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SOURCE TERM MODEL FOR STREAMWISE JET VORTEX GENERATOR MODELLING

Tomasz Kwiatkowski*, Paweł Flaszyński**
** Institute of Aviation, Department of Aerodynamics*
Aleja Krakowska 110/114, 02-256 Warsaw, Poland,
*** The Szewalski Institute of Fluid-Flow Machinery, Polish Academy of Sciences*
Department of Aerodynamics
Fiszera 14 st., 80-231 Gdańsk, Poland

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Abstract

In the paper the new method of modeling of Jet Vortex Generators (JVGs) was proposed. Due to the flow structure details generated by JVGs it is required to create fine grids in the vicinity of JVGs, which increase the computational cost. In order to overcome difficulty with generating meshes of the air jet vortex generator at every investigated location the new source term model of air jet vortex generator was proposed. This model works by adding momentum source term to Reynolds-Averaged Navier-Stokes equations in ANSYS Fluent. The model was calibrated with respect to obtain the best circulation plots agreement. The results of numerical calculations of source term model at various grid types- coarse, medium and fine were compared with the wind-tunnel experiment results and its grid-resolved air jet vortex generator computational model. The calculations were performed in the computational domain for flat plate with single vortex generator with the wall boundary condition on surface, where is placed JVG. The circulation, x-vorticity contours and skin-friction coefficient were examined in order to check the effectiveness of air jet vortex generator source term model.

1 Introduction

In recent years turbulisers are widely used to flow control [1]. The widely used example types of turbulisers may be: thin-plate vortex generators [2, 3, 4], air-jet vortex generators (JVG) [5], rod vortex generators (RVG) [6, 7, 8, 9, 10] or even carborundum. The disadvantage of using fixed type vortex generators such as thin-plate vortex generators, rod vortex generators or carborundum is the fact that they must work at full time of exploitation of device. To overcome this difficulty the air-jet vortex generators may be used, which can be turned off when it is necessary. JVG are devices used to control flow in an active way which have potential to reduce drag and separation region. In order to use appropriate vortex generator by type, shape or size it is necessary to check its influence on flow. The influence of diameter of JVG in experiment research was investigated by Szwaba [11, 12]. In this paper are presented results of numerical calculations of flow in wind-tunnel with JVG which was just examined in wind-tunnel test in Institute of Fluid-Flow Machinery of Polish Academy of Sciences in Gdansk. In order to overcome difficulty of meshing vortex generator for every size or location the vortex generators may be replaced by source term model, which may be applied in various locations in single grid, so it isn't necessary to generate grid with JVG in every investigated location. Using Computational Fluid Dynamics (CFD) methods it is possible to test influence of various JVG parameters such as diameter or angle of incidence on parameters of flow in conjunction with experiment.

2 Numerical approach

2.1 Numerical method

The calculations were performed in ANSYS Fluent 14.5 commercial solver using steady SST k-ω viscous model. Third order MUSCL spatial discretization for convection terms was used with coupled algorithm for pressure-velocity coupling.

2.2 Flow configuration

The extents of computational domain are X_{min}=-0.05m, X_{max}=0.2m (X is the streamwise coordinate), Y_{min}=-0.035m, Y_{max}=0.035m (Y is the spanwise coordinate), Z_{min}=0m and Z_{max}=0.06m (Z is the wall-normal coordinate). The centre of inlet of jet vortex generator to the main flow is at point of X=0m, Y=0m, Z=0m. At the main flow inlet was set pressure inlet boundary condition with the profile of total pressure, turbulent kinetic energy and specific dissipation rate to obtain as close flow conditions as used in the experiment. The Mach Number in main flow was Ma=0.3. At the inlet of jet is set mass flow inlet boundary condition with MFR_{jet}=7.3e-05kg/s of mass flow rate. The diameter of jet hole is D=1mm and the boundary layer thickness at jet location is δ=10mm.

In the Tab. 2.1, it is presented number of cells in every X, Y, Z cartesian coordinates and total number of cells in computational domain. The coarse grid contains the constant spacing of grid in X direction of 1.98E-3m and in Y direction of 1.75E-4m in the smallest cell dimension in centerline of domain with Bell Shaped grading of 0.26 used. The mesh of medium grid was generated using cut-cell method with additional refinement in region, where momentum source can be applied in cells. The fine grid contains minimum cell dimension in Y direction of 3.04E-5m with Bell Shaped grading of 0.17 used. The constant cell size of 9.77E-4m was applied in X direction. The medium grid is refined from Y=-7mm to Y=9mm and from X=-2mm to X=4mm using cut-cell method.

