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Procedia Engineering 147 (2016) 68 – 73

Procedia Engineering

www.elsevier.com/locate/procedia

11th conference of the International Sports Engineering Association, ISEA 2016

Comparison of turbulence modeling approaches to the simulation of a dimpled sphere

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Abstract

Use of computational fluid dynamics (CFD) in the aerodynamic simulation of sports projectiles has always been a challenge. The majority of these are spherical, classic bluff bodies, which typically experience flow transition during flight, and large flow separations. Current research of such flows is predominantly concentrated on the use of computationally intensive large eddy scale (LES) simulation methods, and even direct numerical simulation (DNS). Use of such approaches requires careful application of the models, and significant computational resource. The alternative is the use of unsteady Reynolds-averaged Navier Stokes (URANS) turbulence models, which are typically known to struggle in such flow scenarios. URANS however are, in comparison to LES, computationally economical and as such these models find significant use amongst both industry and academia alike, and their development still continues. In recent years transitional URANS models based on the calculation of intermittency, and hybrid scale resolving simulation approaches (SRS), have started to appear in proprietary CFD codes. Hybrid SRS models such as scale adaptive simulation (SAS) and detached eddy simulation (DES), combine LES with the use of economical well tuned URANS in the simulation of near wall flows. However to date the use of such models in the simulation of sports projectiles has been extremely limited. This paper provides a CFD comparison of these turbulence modelling approaches, with application to the simulation of a dimpled sphere, a golf ball. The study investigates and compares the suitability of URANS, transitional URANS, and SRS models. Simulations are run between 10,000 < Re < 115,000, from sub-critical through transition to supercritical. Comparisons are drawn between predictions of drag coefficient, dimple shear layers and surface shear stress, with URANS being shown to be in reasonable agreement with SRS. However as may be expected although URANS predicted a comparable size of wake to SRS, no small scale structure was observed. Indeed it is shown how URANS failed to demonstrate any large scale time periodic shedding phenomena, instead becoming essentially steady state.

Peer-review under responsibility of the organizing committee of ISEA 2016

Keywords: Dimpled Sphere; CFD; Turbulence Model

1. Introduction

The majority of sports projectiles are spherical, classic bluff bodies. These experience a range of turbulent phenomena in play including transition and flow separations, that can give characteristic flight behaviors; swing of a cricket ball, swerve of a soccer free kick, etc. It is these turbulent phenomena that make the use of Computational Fluid Dynamics (CFD) in the aerodynamic simulation of sports projectiles such a challenge. However the range of turbulence models available within modern CFD codes to resolve these phenomena is large; a result of the fact that no single model is suitable for all scenarios. They exist as Direct Numerical Simulation (DNS), of the Navier-Stokes equations that would resolve all scales of turbulence, is generally viewed prohibitive for all but the simplest of flow problems. Traditionally two families of model exist [1]; RANS (Reynold Averaged Navier Stokes), and SRS (Scale Resolving Simulation) in the form of Large Eddy Simulation (LES), Fig.1. LES methods resolve the largest turbulent scales within a flow, and filter the smaller scales (dependent on mesh resolution) using various subgrid scale models. Use of this approach requires careful application of the models, and significant computational resource, yet it can be used in simulation of transitional flow. The alternative is the use of RANS or URANS (Unsteady-RANS) eddy-viscosity models that compute mean flow with no attempt to resolve spatial or temporal scales. These typically struggle with the simulation of

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Peer-review under responsibility of the organizing committee of ISEA 2016
doi:10.1016/j.proeng.2016.06.191

bluff bodies subject to massive separations, and subcritical flow where shear layers are laminar at separation yet wake structures are turbulent; however they are economical in use. In recent years Hybrid SRS/URANS models have started to appear within codes such as scale adaptive simulation (SAS) and detached eddy simulation (DES), combine LES with the use of economical well tuned URANS in the simulation of near wall flows. Additionally transitional URANS models based on the calculation of intermittency have also appeared.

