THE EFFECT OF SUB-GRID SCALE MODELS ON THE LARGE EDDY SIMULATION OF A CORRUGATED CHANNEL FLOW

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Introduction

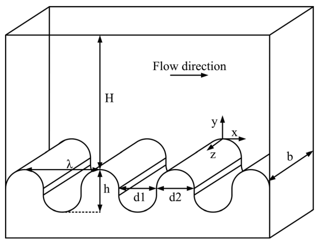
Corrugated channels or multiple cavities, are widely appeared in numerous applications from gas turbine, ship to ship fuel transfer, to heat exchangers in solar energy systems, due to their flexibility, ease of manufacturing and increased heat transfer coefficients. Although devices with such geometry are frequently used for last few decades, its associated flow dynamics, including the flow separation and reattachment on the corrugated surface, momentum exchange between bulk flow and the flow in the corrugation, and the transition from boundary layer to separated shear layer, are still not properly understood. The combination of these effects lead to a minor modification in corrugation geometry triggering a significant change in flow structures and heat transfer characteristics.

Such an interesting and challenging subject has been attracting researchers' interests for almost a century. Its earliest experimental study can be traced back to 1928 when Fritsch ([1] of [2]) investigated the velocity distribution along the mid-plane of various rough surfaces including a corrugated (wavy) channel. It was reported that the velocity distribution depends only on the shearing stress, no matter the stress is changed by different roughness or Re, indicating turbulence plays an important role in corrugated channels. Some pioneer works by Perry et al. [3] and other researchers [4, 5] on square cavities reported when the length-to-height ratio of the cavity is greater than 4, the vertices inside the cavity become unstable and reattachment appear at the bottom of the cavity, and increasing the cavity length and Re will intensify the interaction between bulk flow and cavity flow, but changing of the cavity height did not affect the flow behaviours. Subsequent numerical analysis on this geometry [6] indicated even Reynolds Averaged Navier Stokes (RANS) solution can have a good agreement with experimental data. Nevertheless, numerical prediction of the flow on curved cavities has been proved to be more challenging [7]. Current research of curved wavy corrugated geometry are divided into two categories, i.e. the corrugation with a shape of sinusoidal wave and of periodic hill. Extensive experimental and numerical studies have been conducted for both categories. Results suggest flow separation and reattachment on curved surfaces are very unstable. The flow field can be turbulent around the curved surfaces at a Reynolds number, Re, of as low as 100 as suggested by Direct Numerical Simulation (DNS) of Krettenauer and Schumann [8]. Various studies [9, 10, 11] also demonstrated that the flow separation and reattachment, thereby the entire flow, are profoundly influenced by the modelling approximation, i.e. the wall treatment, SGS modelling and grid density. Therefore, RANS, under resolved Large Eddy Simulation (LES), and improper selection of wall modelling will fail to capture the main characteristics of the flow.

Despite of the fact that extensive studies have been carried out on simple wavy geometry and some best practices have been identified, studies on realistic geometry used in industry which resembles the configuration of the curved wavy corrugated flow have not been systematically performed. Those geometries, such as the flexible pipes and secondary flow system in gas turbine engine, tend to have less (or even no) post-reattachment-recovery region than the case in the periodic hill and much smaller length-height ratio of cavity than those corrugations with a shape of sinusoidal wave. Jaiman et al. [12] performed a numerical simulation on cryogenic flexible pipe for LNG transformation by a RANS and Delayed Detached Eddy Simulation (DDES), and observed a steady solution for RANS and unsteady one for DDES. Unal et al. [7] conducted Unsteady RANS and LES on a corrugation geometry of flexible pipes, and found LES can capture the unstable motion of the separation and reattachment points, and the strong mixing effect between flow in the corrugation and the bulk flow, while URANS fails to do so. But the study also pointed out the time-averaged values predicted by LES are not in good agreement with the experimental data. So the objective of current research is to study the sensitivities of the solution to SGS models on the realistic geometry.