Tab. 2.1 Parameters used for the various grids of computational domain

Parameter	N_X	N_Y	N_Z	Total number of cells
Grid-resolved JVG grid	142	70	182	1 696 192
Orthogonal coarse grid	126	128	60	855 036
Orthogonal medium grid	200	160	60	1 762 000
Orthogonal fine grid	250	256	76	4 165 000

In the Fig. 2.1, it is shown JVG orientation used in computations. The angle of attack of jet α is equal to 90° and the injection angle of a jet θ is equal to 45°, as used in wind-tunnel experiment [11, 12].

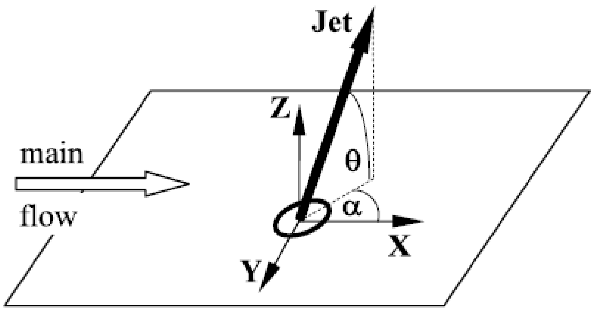

Fig. 2.1 Schematic of JVG orientation [11]

In the Fig. 2.2, there are presented all meshes at slice Y=0m. It is visible that medium grid with used cut-cell method is coarsen at around Z=30mm, which is far above vortex generated by source term model of vortex generator. There is also shown fine mesh in the vicinity of X=0m at grid-resolved JVG mesh, where the JVG inlet is resolved. Also in order to avoid such unnecessary dense meshes, the new source term model of JVG is proposed.