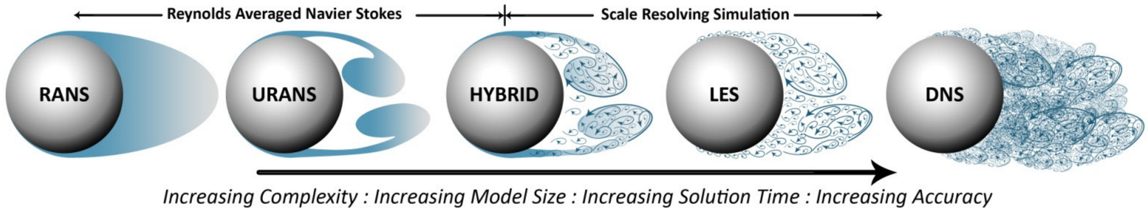

Fig. 1. Example of turbulent spatial scales resolved by modeling approach

When conducting a CFD simulation of a spherical bluff body, instinctively the use of LES would therefore appear most suitable. Indeed the use of LES, and latterly DNS, is where the majority of effort into CFD simulation of spherical bodies has been concentrated. This is also the case of CFD simulation of spheres with a direct sports application. The majority of CFD studies published investigating spherical sports bodies, have been dimpled spheres; golf balls. These studies often compare predicted model performance against the classic experimental paper of Bearman [2]. Ting [3] first used CFD simulation to analyse golf balls, and the influence of novel teardrop dimple configurations [4]. The experimental work of Aoki [5,6] studied the influence of dimple depth (k), and number, on aerodynamic behavior. Aoki [6,7] then used LES simulation to explain the influence of dimple shape on measured drag. Simulations were conducted in the supercritical regime on a 1 million cell mesh, extremely small for such LES simulation. Although the results for traditional arc dimples were in good agreement to experiment, alternative dimple shapes returned drag coefficient, C_d, values close to that of a smooth sphere.

Smith [8] conducted subcritical and supercritical DNS simulation of a non-rotating golf ball, revealing in detail the formation of shear layer instabilities at the leading edge of dimples, that reattach on the trailing edge. This was in agreement with the experimental observations of Choi [9] who hypothesized that the localized flow separations and subsequent reattachment within the dimples increased momentum and delayed overall flow separation. This behavior was also observed by Aoki [10]. The computational cost for such DNS simulation was extremely high. In order to resolve structures properly a mesh size totaling 1.2 billion computational cells was required in the supercritical regime, and understandably required significant computational effort to obtain solution. To date this simulation remains one of the largest single simulations, of an item of sports equipment, ever conducted. The effort in understanding the flow structure is particularly placed in context considering the only other billion cell sports simulations have been full models of yachts or race cars.

Beratlis [11] extended the work of Smith [8], applying the same approach to the simulation of rotating dimpled spheres, to study Magnus effect across the subcritical, critical, and supercritical regimes. Again significant computational resource was required; 260,000 cpu hrs/rotation of supercritical simulation. Magnus effect has also been investigated using LES by both Aoki [12] a supercritical simulation using a 1.5 million cell mesh, and Li [13] across all flow regimes using a 150 million cell mesh. However what is evident from all of these scale resolving simulations, is that predicted drag was in acceptable agreement to experiment. The main difference appears the resolution of the flow details resolved, directly influenced by the mesh resolution.

Although DNS and refined LES simulations are impressive in flow detail they produce, and typically viewed as the only method by which to accurately simulate such flow, day to day use of these methods is beyond the majority of academia and industry. Instead the majority of users strike a balance between the accuracy and economy of the solution, hence the continuing popularity of URANS. Studies comparing turbulence methods to the simulation of spheres have been published. Constantinescu [14] presented a study of the capabilities of URANS, and hybrid SRS to the simulation of a subcritical smooth sphere, and Bogdanovic-Jovanovic [15] presented a comparison of RANS (k-ε, k-ω) and DES (subcritical only), of a dimpled sphere. However the recent appearance of transitional URANS, and hybrid SRS models may be of real interest to the simulation of these bluff bodies; which additionally provide an interesting challenge of model capabilities.

The main objective of this paper is therefore the evaluation of current turbulence models, including URANS, transitional URANS, hybrid SRS and LES, to the simulation of dimpled spheres across subcritical, critical, and supercritical flow conditions.

2. Problem definition

Modelled geometry was based upon a generic dimpled sphere, as previously studied experimentally by Aoki [5], with a diameter d = 42.6 mm and 328 evenly spaced circular dimples as detailed in Fig. 2a. This configuration is comparable to conventional golf ball geometries, and those studied by Bearman [2] and Smith [8]. Dimple variables are shown in Fig. 2b. The computational domain is spherical in shape with a diameter of 30d, the modelled sphere placed centrally, Fig. 2c. The domain was split in half creating separate flow inlet and outlet boundaries. Simulations were conducted from subcritical Reynolds number (Re = 10,000), through transition to the supercritical regime (Re = 115,000) with inlet flow velocity specified accordingly. Turbulence values at flow boundaries were specified using turbulence intensity T_i = 0.3% and turbulent viscosity ratio TVR = 1.

