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NUMERICAL ANALYSIS OF A REATTACHED FLOW BEHIND A RIB

(Communicated by Academician Oleg G. Penyazkov)

Abstract. Turbulent characteristics of a reattached flow separated from a rib in an air flat channel were numerically analyzed by RANS and LES methods. The both methods showed low pressure regions in corners formed by the rib and the channel walls that caused a vorticity tube to be formed along the rib. Nevertheless in RANS, a reattached flow was identified as two-dimensional with a velocity decreasing near the channel bottom wall. In LES, the low pressure regions caused transverse and normal motions in the separation region that resulted in redistributions between velocity components, Reynolds stresses and the velocity decrease near the channel bottom wall, i.e., the formation of three-dimensional reattached flow.

Keywords: reattached turbulent flow, rib, LES, RANS, flat channel

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ЧИСЛЕННЫЙ АНАЛИЗ ПРИСОЕДИНЕННОГО ТЕЧЕНИЯ ЗА РЕБРОМ

(Представлено академиком О. Г. Пенязьковым)

Аннотация. Турбулентные характеристики присоединенного течения срывающегося с ребра в плоском воздушном канале численно анализируются методами RANS (осредненные уравнения Рейнольдса) и LES (метод крупных вихрей). Оба метода показали формирование симметричных зон низкого давления в углах, образованных ребром со стенками канала. Эти зоны вызывали генерацию вихревой трубки вдоль длины ребра. Тем не менее, присоединенное течение было идентифицировано в RANS как двумерное с уменьшением скорости у нижней стенки канала. Метод крупных вихрей показал возникновение в отрывной зоне течений в поперечном и нормальном направлениях. Они приводили к изменению соотношений между компонентами скорости и напряжений Рейнольдса, а также к снижению скорости присоединенного течения у нижней стенки канала, т. е. к формированию трехмерного течения.

Ключевые слова: возвратный турбулентный поток, ребро, LES, RANS, плоский канал

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Introduction. Separated flows are common in several engineering applications such as aircraft wings, turbine and compressor blades, diffusers, buildings, suddenly expanding pipes, combustors, etc. These flows drastically changed transport of momentum, heat and mass. Due to the fact, interest in separation control draws attention of researchers over decades. A flow, separated from a rib due to a favorable pressure gradient, reattached the wall at some distance downstream, forming a separation region. In earlier studies, the reattachment length of a separated flow was usually a primary parameter of interest because in many cases it is desirable to make it as short as possible. With advances in measuring techniques and discovery of the coherent structures influence on progress of the separation region, main interest has been shifted to study structure variations caused by different sources of separation [1–6]. To date, researchers are also concentrating on reattached parameters of separated flows because they influence flow progress downstream.

Originally, a main source of information on transport processes in separated flows was experiment, but with progress in computer facilities, numerical simulations became a powerful tool of research. Nowadays, numerical methods allow getting characteristics of a three-dimensional flow with high spatial resolution and, at the same time, visualizing a flow in different directions. Two methods – RANS (Reynolds-averaged Navier-Stokes) and LES (Large Eddy Simulation) – are mostly used in investigations. Historically, RANS is the first method extensively applied to study flow characteristics, including separated flows. The method is mostly suitable for studying steady flows, but separated flows are unsteady. RANS showing a good correlation of integral parameters (velocity, reattachment length) with experiment, shades structure features of flow. Developed very intensively over last decades LES permits highlighting unsteady flow nature, but at the expense of computer resources and computation time.

The present study aims to show distinctions of the same reattached flow behind a rib, applying RANS and LES.

RANS and LES simulations of two-dimensional laminar flows separated from a backward-facing step were compared using OpenFoam [7]. For a lower Reynolds number (Re = 389), the RANS and LES results were in a good correlation with experiment. For a higher Reynolds number (Re = 1000), the RANS simulations were poor but the LES simulations showed a good agreement with experiment.