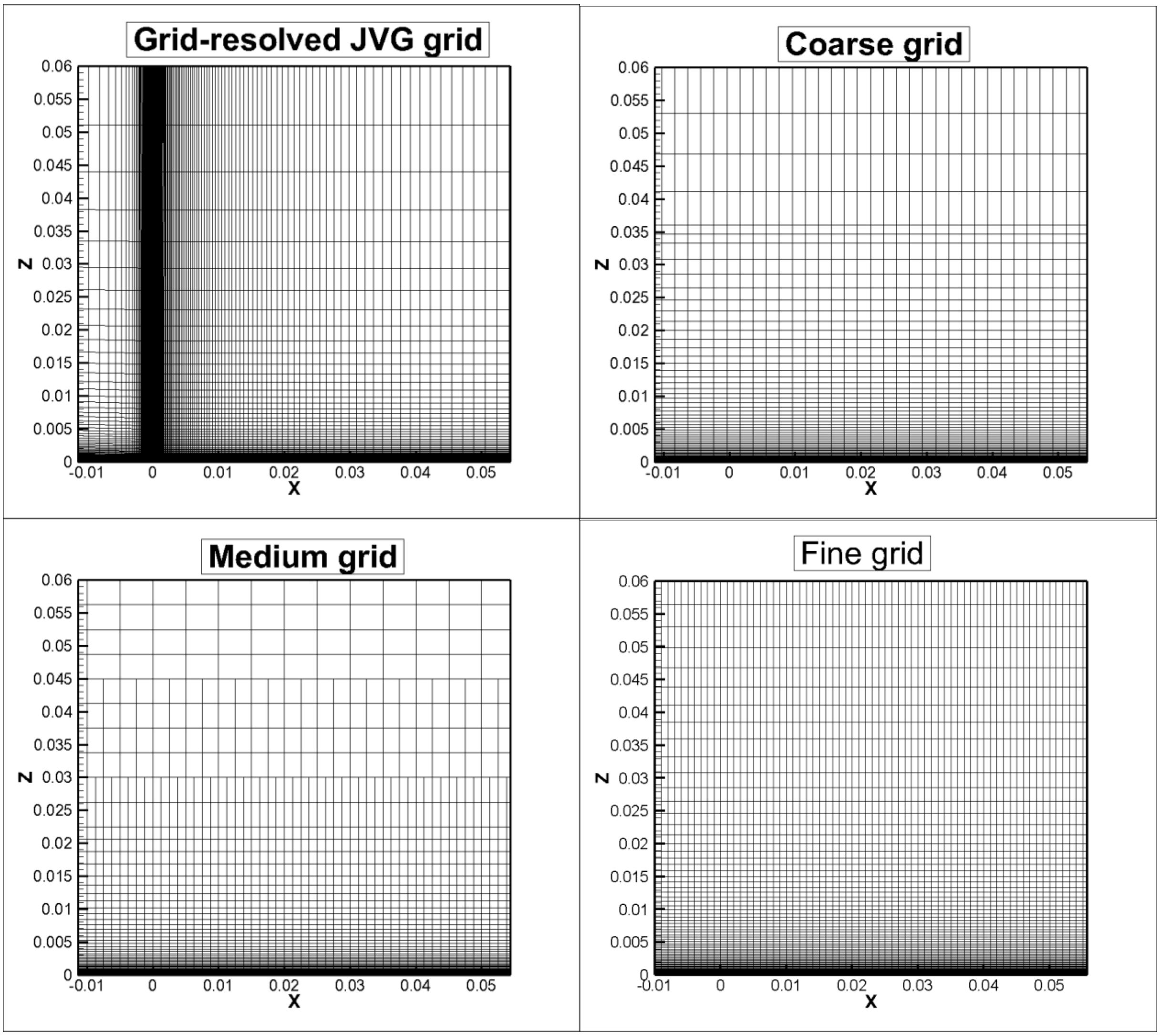

Fig. 2.2 The mesh at slice of Y=0m

3 Source term model of JVG - other approaches and new approach

3.1 Previous approaches to VG modelling

According to May [13] the vortex generators may be modelled in two ways- by vortex-source model and lifting-force model. In vortex source model the circulation Γ is added to governing equations in plane normal to the circulation, but disadvantage of this method is the fact that circulation must be known in advance.

It is widely supposed that numerical calculations of models of lifting-force models of vortex generators was begun in 1999 by Bender et al. [14], who proposed first VG's direct numerical model based on mesh cells, of which only some are used as source term. This model was named as BAY from first researchers surnames - Bender, Anderson and Yagle. In the cells there are averaged distributed forces added to Navier-Stokes equation's source term in the way of momentum sources applied in finite volumes. The BAY model was used to predict fixed thin-plate type of vortex generator's influence on flow. In this model the lifting force source term, L_i acting at grid point i, is added to the governing discretized finite volume momentum (1) and energy (2) equations.

$$\Delta V_i \frac{\Delta \rho \overline{u_i}}{\Delta t} = \sum_j \overrightarrow{F_M} \Delta S + \overrightarrow{L_i} \qquad (1)$$

$$\Delta V_i \frac{\Delta \rho \vec{E}}{\Delta t} = \sum_j \overrightarrow{F_E} \Delta S + \overrightarrow{u_i}\overrightarrow{L_i} \qquad (2)$$

The L_i is source term representing lift force generated by thin-plate VG. The *j* is the flux summation along the boundary of the *i* cell.

Because the local velocity vector becomes parallel to the VG's surface, the source term (u_iL_i) in the energy equation (2) disappears. The vorticity is generated by lifting force which depends on local velocity values and vortex generator's geometry, especially the angle of attack of thin-plate vortex generator.

$$\overrightarrow{L_i} = c_{VG} S_{VG} \frac{\Delta V_i}{V_m} \alpha \rho u^2 \vec{l} \tag{3}$$

The source term ($\mathbf{L_i}$) which is based on assumption that vortex generator is modelled as ultra-thin airfoil calculated by the Zoukowski Lift Theorem and can be formulated as lifting force (3) generated by VG, including losses caused of deviation of flow on the VG's surface. In the equation (3) **l** is the unit vector of lift force, c_{VG} is calibration constant, S_{VG} is VG's area, ΔV_i is the cell's volume, V_m is total VG's volume and the physical interpretation of two last values quotient is the percentage of the total lift force generated in volume cell *i*. The VG's angle of incidence is represented by α with respect to the flow direction, ρ is the local density in the finite volume, **u** is the local velocity in the cell. The empirical value of BAY constant c_{VG} was originally suggested by BAY model proposers as 5, but according to other researches [15] the solution may be more accurate for constant c_{VG}=7. If V_m is different than the volume of the vortex generator, model works in linear mode and is strongly dependent on the constant c_{VG}. The spatial orientation of VG's may be represented by 3 unit vectors **n**, **b** and **t** as presented the Fig 3.1. The **u** in the Fig. 3.1 corresponds to the velocity vector and α is the vortex generator's angle of incidence. The surface of modelled VG's (in this case is a rectangle-shaped) is dashed. The unit vector's **n** direction is normal to the VG's surface, on the side where works lift force. The unit vectors **b** and **t** are tangent to the VG. The unit vector **t** is oriented in the direction of flow. The unit vector **b** is the vector product of unit vectors **n** and **t** and is oriented in the spanwise direction of the VG. Because the equation (3) is difficult to implement in direct way as discretized equations, the unit lift vector is defined (4). Using small angle approximation there can be obtained equation (5).