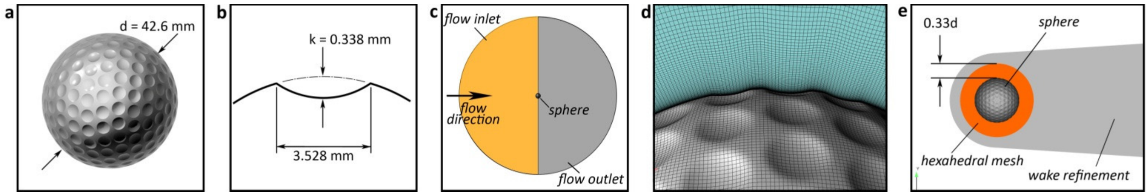

Fig. 2. (a) modeled golf ball; (b) modeled dimple depth; (c) modeled flow domain; (d) mesh detail; (e) mesh regions

3. Computational setup

This study was conducted using the commercial CFD code ANSYS Fluent V15, comparing URANS, transition, and scale resolving simulation (SRS) turbulence methods. The governing equations and turbulence models were solved in a time dependent manner, using non-iterative time advancement. This was implemented with fractional step pressure-velocity coupling. A time step of T_s = 0.02d/U where U is free stream velocity, was used for advancing solution. This was reduced when necessary to ensure adequate time step convergence (less than 10^{-4} for all residuals), particularly important with SRS models. For example, LES required T_s = 0.002d/U to ensure adequate convergence. All simulations used 2nd-order spatial and temporal discretisation for all equations unless otherwise stated. Simulations were monitored for residual, force coefficient, and variable convergence. All simulations were performed on a Hewlett Packard HPC using a parallel distribution across up to 84 processing cores.

3.1. *Mesh*

The use of transition, and SRS models, requires high quality mesh and careful consideration should be made for wall bounded flow. When creating such mesh it is important that y+ ≈ 1, normalized distance to the wall surface from the centre of the first computational cell. It is also important to ensure sufficient nodes are placed across the boundary layer, (approximately 10 nodes with URANS, 30 nodes with SRS). The sphere surface in this study was meshed with pure quadrilaterals using a cubed fitted sphere approach. This essentially wrapped the sphere, creating a slight rounded edge profile to each dimple, Fig. 2d. Each dimple had a minimum of 16 nodes across its diameter. Fully structured hexahedral mesh was constructed from this surface, and it was found from mesh dependency studies that a minimum of 40 layers of pure hexahedral mesh was required. In this study 80 layers were constructed extending a distance 0.33d from the sphere surface, Fig. 2e. The surrounding flow domain was filled with polyhedral mesh, with a refined mesh in the wake region of the sphere. This created a mesh containing 9.95 million hexahedral cells, with a combined total size of 15.15 million cells.

3.2. *Turbulence models*

URANS, transitional URANS, and SRS methods, have all been implemented, as detailed in Table 1.

Table 1. Applied turbulence models.

Turbulence Model	Model Family	Notes
k-ω SST	URANS	Shear Stress Transport formulation [16]
Low Re k-ω SST	URANS	Inclusion of the Wilcox low Reynolds number terms [*]
Transition SST	URANS	SST with inclusion of equations for Intermittency and transition onset criteria
SAS – Scale Adaptive Simulation	SRS – URANS	Coupled with Transition SST for near wall flow
DDES – Delayed Detached Eddy Simulation	SRS – URANS	Coupled with k-ω SST Low Re for near wall flow
LES (WALE) – Large Eddy Simulation	SRS	WALE – Wall Adapting Local Eddy Viscosity Model