Case Configuration

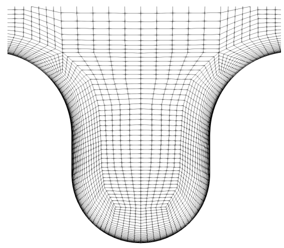
The corrugated channel investigated in present work is a 2D representation of a widely used commercial stainless steel flex pipe (heat exchanger) with a circular cross section. The geometry has a rectangular cross section, as shown in Fig. 1a, the bottom wall has a wavy shape with periodic grooves, whereas top wall and two sidewalls are both flat plates. A experiment with identical geometry and dimension is carried out by using Particle Image Velocimetry (PIV) technique [13], the dimensions of the geometry is shown in Fig. 1b.



(a)

Variables	Description	Value (mm)
H	channel height	15.85
h	corrugation height	4.15
λ	wavelength of the corrugation	6.6
d_1	diameter of the groove	3.0
d_2	corrugation diameter	3.6
b	channel width	20

(b)



(c)

Figure 1: (a). Schematic Representation of Corrugated Channel; (b). Dimentions of the corrugated channel; (c). Mesh used in current LES.

The structured hexahedral mesh used in current study is shown in Fig. 1c. The mesh density increases as approaching the wall. The first layer distance on corrugated wall is less than 0.005 mm, on top wall is less than 0.006 mm and on side walls is less than 0.06 mm. A posterior analysis shows that y^+ value for corrugated wall is less than 0.25 with mean value of 0.04, for top wall it is less than 0.16 with mean value of 0.11, for side walls it is less than 2.4 with average value of 0.72, justifying the use of no-slip wall boundary condition. The total number of mesh cells for each corrugations is 0.9 million.

SGS Models

The SGS models studied in current research are listed in Table 1, which are all the standard implementations in OpenFOAM v1612+.

Table 1: Summary of SGS models tested in current channel flow case.

SGS Models	Model Description
SMAG+VD	Smagorinsky SGS model ($C_s = 0.2$) with van-Driest wall damping function
KEQ+VD	k-equation SGS model with van-Driest wall damping function
DyK	Dynamic k-equation SGS model
WALE	Wall-adapting local eddy-viscosity (WALE) SGS model

Numerical Setup

Re, based on bulk velocity, U_b, and hydraulic diameter of the channel is 5300. The density and laminar viscosity of the fluid is $\rho = 998.2kg/m^3$ and $\mu = 0.001\ Pa\ s$ respectively, leading to U_b = 0.3 m/s. Periodic Boundary Condition (BC) is applied on both inlet and outlet, i.e. the two plane normal to x direction. The corrugated wall, two side walls, and the top walls are set to be no-slip, matching the BC used in experiment. Due to the shape of the corrugated wall, U_b for the whole computational domain must be carefully adjusted to ensure the desired bulk velocity at the inlet. Spatial interpolation of convection and diffusion terms are based on second order central differencing scheme. Time marching is approximated by second order backward differencing implicit scheme with a time step size $\Delta t = 5 \times 10^{-5}s$. The decoupling of velocity and pressure in the equation is obtained by Pressure Implicit with Splitting of Operators (PISO) algorithm. Velocity components are calculated by one momentum predictor step using smooth solvers with symmetric Gauss-Seidel smoother. While pressure field is corrected twice by generalised geometric-algebraic multi-grid (GAMG) solver with Gauss-Seidel smoother for the first corrector step and diagonal incomplete-Cholesky/LU with Gauss-Seidel (DICGaussSeidel) for the second one. A fully developed flow field with SMAG+VD are used as initial condition for all cases with other SGS models. All cases are allowed for a further 1s simulation to ensure the fluctuation induced by change of SGS model to be settled, followed by an averaging window of 8s. Flow field became statistically steady before data processing.

