. [11] carried out both CFD simulations and aerodynamic experiments in the wind tunnel for the Ahmed Car body with two slant angle configurations. The simulation was carried out using Fluent software with Reynolds Stress model. For the angle of 25° the drag coefficient 0.299 and the lift factor 0.345 were obtained in the wind tunnel experiment, while in the CFD simulation gave the values 0.295 and 0.387 for the drag and lift coefficient, respectively.

T. Han [12] carried out aerodynamic optimization of the Ahmed Car shape. The CFD solver with $k$-$\varepsilon$ turbulence model was coupled with the optimization subroutine.

S. Banga et al. [10] applied Fluent with the realisable $k$-$\varepsilon$ turbulence model to study the effect of the rear slant angle of the Ahmed Car (ranging from 7.5° to 30°) on its aerodynamic characteristics.

R. Minguez et al. [7] carried out LES simulation of the Ahmed Car body using the spectral vanishing viscosity (SVV) technique. The rear slant angle was 25°, and the Reynolds number was 768,000.

The purpose of this work is to perform numerical simulation of the unsteady detached flow around the Ahmed Car type simplified model, based on the Navier– Stokes equations.

**Problem definition and numerical methods.** In the present paper the results of numerical simulation of the flow around Ahmed Car model [4 – 6] near the track structure are considered (fig. 1). The flow velocity was $V = 40$ m/s.

The Ahmed Car body consists of a parallelepiped 1.05 m long, 0.28 m tall and 0.39 m wide, with rounded front edges and an inclined section of the rear upper edge. The Reynolds number, based on the body length, was 2.6 million. Two geometries with different rear slant angles, 25 and 35 degrees, were used in the simulations. The model was located near the plane simulating the track structure at a distance of 0.05 m (fig. 1, 2).

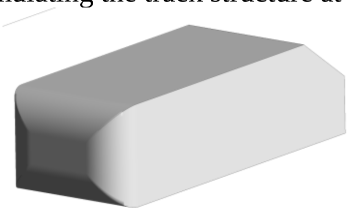
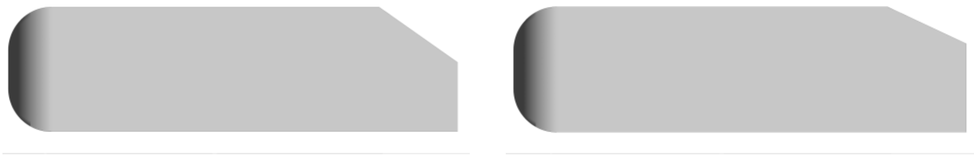


**Fig. 1. General view of Ahmed Car model**



*a* *b*

**Fig. 2. Side view of Ahmed Car with different slant angles:** *a* – 35º ; *b* – 25º

To investigate the viscous incompressible fluid flow around Ahmed Car model, the continuity equation and Reynolds averaged unsteady three-dimensional Navier – Stokes equations were used:

$$\frac{\partial u_j}{\partial x_j} = 0,$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(u_i u_j\right) = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\frac{\partial u_i}{\partial x_j} - \overline{u_i u_j}\right).$$

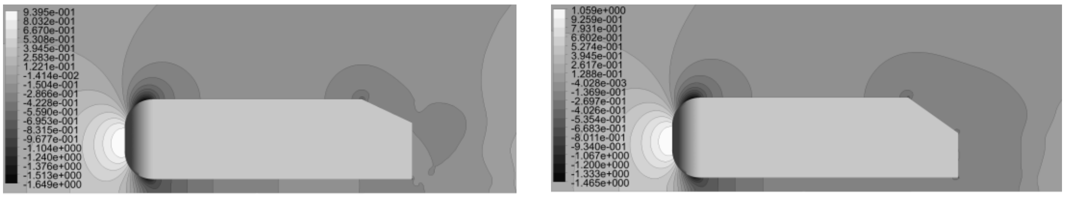
Here $x_i$ – are the Cartesian coordinates, $u_i$ – are the Cartesian components of the velocity vector, $i, j = 1,2,3$, the summation over the same indices is assumed, $t$ – is the time, $p$ – is the pressure, $\rho$ – is the density, $\nu$ – is the viscosity coefficient, $\overline{u_i u_j}$ – are the Reynolds stresses. To close the system of governing equations, the Shear Stress Transport (SST) turbulence model was used [14].