All models assessed, with the exception of LES, are either based on or incorporate the k-ω SST model as proposed by Menter [16]. This is a well respected model for the simulation of flows subject to separation. The model has been compared in its basic form and with the inclusion of Wilcox low Reynolds number terms [17]. Including these terms is recognised to create a pseudo transitional behaviour, however the model does not directly attempt to solve transition [16]. In contrast the transition SST model does attempt to predict transition, coupling the k-ω equations with additional equations that solve intermittency and transition-onset momentum thickness Reynolds number [18]. Although a range of transitional models are available in Fluent, these all typically behave in a similar manner, so Transition SST was chosen as representative. A series of SRS methods have been included in the present study; SAS, DDES, LES. These models are capable of resolving a range of turbulence spectra, more than a single mode vortex, which can be a characteristic of URANS SST, and as a result have increasingly stringent mesh quality requirements. LES is suitable for the simulation of transitional flow with appropriate subgrid scale modelling, and was included here using WALE (Wall-Adapting Local Eddy-viscosity) formulation. WALE was chosen as the model provides zero eddy viscosity when dealing with laminar flow, important for transition. SAS and DDES models incorporate LES modelling of free stream flow with URANS simulation of near wall flow, and are therefore less computationally expensive. Both SAS and DDES can be coupled with transition models, however only the DDES can be applied with Wilcox low Reynolds number terms. SRS models additionally require use of bounded central differencing when solving the momentum equations, as 2^{nd}-order schemes are numerically diffusive. An extensive discussion of turbulence models will not be recounted here but can be found in Spalart [1] and Menter [16,18,19].

4. Results

Results of predicted C_d vs Re for turbulence models assessed are shown in Fig. 3. Values are shown in comparison to the experimental works of Bearman [2], Aoki [5], and Choi [9], and clearly demonstrate the influence dimple depth (k) has upon transition. DNS values of Smith [8] are also included. URANS was shown to produce reasonable results, with good agreement as expected in the supercritical regime. The k-ω SST model with low Re terms is shown to outperform the standard k-ω SST model, in particular a sudden drop in C_d is predicted between $55{,}000 < Re < 65{,}000$ revealing its pseudo transitional characteristics. This was in contrast to the transition SST model that did not predict a transition crisis, but instead demonstrated a linear reduction in C_d vs Re, resulting in over prediction of supercritical C_d. The reason for this behavior is unknown but could be attributable to the mesh; transitional models have particularly stringent requirements which may not have been met, or the model with current coefficients may not be suitable for this application; this requires further investigation. SRS approaches overall outperform URANS, particularly in the subcritical region. LES and DDES both outperform SAS; DDES performed particularly well. It is believed the performance of SAS was in part due to coupling with Transition SST, whereas DDES used low Re k-ω SST, not possible with SAS.

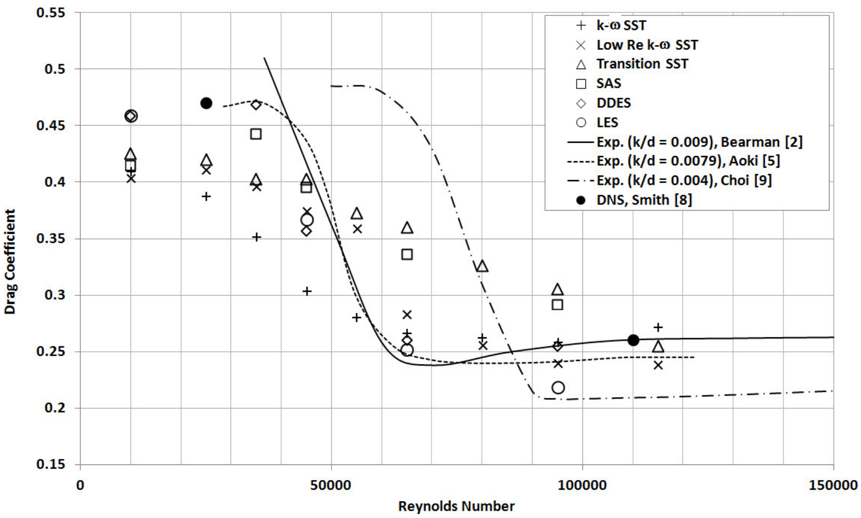

Fig. 3. Drag coefficient from current study with data from Bearman [2], Aoki [5], Choi [9], and Smith [8]

Filled contour plots of instantaneous spanwise vorticity shown in Fig. 4 reveal detail of flow separation and turbulent flow structure around the sphere; influence on structure of turbulence model choice, is clearly visible. The downstream progression of flow separation with increasing Re can be seen in the URANS models, and the influence in transition delay visible for low Re k-ω SST. As would be expected only mean flow field representation of the detached shear layer is predicted, devoid of turbulent structure. The URANS models essentially behave close to a steady manner with only localized small scale shedding that quickly dissipates and does not develop into a full unsteady wake. Transition SST produces shear layers with greater instability, however again no large scale turbulent wake structure are evident. Kelvin-Helmholtz structures are evident however in SRS simulation, particularly DDES and LES. These models predict the laminar shear layer separation and subsequent transition to turbulent structure. In contrast to DDES and LES, SAS produces weak instability in the detached shear layer, and does not appear to resolve any small scale turbulent structure within the wake behind the sphere. SAS can however fall back to URANS behavior where instability is not particularly strong, whereas DDES will always behave in a LES mode. It is for this reason in part that DDES has mesh quality constraints closer to LES than SAS.