Subject of investigation. Investigations were carried out in an air flat channel, whose sizes of a cross section (0.021 × 0.150 m ($H \times B$)) were identical to the ones of the experimental setup described elsewhere [1]. A rib of a height (Δ) equal to 0.003 m with its thickness of 0.005 m was located across the channel width, ahead of a back-facing step.

Simulation methods. A three-dimensional velocity field was computed by RANS using ANSYST Fluent 18 and two models: k-Ω SST and k-ε with standard wall functions. LES computations were done by OpenFOAM (Open Field Operation and Manipulation) using two eddy viscosity models: Smagorinsky [8] and one-equation (oneEqEddy) [9]. The velocity and pressure fields were linked by a PIMPLE (merged PISO-SIMPLE) algorithm.

In numerical computations, the developed velocity profile (power law of 1/7) was assigned at the channel entrance. The Reynolds number based on the channel height and bulk velocity (U_0 = 25 m/s) was Re_H = 36167. A turbulence intensity of 5 % was set for each velocity components.

The computational domains included the channel part before the rib as well as the length of the recirculation zone behind the backward-facing step. In RANS, the domain was one meter in length with a computational grid of 12000000 cells. In LES, the domain was shorter – 0.5 m and the grid had 2209500 cells.

Results. The experiment [10] showed that low pressure regions were generated in corners formed by the rib and the channel sidewalls. The same regions were identified by both numerical methods (fig. 1).

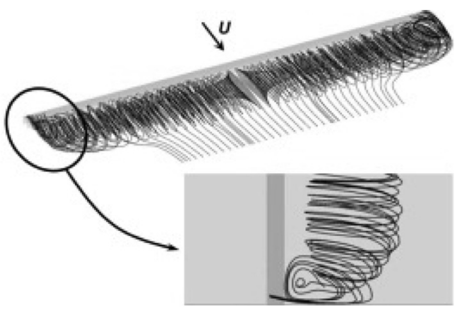

Fig. 1. Vorticity tube behind a rib

Fluid was sucked into these regions, which were the sources of a vorticity tube formed along the rib, involved into the tube and issued in the middle part of the channel.

Mean and turbulent characteristics were calculated at the boundary of reattached flow for two heights 0.2Δ, 0.5Δ and in two cases: a) without rib; b) with rib.

RANS investigations. A longitudinal velocity profiles (U_x) along the channel height and width were normalized by a maximum velocity (U_{max}) in the channel center. The nume-