As initial conditions, the undisturbed flow parameters adopted. Boundary conditions: the parameters of the undisturbed flow were set at the outer domain boundaries and the no-slip wall boundary on the Ahmed Car body and on the track structure.

Integration of equations employs a control volume method. In the calculations, a second-order approximation numerical method in time and spatial variables were used [1, 4]. The numerical technique is implemented in program-methodical ware, written in the Fortran language. The computational domain around the Ahmed Car body is divided into control volumes by an unstructured hexahedral mesh consisting of 3.5 million cells.

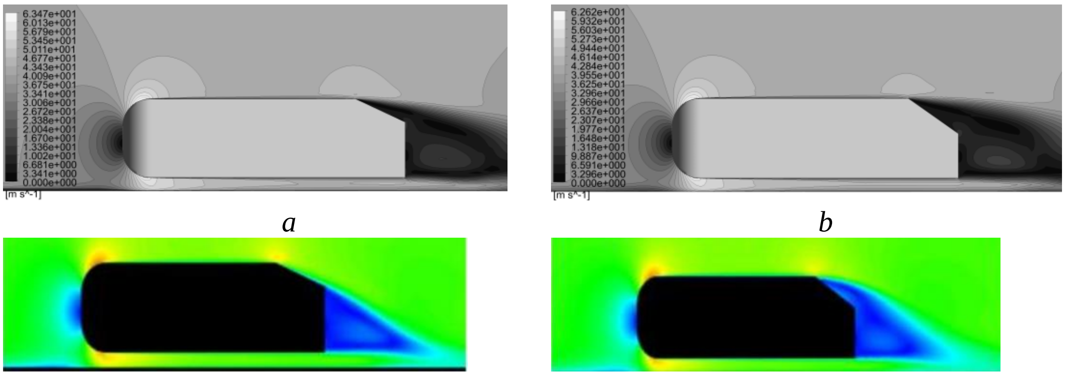
**Simulation results.** As a result of the numerical simulation, the distributions of the gas parameters in the region around the Ahmed Car model are obtained, as well as the impact exerted by the oncoming flow on the model case. The flow visualization around the Ahmed Car body is showed in fig. 3 – fig. 9.

The distributions of the pressure coefficient and velocity vector modulus in the longitudinal median section and on the Ahmed Car model body are represented in fig. 3, fig. 4, fig. 9. The spatial structure of the flow, the surface streamlines, and the reverse flow region are shown in fig. 5 – fig. 8.