Results and Discussion

Despite of not showing here, all SGS models tested in current study are able to predict a chaotic, 3-dimensional and unstable flow field. Fig. 2a and Fig. 2b show the effect of various corrugation lengths and grid density on the normalised mean stream-wise velocity $\langle u \rangle / U_{mean}$, at mid-plane predicted by SMAG+VD. They suggest the suitable channel length for performing the simulation is $L = 16\lambda$ and current grid (referred to as Grid 1 in Fig 2b) is adequately fine, since further increase of channel length and grid density (Grid 2 in Fig 2b) have almost no effect on result. The adequacy of the grid density are also confirmed by the energy spectrum analysis (Fig. 2d) for a point close to the rising slope of the corrugation, as the spectrum is continuous and largely follow the slope of $\kappa^{-5/3}$. So all simulation are carried out with $L = 16\lambda$ on Grid 1.

The $\langle u \rangle / U_{mean}$ at mid-plane predicted by various SGS models are shown in Fig. 2c. It suggests that the simulation is insensitive to the selected SGS models, since all models predict a similar magnitude of $\langle u \rangle_{max}$ which locate at $y/h = 1.93$, slightly above the centreline ($y/h = 1.91$), suggesting the effect of corrugated wall on bulk flow is captured by different SGS models to a certain extent. The profile of time-averaged Reynolds stresses which is presented in Fig. 3 also demonstrate the insensitivity of the result on different SGS models. The magnitude and location of the maximum turbulent intensity obtained by different models are very similar for both top and corrugated wall with only marginally difference being observed on DyK. The CPU time is also compared between different models, it is found WALE is around 4% faster than SMAG+VD, whereas KvD and DyK are respectively 27% and 20% more time consuming than SMAG+VD.

Conclusion

The effect of SGS models on the prediction of a corrugated channel flow is investigated. A grid independence study was conducted prior to the main simulation, which found a total channel length of $L = 16\Lambda$ and Grid 1 are suitable for current study. Simulation outcome for SGS models of SMAG+VD, KvD, DyK and WALE are studied. It is learned that both time-averaged stream-wise velocity and turbulent intensity results are insensitive to SGS models. CPU time required for different SGS models is also compared, which shows the simulation of WALE are slightly (4%) faster than SMAG+VD, and KvD and DyK are over 20% slower than SMAG+VD. Therefore, WALE with $L = 16\lambda$ and Grid 1 will be used for further study on the corrugated channel flow.