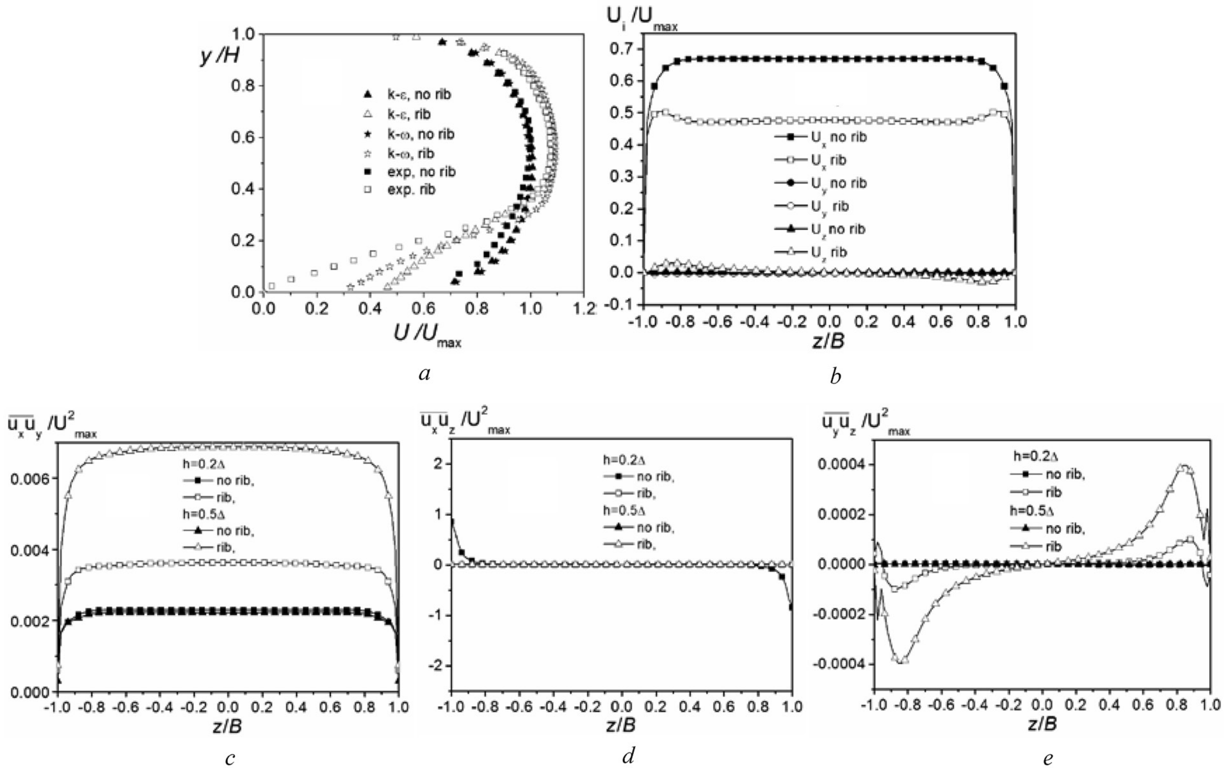

Fig. 2. Velocity and Reynolds stress distributions across the channel: *a* – along the height; *b*, *c*, *d, e* – along the width

rical profiles differed from the experimental one due to the asymmetry of the latter only near the lower wall (fig. 2, *a*).

Because of the rib, the velocity decreased near the channel bottom (stronger in experiment) and increased in the channel upper part. The velocity variation across the channel height did not influence a two-dimensional character of the flow identified by the both models. Distributions of flow turbulent characteristics across the channel were presented only for the k-ε model.

Small deviations from uniformity were observed for longitudinal and transverse velocity components only near the sidewalls at a height of 0.5Δ as their response to the low pressure regions (fig. 2, *b*).

Reynolds stresses sensitive to structure transformations also showed rather uniform distributions $\overline{u'_x u'_y}$ across the channel width at different heights (fig. 2, *c*). The stress $\overline{u'_x u'_z}$ was almost zero along the channel width and the stress $\overline{u'_y u'_z}$ deviated from zero to the sidewalls and the stronger the larger is the parameter *h* (fig. 2, *d*, *e*). But these deviations were more than by an order of magnitude smaller in comparison with the stress $\overline{u'_x u'_y}$.

Thus, the flow parameters changes at the boundary of the reattached flow due to the rib was shown mostly only in the decreased velocity at the channel bottom wall as measured in experiment [1] and the reattached flow remained two-dimensional.

LES investigations. In the channel without rib, the longitudinal velocity profiles computed by the Smagorinsky and oneEqEddy models at the reattachment of the separated flow were more flat in the channel central part and lower at the walls in comparison to the experimental and RANS ones (fig. 3, *a*). Apparently, in LES, it was a result of a shorter computational domain. The velocity normalization was the same as in RANS.

The Smagorinsky model showed a stronger velocity decrease near the wall due to the rib and demonstrated a better qualitative agreement with experiment. It seems the distinctions in velocity profiles were caused by a different reattached length of the separation regions behind the rib. When the Smagorinsky model was used the region ended at 10Δ ahead of the step edge while this region calculated by the One Equation model ended at 4Δ ahead of the step edge. The length of the last region was nearly