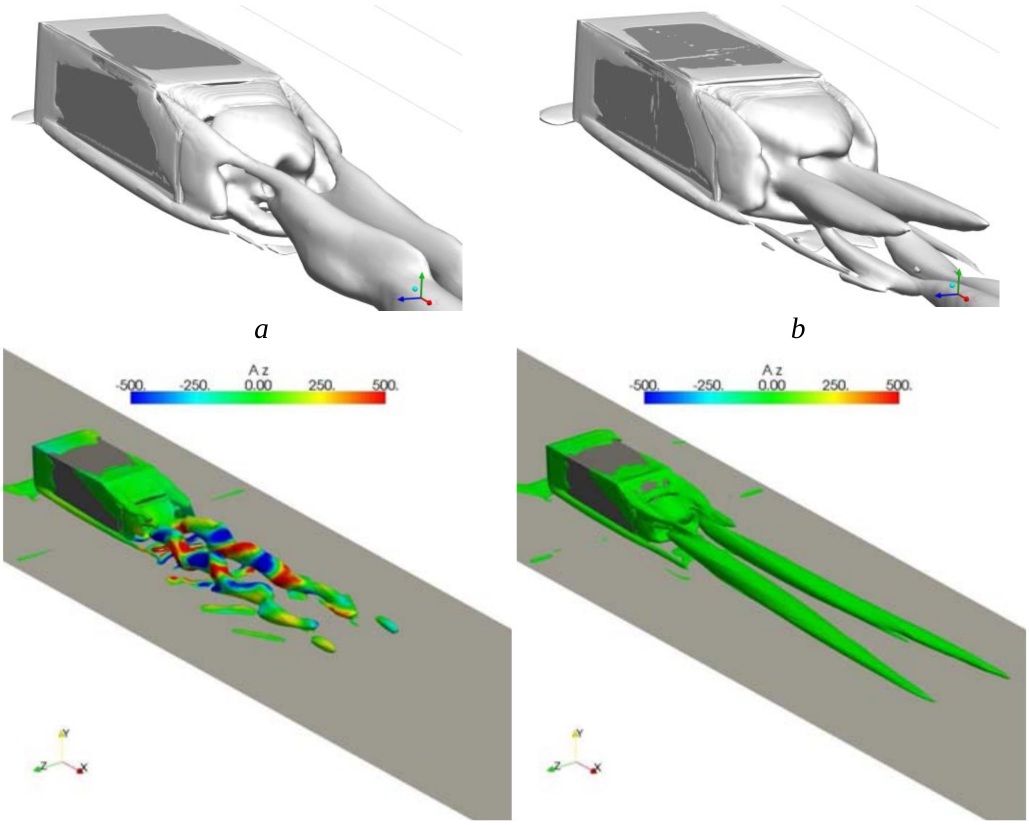
*a* *b*

**Fig. 3. Pressure distribution in the Ahmed Car symmetry plane in the case of slant angle:** *a* – 25º ; *b* – 35º



*a* *b* *c* *d*

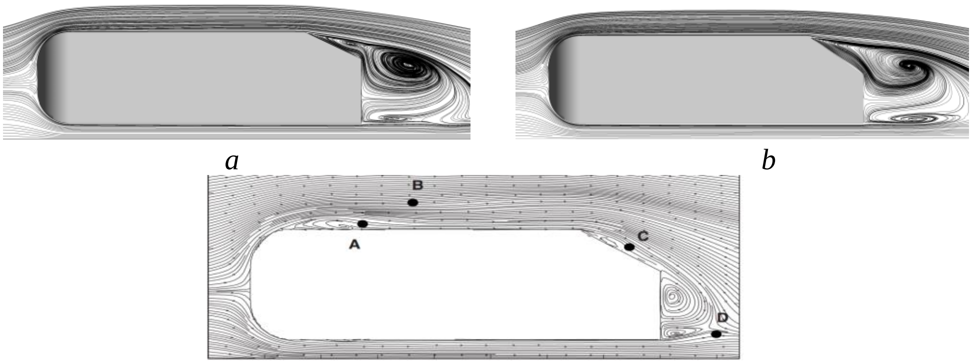
**Fig. 4. The distribution of the velocity vector modulus in the Ahmed Car symmetry plane with the different slant angles:** *a* – 25º ; *b* – 35º were obtained by author of this paper; *c* – 20º ; *d* – 30º given in Banga S. [10]




*a* *b*

*c* *d*

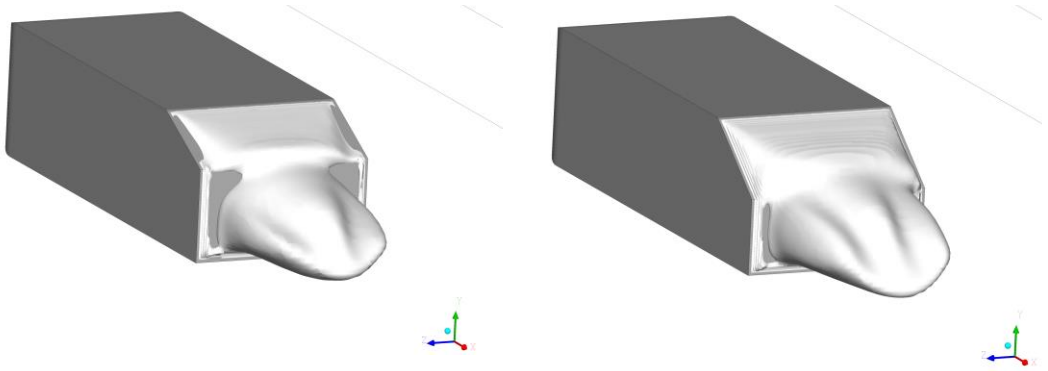
**Fig. 5. The velocity invariant Q isosurface around Ahmed Car with the different slant angles:**
*a* – 25° ; *b* – 35° were obtained by author of this paper; *c* – 25° ; *d* – 35° given in Ceyrowsky [13]