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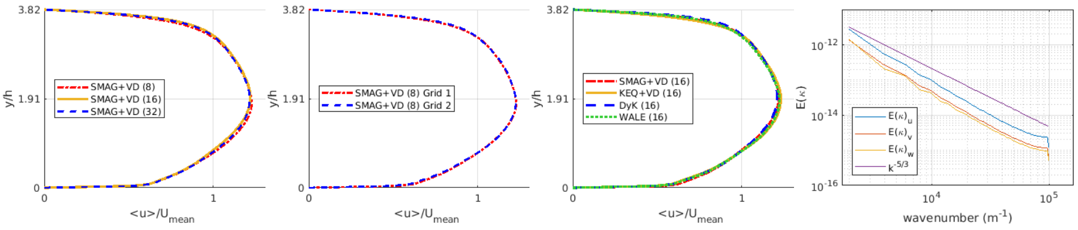
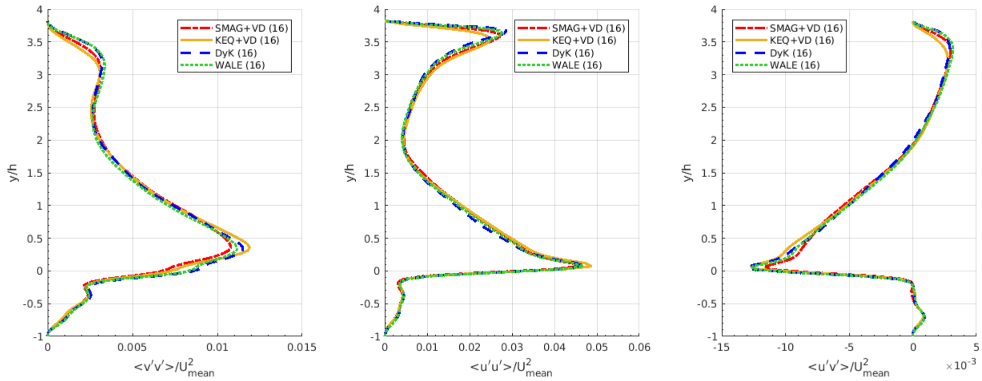
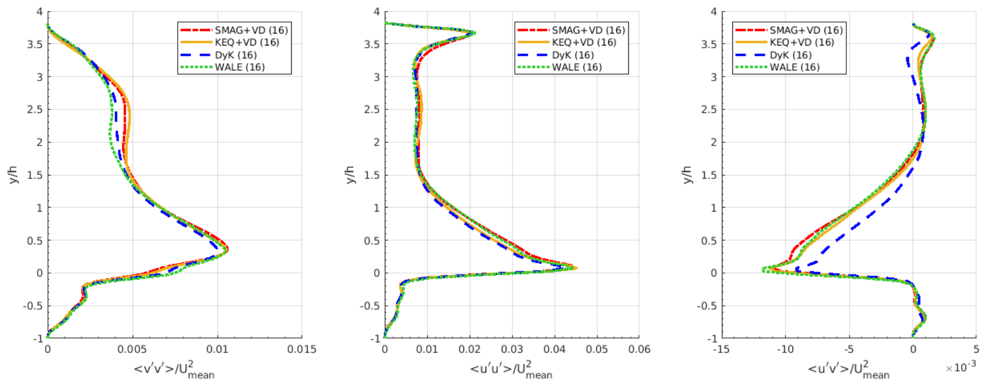


(a) **(b)** **(c)** **(d)**

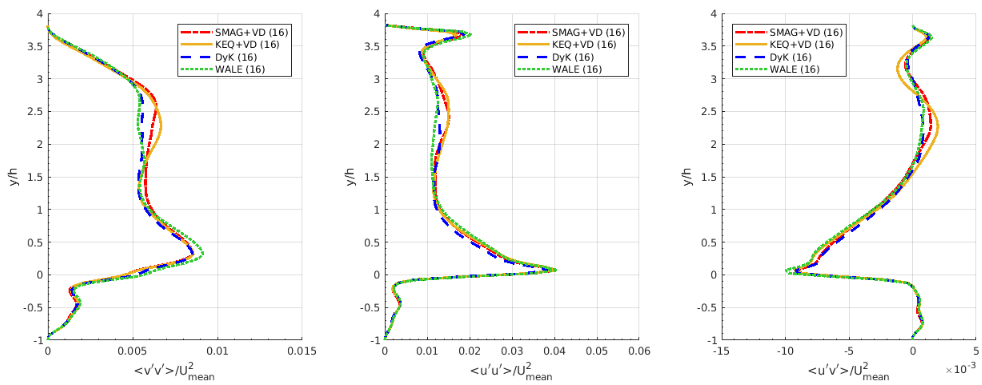
Figure 2: Predicted normalised mean stream-wise velocity, $\langle u \rangle / U_{mean}$, at mid-plane: (a). by SMAG+VD on different lengths of computational domain; (b). by SMAG+VD on different grid densities; (c). by different SGS models under 16 corrugations case. Also, (d). Energy spectrum, $E(\kappa)$, as a function of wavenumber recorded for a point close to the rising slope of the corrugation.



(a) $z/b = 0.5$



(b) $z/b = 0.75$



(c) $z/b = 0.85$

Figure 3: Profile of resolved Reynolds stresses, $\langle u'u' \rangle$, $\langle v'v' \rangle$ and $\langle u'v' \rangle$, normalised by mean velocity square at different location along z direction predicted by different SGS models.