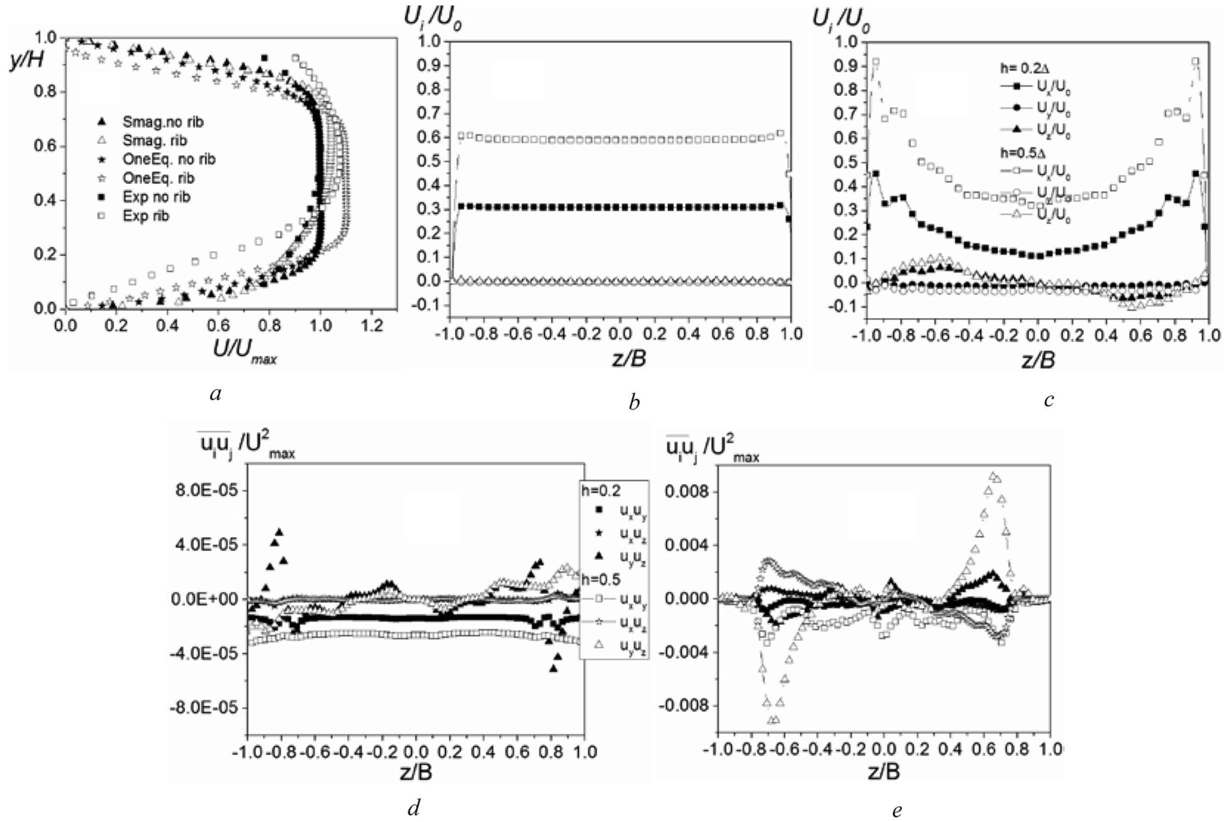

Fig. 3. Velocity distributions along the height (*a*) and width (*b*, *c*) of the channel; Reynolds stress across the channel (*d*) without rib; *e*) with rib

the same as the one calculated by RANS (k–ε model) so the analysis of flow characteristics across the flow ahead of the step edge was done using the one EqEddy model.

In the channel without rib, the velocity field was two-dimensional: the velocity component U_x uniformly distributed across the channel and others components were equal to zero. The rib caused the velocity components U_x and U_z to increase strongly near the sidewalls in comparison with their values in the channel center (fig. 3, *c*). The normal velocity (U_y) slightly decreased with increasing parameter *h*.

Small Reynolds stresses were distributed rather uniformly in the channel without rib, which is typical for a two-dimensional flow (fig. 3, *d*). These stresses increased due to the rib by two orders of magnitude and enhanced to the sidewalls, reflecting a three-dimensional flow structure (fig. 3, *e*).