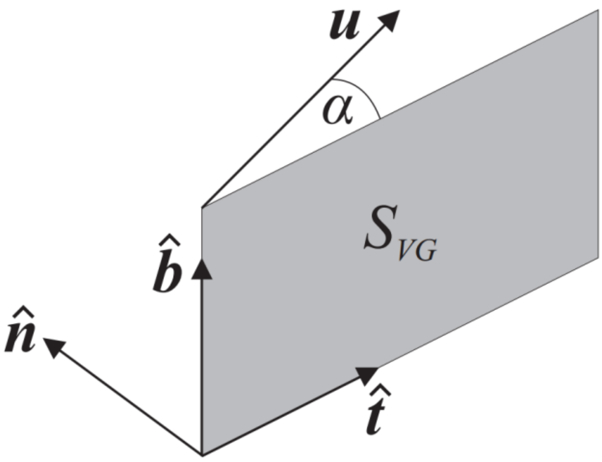

Fig. 3.1 Spatial orientation of unit vectors **n, b** and **t** defining VG's orientation [16]

$$\boldsymbol{l} = \frac{\boldsymbol{u}}{|\boldsymbol{u}|} \times \boldsymbol{b} \tag{4}$$

$$\propto = \sin \propto = \cos\left(\frac{\pi}{2} - \propto\right) = \frac{\boldsymbol{u} \cdot \boldsymbol{n}}{|\boldsymbol{u}|} \tag{5}$$

For the purpose of side force loss calculations caused by small angle approximations for high angles of attack the term (6) is added.

$$\frac{\boldsymbol{u} \cdot \boldsymbol{t}}{|\boldsymbol{u}|} \tag{6}$$

After taking into account all earlier approximations the final source term equation is given by (7), which is easy to implement in numerical code to calculations.

$$L_i = c_{VG} S_{VG} \frac{1}{V_m} \rho \left(\frac{\boldsymbol{u}}{|\boldsymbol{u}|} \times \boldsymbol{b}\right) \left(\frac{\boldsymbol{u} \cdot \boldsymbol{t}}{|\boldsymbol{u}|}\right) \tag{7}$$

3.2 Example of modelling JVG

Except of modelling thin-plate vortex generators using BAY model there is possibility to model JVG too. According to Waithe [17] the source term model for steady blowing micro jet on a three-dimensional flat plate was implemented. The orientation of the jet used by Waithe is presented in the Fig. 3.2. He introduced mass flow, momentum and energy terms to the mass flow, momentum and energy equations representing the mass flow, momentum and energy, which are added by a steady blowing micro jet.

$$S_1 = c\frac{A_i}{A_{tot}}\rho A_{jet} MFR_{jet} U_\infty \quad (8)$$

$$S_i = S_1 U_\infty t_i, \text{ where i=2,3,4} \quad (9)$$

$$S_5 = \sum_{i=2}^{4} S_i t_i U_\infty \quad (10)$$

The equation (8) is the mass flow term, the S_i is the momentum term (9), S_5 is the energy term (10), c is calibration constant, A_i is the total cell area, A_{jet} is the area of the jet, ρ_∞ is the free stream density, U_∞ is the free stream velocity, MFR_{jet} is the mass flow rate of the jet and t_i is the directional component of the unit vector **t**.

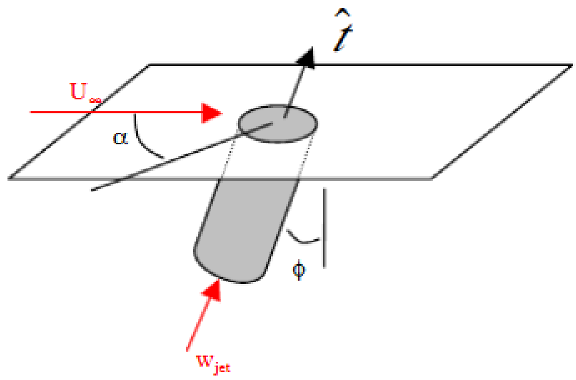

Fig. 3.2 Schematic jet orientation and definition of unit vector t used by Waithe [17]