*a* *b*

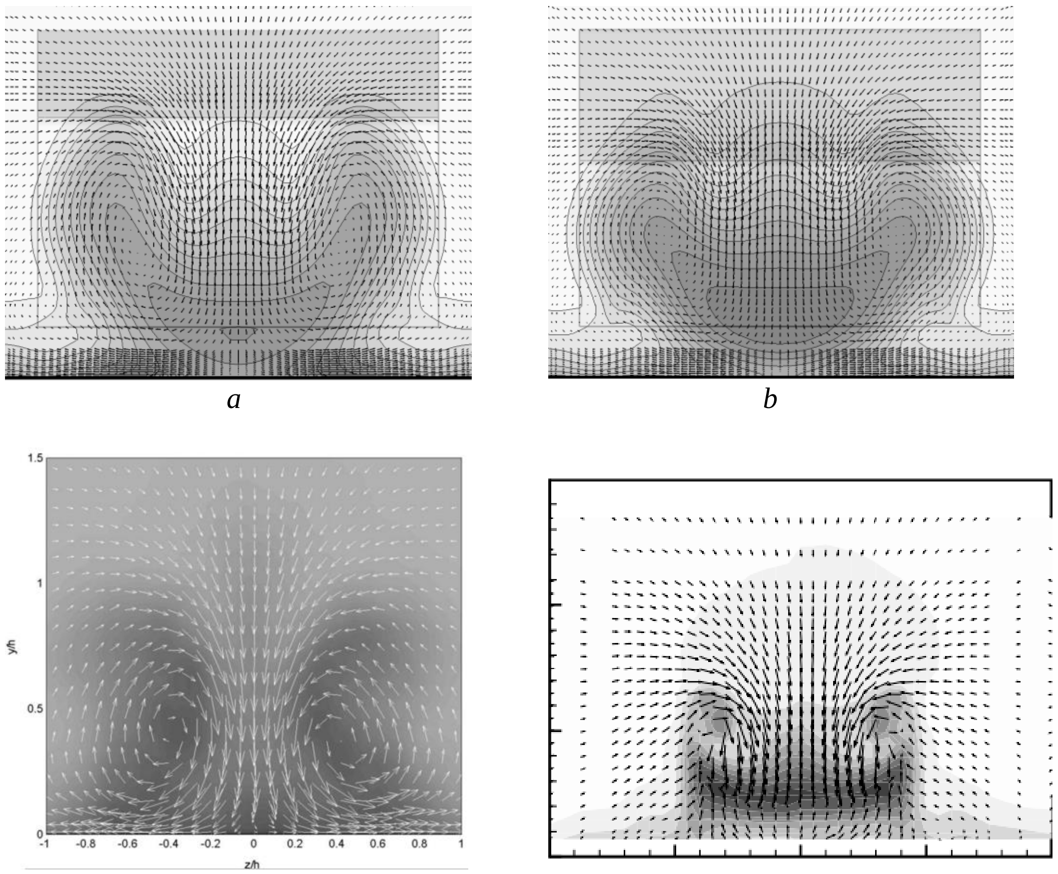
*c*

**Fig. 6. The streamlines in the Ahmed Car symmetry plane with the different slant angles:**
*a* – 25° ; *b* – 35° were obtained by author of this paper; *c* – 25° were obtained in [7]