The increase of the stresses $\overline{u'_x u'_z}$ and $\overline{u'_y u'_z}$ showed the growth of transverse and normal interactions in the flow.

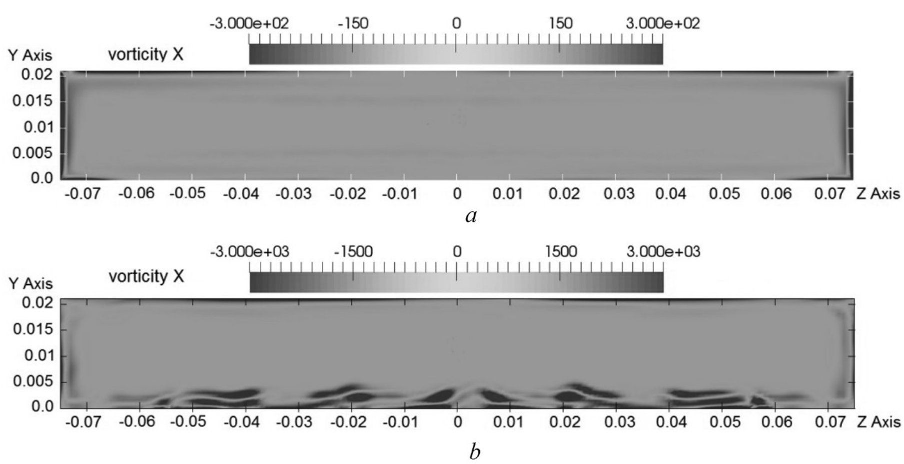

Fig. 4. Vorticity field across the channel at the reattachment position: *a* – channel without rib; *b* – channel with rib

The vorticity $\omega_x = (\partial U_z / \partial y - \partial U_y / \partial z)$ was generated mostly near the walls being almost zero across the channel without rib (fig. 4, *a*).

The rib caused pairs of opposite-sign vortices to be formed near the channel bottom (fig. 4, *b*). The vorticity intensity of these pairs was by an order of magnitude higher than the maximum vorticity in the channel without rib. The generated vortices resulted in energy redistribution within the channel cross section, which was shown in a longitudinal velocity decrease at the channel bottom.

Conclusions. Parameters of a reattached flow separated from a rib were documented by two numerical methods: RANS and LES using different turbulence models: k–ε, k–Ω and Smagorinsky and oneEqEddy respectively. The both methods showed a velocity decrease at the boundary of the reattached flow, but in RANS, this flow was identified as two-dimensional, while in LES – as three-dimensional.

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References

1. Terekhov V. I., Smuls'kii Ya. I., Sharov K. A. Experimental study of the separated flow structure behind a backward-facing step and a passive disturbance. *Journal of Applied Mechanics and Technical Physics*, 2016, vol. 57, no. 1, pp. 180–187. doi.org/10.1134/s002189441601020x

2. Isomoto K., Honami S. The effect of inlet turbulence intensity on the reattachment process over a backward-facing step. *Journal of Fluids Engineering*, 1989, vol. 111, no. 1, pp. 87–92. doi.org/10.1115/1.3243604

3. Park H., Jeon W., Choi H., Yoo J. Y. Mixing enhancement behind a backward-facing step using tabs. *Physics of Fluids*, 2007, vol. 19, no. 10, pp. 105103. doi.org/10.1063/1.2781597

4. Miau J., Chou J. H., Lee K. C., Chen M. H. Control of separated flow by a two-dimensional oscillating fence. *AIAA Journal*, 1991, vol. 29, no. 7, pp. 1140–1148. doi.org/10.2514/3.10715

5. Chun K. B., Sung H. J. Control of turbulent separated flow over a backward-facing step by local forcing. *Experiments in Fluids*, 1996, vol. 21, no. 6, pp. 417–426. doi.org/10.1007/bf00189044