Prediction of vortical structures can be confirmed by visualizing Q criterion flow structure as shown in Fig. 5. These reveal the core locations of turbulent vortices and structures, whilst avoiding the display of shear layers that may conceal such structure. SAS can be seen to predict large scale turbulent vortex shedding in the wake, however the initial shed structures are comparable to URANS. This is in contradiction to the wide spatial and temporal range of structure that might actually be expected and as seen in the LES simulation. URANS is seen to fail to predict any large scale shedding within the wake, however vortex tubes visibly roll away from the dimples, before dissipating out. The influence of the mesh resolution within the wake is also clearly evident. This region was meshed using polyhedral cells, and the transition between polyhedral and hexahedral mesh has a clear influence on the resolved wake. Particularly noticeable is the sudden reduction of turbulent spatial scales resolved using LES. This could be improved by the use of pure hexahedral mesh in the wake region.

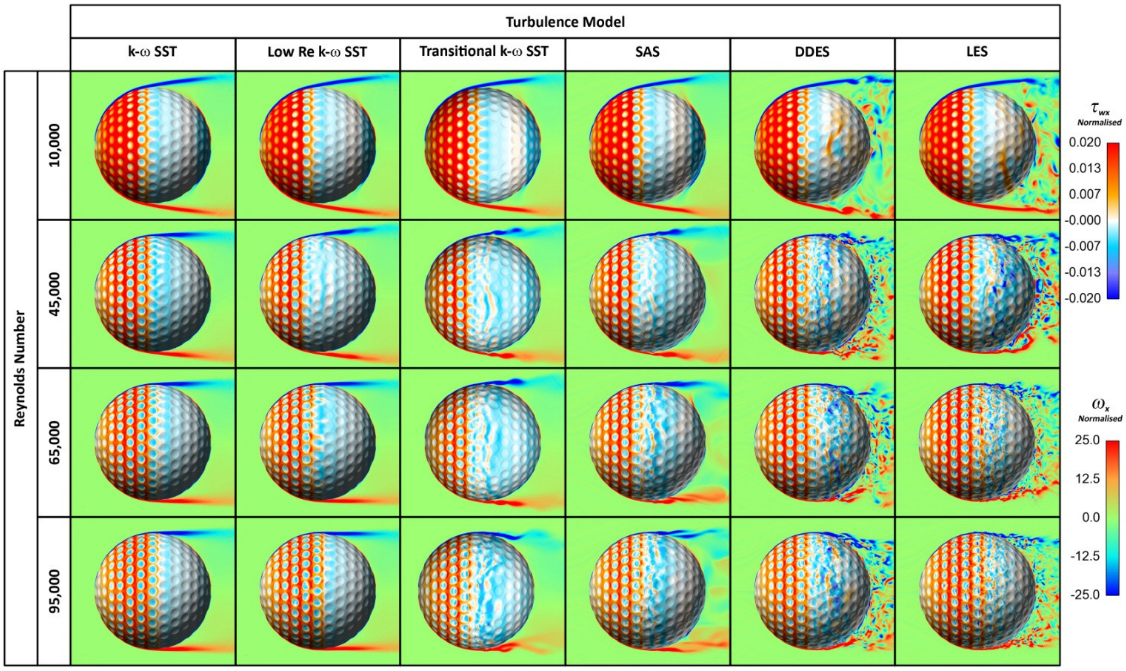

Fig. 4. Instantaneous contour plots of surface shear (τ_{wx}), and flow field spanwise vorticity (ω_x)