3.3 A new ABAY model

A new ABAY model is a modification of BAY model for JVG cases. The name jBAY is reserved by Jirasek [18], who proposed a model of thin-plate vortex generator defined by grid points. A new approach to model JVG doesn't consider MFR_{jet}, takes into account the directional components of two unit vectors (**b** and **t**) of three (**n**, **b** and **t**) proposed originally by Bender et al. and assumes that vortex generator's angle of attack is equal to 1, because compound and injection angle of jet is just defined by unit vectors **b** and **t** orientation. Additional argument of doing this assumption is that the u velocity gradient in boundary layer is very high and it is difficult to control lifting force in this region. The volume of cell V_i is also assumed as 1 in order to reduce computational cost of calculating cell volume. The lifting force used in computations is (11).

$$L_i = c_{VG} S_{VG} \frac{1}{V_m} \rho\alpha \left(\frac{\boldsymbol{u}}{|\boldsymbol{u}|} \times \boldsymbol{b}\right) \left(\frac{\boldsymbol{u}\cdot\boldsymbol{t}}{|\boldsymbol{u}|}\right) \quad (11)$$

The calibration constant c_{VG} was calibrated and it was observed that the best circulation behind JVG plot agreement is obtained for the c_{VG} set to 35. S_{VG} is the area of the jet inlet with respect to the diameter of 1mm. The V_m is the sum of volume of cells, where source term is applied, which is the area of the jet inlet multiplied by the height of model of vortex generator, which was assumed as H=1mm, which is 1/10 of boundary layer thickness. The density ρ is calculated in every volume cell. As shown in the Fig. 3.3 the unit vectors values were used as presented in the Tab. 3.1 which correspond to vortex generator's orientation as mentioned above. In the Fig. 3.3 with the dashed edge is drawn the shape of modelled JVG.

Tab. 3.1 Parameters of unit vectors used in ABAY model of JVG

Parameter	Value
n_x	0
n_y	0.5
n_z	0.5
t_x	-1
t_y	0
t_z	0
b_x	0
b_y	0.5
b_z	0.5

The cells representing the grid-resolved JVG is presented in the Fig. 3.4. The source term is added to the cell selected in the model of vortex generator if cell's centroid is in the region selected by constraints (12) and (13).

$$X^2 + Y^2 < D^2 \quad (12)$$

$$Z < H \quad (13)$$

where D=1mm is the diameter of jet inlet and H=1mm is the height of cells, where source term is applied and is equal to 1/10 of boundary layer thickness.

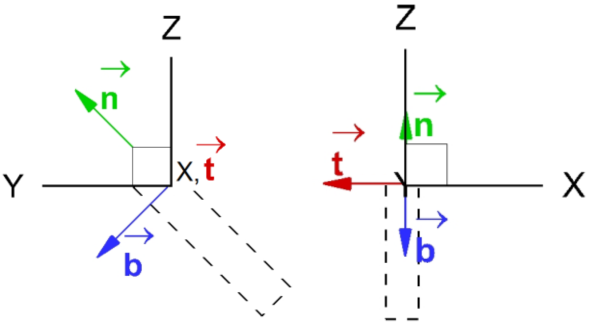

Fig. 3.3 Representation of unit vectors used in new ABAY model of JVG

As shown in the Fig. 3.4 the mesh of grid-resolved JVG is complex, because the existence of JVG requires mesh refinement and topology adjustment

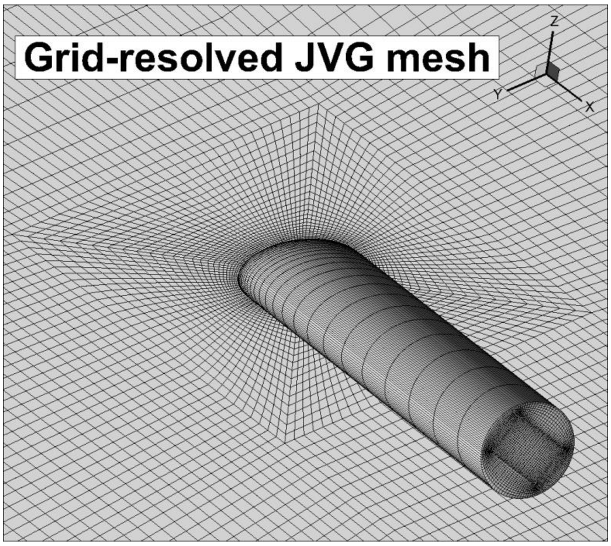

Fig. 3.4 Grid-resolved JVG mesh

4 Results

The mesh dependence study was carried out and its influence on circulation, x-vorticity and skin-friction coefficient distribution is shown. In the Fig. 4.1, there are presented circulation plots behind the JVG inlet for various BAY C constants from C=30 to C=60 with interval of C=5 in fine grid, which was used to compute circulation downstream and choose the ABAY C constant, for which is obtained the best agreement with grid-resolved model of JVG.