6. Yoshioka S., Obi S., Masuda S. Organized vortex motion in periodically perturbed turbulent separated flow over a backward-facing step. *International Journal of Heat and Fluid Flow*, 2001, vol. 22, pp. 301–307. doi.org/10.1016/s0142-727x(01)00092-3

7. Gong Y., Tanner F. X., Comparison of RANS and LES Models in the laminar limit for a flow over a backward-facing step using OpenFOAM. *19th Int. Multidimensional Engine Modeling Meeting SAE Congress*. Detroit, Michigan, USA, 2009. Available at: http://www.erc.wisc.edu/documents/10-MTU_Gong-Tanner.pdf

8. Pope S. B. *Turbulent Flows*. Cambridge, Cambridge University Press, 2000. 773 p. doi.org/10.1017/cbo9780511840531

9. Schumann U. Subgrid scale model for finite difference simulations of turbulent flows in plane channels and annuli. *Journal of Computational Physics*, 1975, vol. 18, pp. 376–404. doi.org/10.1016/0021-9991(75)90093-5

10. Terekhov V. I., Bogatko T. V., Djachenko A. Ju., Smulskii Ya. I., Yarygina N. I. *Heat transfer in subsonic separated flows*. Novosibirsk, Novosibirsk State Technical University, 2016. 272 p. (in Russian).

Список использованных источников

1. Terekhov, V. I. Experimental study of the separated flow structure behind a backward-facing step and a passive disturbance / V. I. Terekhov, Ya. I. Smuls'kii, K. A. Sharov // J. Applied Mech. and Technical Phys. – 2016. – Vol. 57, N 1. – P. 180–187. doi.org/10.1134/s002189441601020x

2. Isomoto, K. The effect of inlet turbulence intensity on the reattachment process over a backward-facing step / K. Isomoto, S. Honami // ASME Trans. J. Fluids Eng. – 1989. – Vol. 111, N 1. – P. 87–92. doi.org/10.1115/1.3243604

3. Mixing enhancement behind a backward-facing step using tab / H. Park [et al.] // Phys. Fluids. – 2007. – Vol. 19, N 10. – P. 105103. doi.org/10.1063/1.2781597

4. Control of separated flow by a two-dimensional oscillating fence / J. Miau [et al.] // AIAA J. – 1991. – Vol. 29, N 7. – P. 1140–1148. doi.org/10.2514/3.10715

5. Chun, K. B. Control of turbulent separated flow over a backward-facing step by local forcing / K. B. Chun, H. J. Sung // Exp. Fluids. – 1996. – Vol. 21, N 6. – P. 417–426. doi.org/10.1007/bf00189044

6. Yoshioka, S. Organized vortex motion in periodically perturbed turbulent separated flow over a backward-facing step / S. Yoshioka, S. Obi, S. Masuda // Int. J. Heat Fluid Flow. – 2001. – Vol. 22, N 3. – P. 301–307. doi.org/10.1016/s0142-727x(01)00092-3

7. Gong, Y. Comparison of RANS and LES Models in the laminar limit for a flow over a backward-facing step using OpenFOAM / Y. Gong, F. X. Tanner // 19th Int. Multidimensional Engine Modeling Meeting SAE Congress. – Detroit; Michigan, USA, 2009.

8. Pope, S. B. Turbulent Flows / S. B. Pope. – Cambridge: Cambridge University Press, 2000. – 773 p. doi.org/10.1017/cbo9780511840531

9. Schumann, U. Subgrid scale model for finite difference simulations of turbulent flows in plane channels and annuli / U. Schumann // J. Comput. Phys. – 1975. – Vol. 18, N 4. – P. 376–404. doi.org/10.1016/0021-9991(75)90093-5

10. Теплообмен в дозвуковых отрывных потоках / В. И. Терехов [и др.]. – Новосибирск: Изд-во НГТУ, 2016. – 272 с.

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