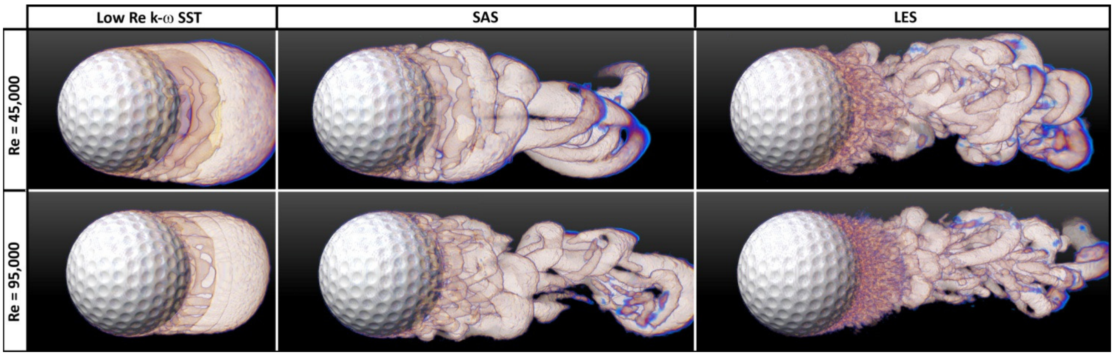

Fig. 5. Q criterion flow structures

All turbulence modelling approaches resolved dimple shear layer structure. An example of this is shown for Re = 65,000, where flow behavior moves from critical to supercritical, in Fig. 6a. Shear layers across two rows of dimples are shown, at dimple centres 67.5^{o} and 78.75^{o} respectively, measured from the stagnation point on the front of the sphere. As seen in agreement with Smith [8] and Choi [9], shear layers detach from the dimple leading edge, and a small region of circulating flow resides in the dimple. The shear layer is seen to reattach on the dimple trailing edge. Shear layers were observed to begin formation across dimples from 33.75^{o}, and the flow was measured to final separate fully from around 105^{o}~112^{o}, dependent upon model. The extent of the URANS mean predicted shear layer was not as large as seen with SRS methods, where individual structures could also be viewed to pass across the dimples. The resolution of the structures across the dimple shear layers appear stretched which is again attributable to the underlying mesh. Shedding was most evident with LES, which was not reliant on URANS solution of the boundary layer. Filled contours of wall shear stress, Fig.6b. reveal layer separation and reattachment, and show the influence and movement of turbulent structures within and across the dimples.

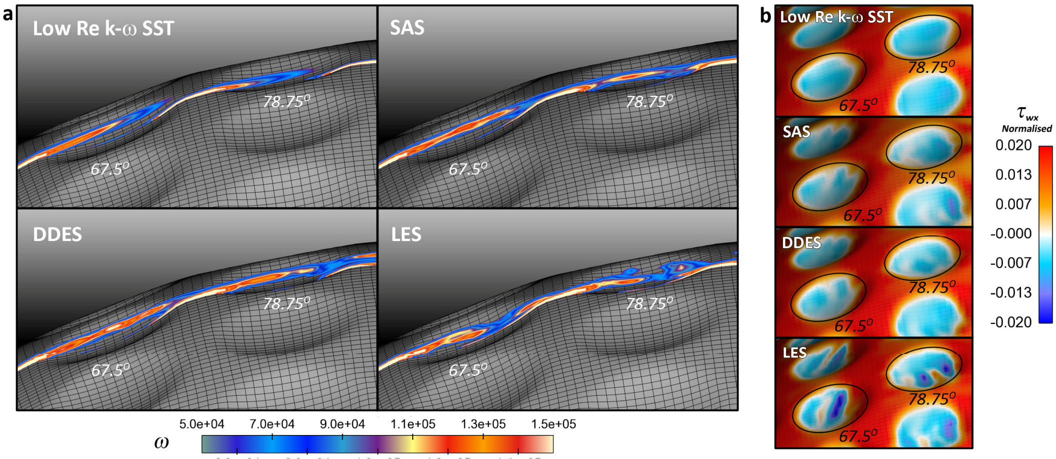

Fig. 6. (a) Clipped contours of instantaneous voticity magnitude (ω), Re = 65,000; (b) contours of instantaneous surface shear stress (τ_{wx}), Re = 65,000

5. Conclusions

A comparison of turbulence modeling approaches to the simulation of a dimpled sphere has been presented. The study compared URANS, transition, and SRS models, simulating 10,000 < Re < 115,000 from subcritical through transition to supercritical flow. URANS, in low Re formulation, was shown to produce reasonable prediction of C_d and shear flow structure. However as might be expected SRS produced superior results especially in the subcritical regime. DDES performed particularly well, comparable to LES. Transition models require further investigation. URANS failed to predict time dependent turbulent flow structure of dimple shear layers and large scale periodic shedding of wakes as revealed by SRS. Influence of mesh quality, resolution, and spacing, was also evident.

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