*a* *b*

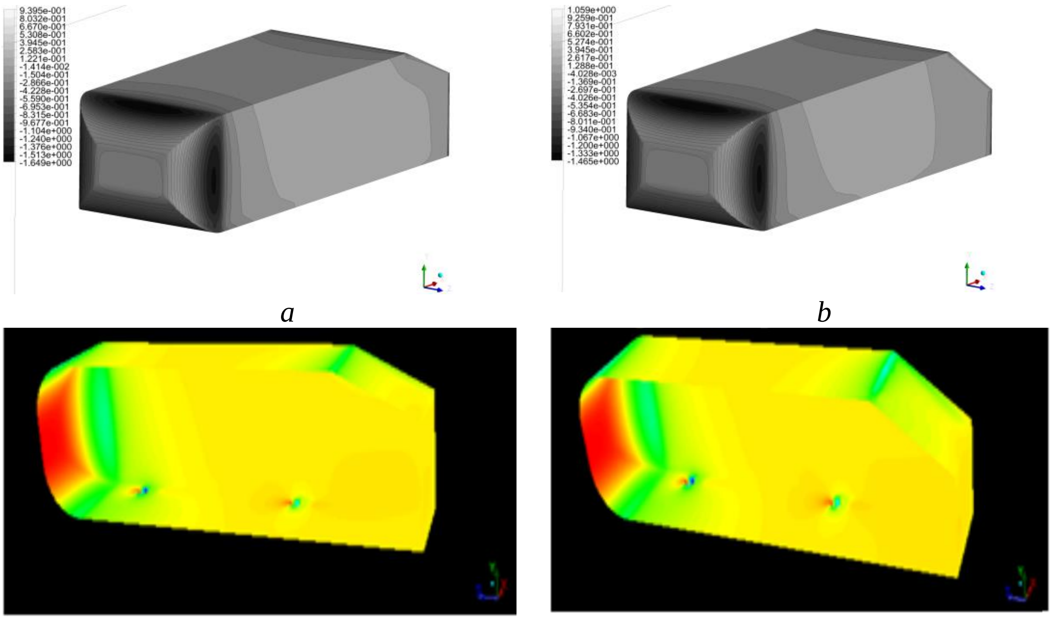
**Fig. 7. Reverse flow area behind the Ahmed Car with the slant angle:** *a* – 25º ; *b* – 35º




*a* *b*

*c* *d*

**Fig. 8. The distribution of the averaged velocity vectors and the isolines of the velocity modulus in the wake of the Ahmed Car:**
*a* – 25º ; *b* – 35º were obtained by author of this paper;
*c* – 25º were obtained in [7]; *d* – 25º were obtained in [9]

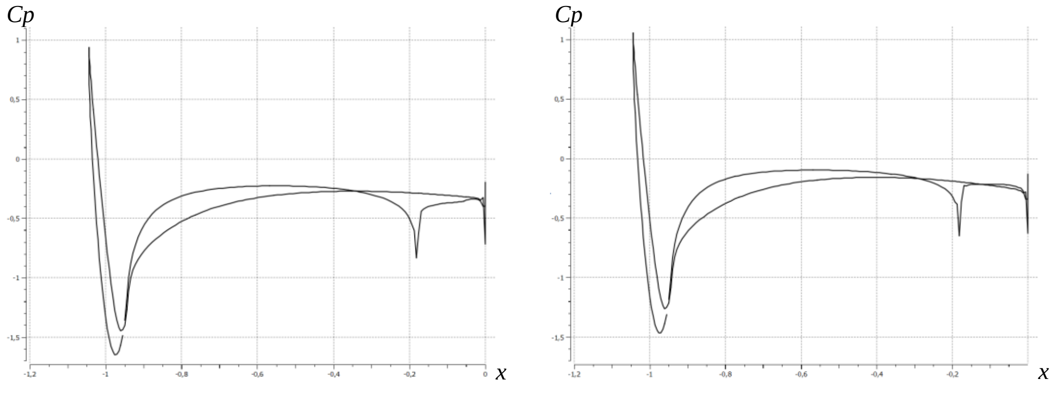


*a* *b* *c* *d*

**Fig. 9. The distribution of the pressure coefficient *Cp* along the Ahmed Car surface and the distribution of pressure over the Ahmed Car surface:**
*a* – with the slant angle of 25º ; *b* – with the slant angle of 35º; *c* – with the slant angle of 20º; *d* – with the slant angle of 30º; *a,b* – the distributions of the pressure coefficient *Cp* along the Ahmed Car surface were obtained by author of this paper; *c,d* – the distribution of pressure over the Ahmed Car surface given in [10]

For comparison with the results of other authors, the distributions of the velocity modulus in the longitudinal section (fig. 4c, 4d) and the pressure distribution along the Ahmed Car body (fig. 9c, 9d) from the work of Banga S. [10], the distribution of the velocity vectors in cross section for the Ahmed Car body (Figures 8c, 8d) from the works of Minguez M. [7] and Lienhart H. [9], the streamlines in the longitudinal section (fig. 6c) from the Minguez M. paper [7] are presented.