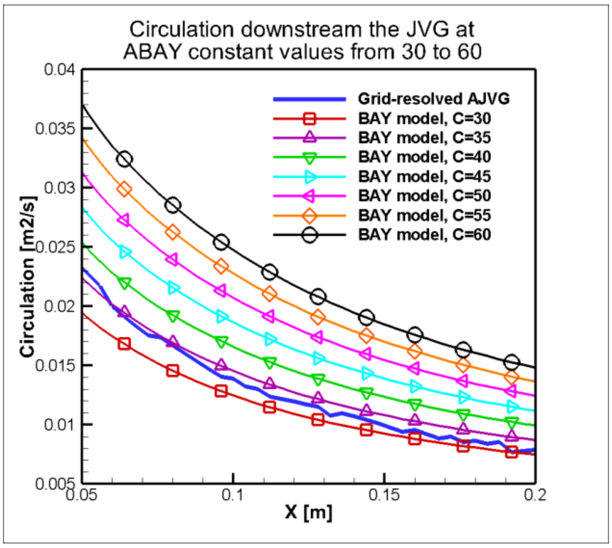

Fig. 4.1 Comparison of circulation values behind grid-resolved JVG with circulation values behind ABAY models constant values from 30 to 60. For the cases of BAY model the fine grid was used

In the Fig. 4.2 is presented circulation downstream the JVG's hole for grid-resolved JVG and BAY models with constant C=35 in various grids. The very good agreement of circulation values is obtained. The highest differences in plots were observed in the region shortly downstream of JVG, from 0mm to 10mm. It is caused by different models and vortex creation differences.

In the Fig. 4.3 are presented x-vorticity contours at section 4cm downstream JVG. In the contours is shown very good agreement of vortex shape and x-vorticity values and independence of used grid. With the closed edge is drawn the shape of grid-resolved JVG and with dashed edge is drawn the shape of JVG surface in grids, where wasn't used the grid-resolved JVG. The primary vortex colored by red colors is clockwise rotating and is ellipse shaped.

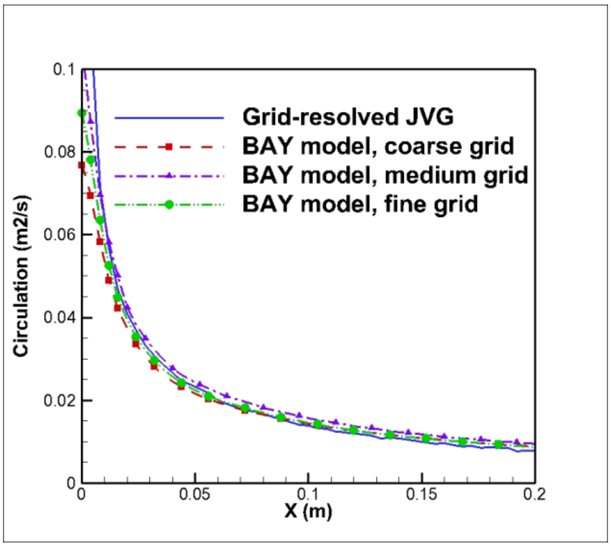

Fig. 4.2 Circulation downstream the JVG's hole

In the Fig. 4.4 are presented the skin-friction coefficients at sections 48mm (left plot) and 108mm (right plot) downstream of JVG. Good agreement of skin friction coefficient distribution is obtained. In the region of JVG influence, the values are a bit different. This difference may be caused by different intensity of vortex calculated in CFD and measured in test section.

In the Fig. 4.5 are presented streamwise x-vorticity plots for all investigated cases at location X=0.02m at two different heights above wall surface 1mm (left plot) and 2mm (right plot). The source term model properly captures the x-vorticity changes in the boundary layer, which is turbulent.

5 Conclusions

The original BAY model was modified so it could work also in other type of vortex generator - jet (fluidic) vortex generator. Numerical simulations are carried out with the implemented JVG model based on lifting-force theory in order to predict effects as induced by

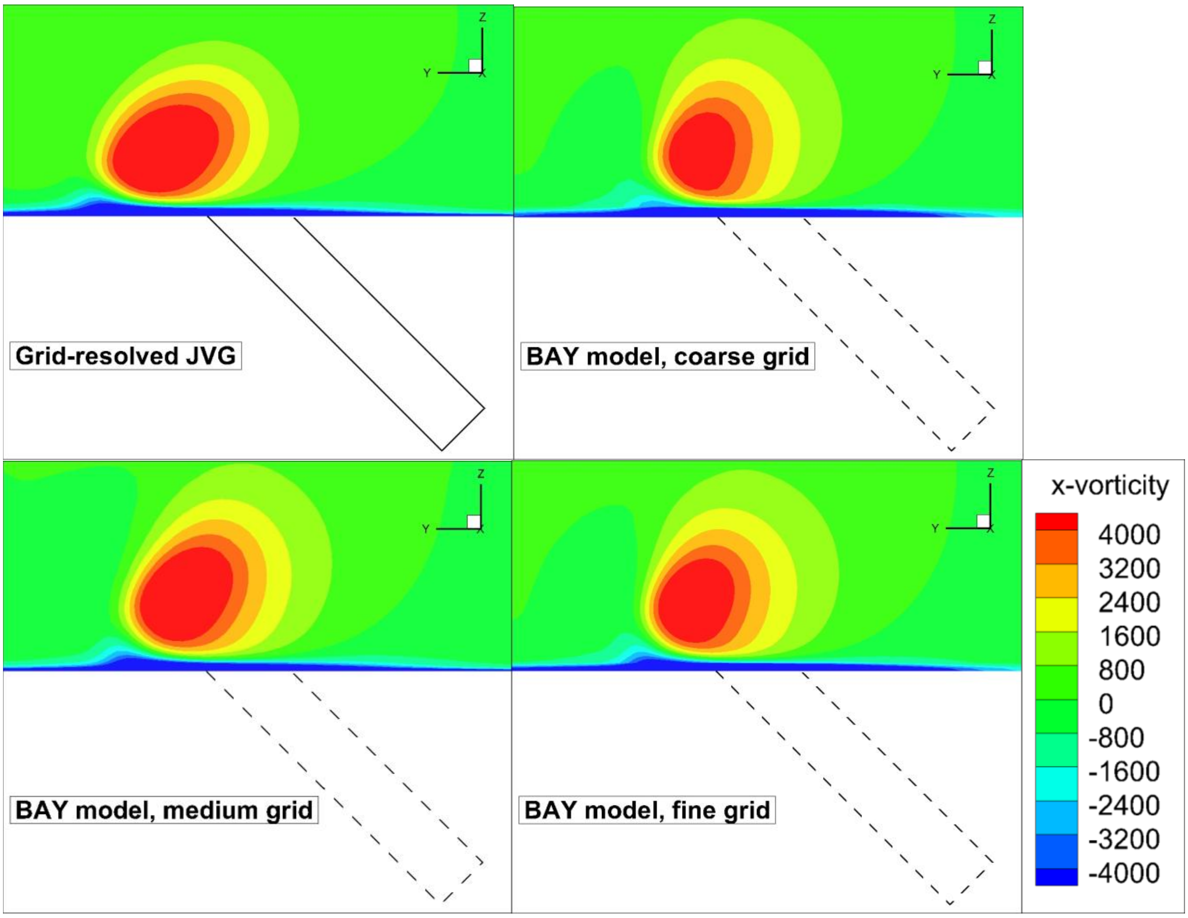

Fig. 4.3 X component of vorticity contours at section 4cm downstream JVG for grid-resolved JVG and its BAY models used in coarse, medium and fine grids