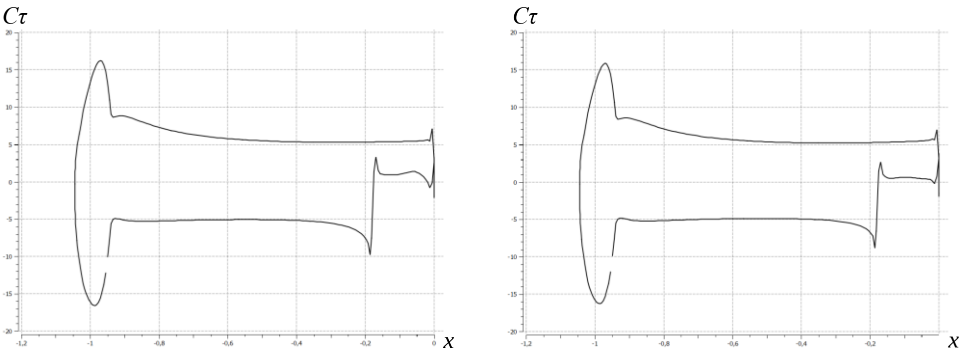
The distribution of the pressure coefficient and friction coefficient along the central cut line on the Ahmed Car body are shown in fig. 10 and fig. 11.




*a* *b*

**Fig. 10. The distribution of the pressure coefficient *Cp* along the cut line in the center of the Ahmed Car body with the different slant angles:** *a* – 25º ; *b* – 35º

The pressure, friction and velocity distributions (fig. 5, 6, 9, 10) show a typical pattern of the flow over the blunt body: a region of air braking and pressure increase is formed in front of the nose, zones of reduced pressure and acceleration of air flow form behind the leading edges.




*a* *b*

**Fig. 11. The distribution of the friction coefficient *Cτ* along the cut line in the center of the Ahmed Car body with the different slant angles:** *a* – 25° ; *b* – 35°

The averaged aerodynamic characteristics of Ahmed Car are determined in numerical simulation. For the rear slant angle of 25$^o$, the drag coefficient is $C_d$ = 0.255, and for the slant angle of 35$^o$, the coefficient is $C_d$ = 0.268. For comparison, in Drage P. work [11] for the rear slant angle of 25$^o$, the drag coefficient $C_d$ was 0.299 and 0.295 for the experiment and for CFD, respectively. According to the results of experiments, Ahmed S.R. [6] received $C_d$ = 0.28 for 25$^o$ and more than 0.38 for 35$^o$. Gilliéron P. [8] received values of 0.34 and more than 0.38 for 25$^o$ and 35$^o$, respectively. Banga S. [10] received the drag coefficient of about 0.28 for 25$^o$ and 0.294 for 35$^o$.

The results of the calculations reproduce all known features of the flow structure in the flow around the Ahmed Car body. The visualization of the spatial flow and surface streamlines shows the flow separation on the rear edges of the Ahmed Car body with the formation of a system of attached large transverse vortices and several oppositely rotating longitudinal vortices coming down from the rear side edges of the body and forming a vortex trail behind the model body. One large transverse vortex is located just behind the entire back surface of the model case, but at a bevel angle of 25 ° it is divided into two transverse vortices by the trailing edge. A large transverse vortex has a system of oppositely rotating longitudinal vortices. Two large opposite-rotating longitudinal vortices move away from the body and form a vortex trail behind the body. Two longitudinal vortices of a smaller scale descend from the lower lateral edges of the nose and are located along the entire body to the zone of the rear vortices.

**Conclusions.** The numerical simulation of the unsteady separated flow around the Ahmed Car model, based on the unsteady three-dimensional Reynolds-averaged Navier–Stokes equations is performed.

The results of visualization of the spatial vortex structure in the flow around the model body and the distribution of pressure and friction on its surface are presented. Analysis of the results showed the presence of the flow detachment behind the model rear surface and a system of transverse and longitudinal vortices. The two largest longitudinal

transversely rotating vortices form a vortex trail behind the Ahmed Car body. The drag coefficients are presented, which are in good agreement with the results of other authors.

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