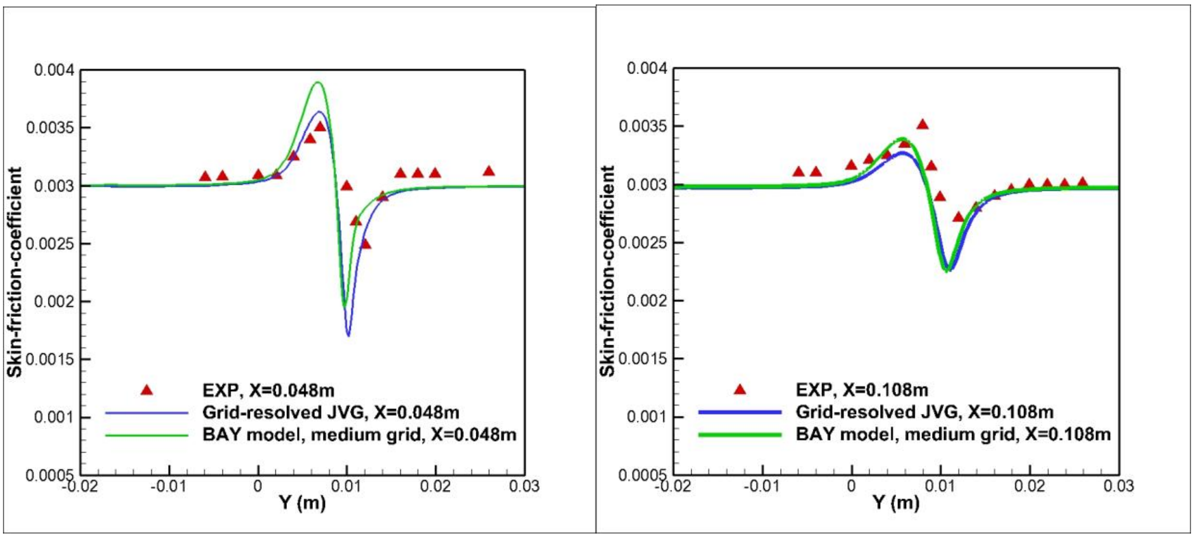

Fig. 4.4 Skin friction coefficient in surface traverse at X=0.048m (left plot) and at X=0.108m (right plot) and comparison with experiment results

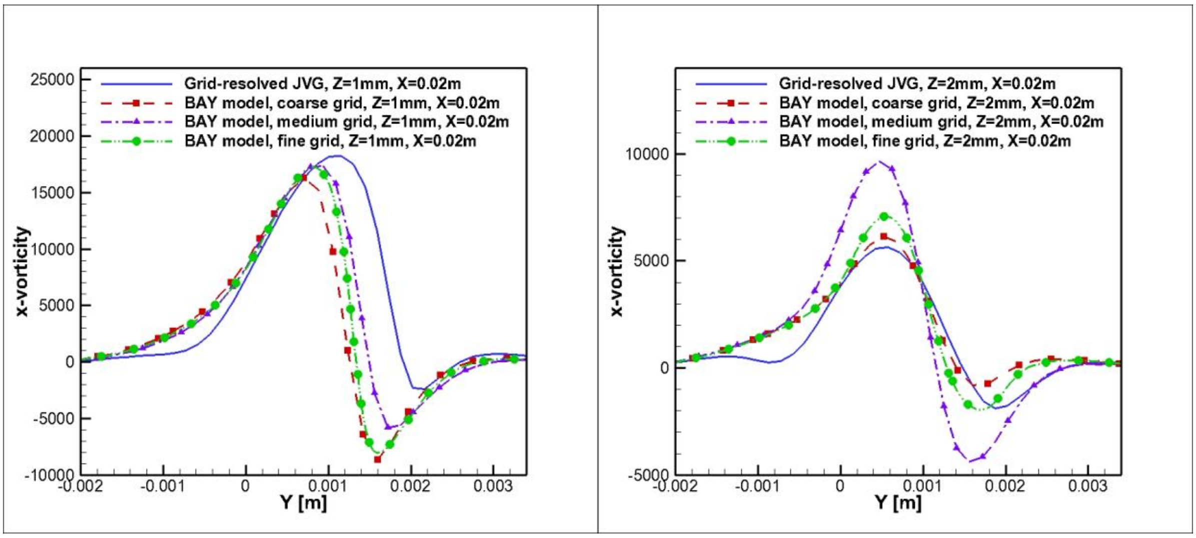

Fig. 4.5 Cross stream x-vorticity for grid-resolved case compared with source term models at various grids at X=0.02m and Z=1mm (left) and Z=2mm (right)

grid-resolved JVG. It has been proven that new modification of BAY model is very good model to predict flow with an active JVG using the ANSYS Fluent solver using source term method implemented in User Defined Function. The only region where model fails to reproduce the grid-resolved JVG effects is the region closely downstream of the hole (few diameters to the hole). Proposed modification of BAY model enables to model vortex generators of various diameters and injection angles to the main flow. Thus BAY model is a good candidate to predict flows behind JVGs. The disadvantage of BAY model is the fact that its constant must be calibrated, in example using experimental data or grid-resolved model computation results.

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7 Contact Author Email Address

Paweł Flaszyński pflaszyn@imp.gda.pl

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