

**DRAG REDUCTION IN TURBULENT CHANNEL FLOWS  
BY MODIFYING LARGE SCALES OF THE FLOW**

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**DEPARTMENT OF APPLIED MECHANICS  
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BY MODIFYING LARGE SCALES OF THE FLOW**

by

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Submitted  
*in fulfilment of the requirements of the degree of Doctor of Philosophy*

to the



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# Certificate

This is to certify that the thesis titled, “**Drag reduction in turbulent channel flows by modifying large scales of the flow**”, being submitted by **Mr. Ajay Kumar Sood** to the Department of Applied Mechanics, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is a record of bona-fide work carried out by him under our guidance and supervision during July, 2010 to March, 2017. In our opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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(Ajay Kumar Sood)

# Abstract

*In this thesis, a novel method for obtaining drag reduction in turbulent flows is introduced and characterized. In the method, the large scales of turbulent flows are modified by the introduction of moving shear free surfaces (SFSeS) into the flow, due to which drag reduction takes place. These moving surfaces are taken in the form of very thin plates having negligible thickness and with a very small mass. Turbulent flows are usually characterized by large transport of momentum. The present technique of drag reduction works by attenuating the lateral transport of momentum. This technique is passive and works only for turbulent flows. Numerical simulations have been performed using ANSYS CFX 15.0. The simulations have been performed by using SFSeS placed at fixed locations and updating their velocities per iteration/time step based on the force acting on the SFSeS. The interaction between the plates and the fluid is two way, i.e. due to the action of fluid forces, the velocity of the plate is changing and due to the motion of the plate the flow field around the plate is also changing. Use of both moving as well as stationary meshes has been made and it has been shown that when the flow becomes fully developed the results given by both moving and stationary meshes are equivalent. For improved accuracy and ease of implementation, it was decided to make use of stationary meshes with SFSeS at fixed locations and their velocities updated. In the first part of the thesis, Reynolds Averaged Navier-Stokes (RANS) simulations have been presented which study the optimization of the implementation, in the second part, results of Large Eddy Simulations (LES) simulations are discussed to understand the physics of the phenomenon. The 2-D and 3-D RANS simulations were performed using Shear Stress Transport (SST) turbulence model for a turbulent channel flow and these*

simulations are used to optimize the shape, size, placement and the number of SFSEs. The drag calculations are done with the total pressure drop across the ends of the channel and thus also involve any drag due to the SFSEs themselves. Thus there is no additional penalty to be considered either in the simulations or in the actual situations. It has been found that the amount of drag reduction strongly depends upon the number, shape, size and location of the SFSEs. Using multiple number of plates was also found to increase the drag reduction significantly. Solidity ratios of SFSEs of less than unity are optimal in the lateral direction, while reducing the solidity ratio to even 50% in the flow direction does not significantly affect the drag reduction. The phenomenon is confirmed to be governed by a 'slow' turbulent time scale. Further, the efficacy of the method is seen to depend on the ratio of two time scales - an advection time-scale indicating the 'resident time' near an SFS and the turbulent time-scale. Also, it is observed that the SFSEs placed in the region of maximum kinetic energy production have the greatest effect, while SFSEs placed along the axis have little effect. Large eddy simulations (LES) simulations have also been performed for the same flow using the dynamic Smagorinsky model. LES data has been post processed and the terms of the turbulent kinetic energy and Reynolds stresses budgets have been analysed. The balances are used to understand the observations from the RANS simulations and experiments. The effect of the SFSEs on the balance of terms is quantified. Turbulence production is almost completely suppressed near the SFSEs placed in the regions of maximum production, and this reduces the turbulence overall in the flow, leading to drag reduction. The time scales of imposition and relaxation of the phenomenon are analysed and found to be the 'slow' turbulent time scales. A simple stability analysis shows that the SFS moving parallel to the flow is stable. Implications of the simulations to practical implementations of the phenomenon are discussed.

## Abstract

इस थीसिस में, अशांत में ड्रैग को कम करने के लिए एक उपन्यास विधि पेश किया है और विशेषता विधि में, अशांति के बड़े पैमाने हैं एड द्वारा कतरनी मुक्त सतहों (एसएफएसएस) में चलने की शुरुआत में ओउ, जिसके कारण खींचें कमी हुई है। ये चलती सतहें बहुत पतली प्लेटों के रूप में ली जाती हैं नगण्य मोटाई और बहुत छोटी द्रव्यमान के साथ। अशांत ओह आमतौर पर हैं गति के बड़े परिवहन की विशेषता ड्रैग कटौती की वर्तमान तकनीक गति के पार्श्व परिवहन को हटाकर काम करता है यह तकनीक निष्क्रिय है और केवल अशांत के लिए काम करता है। संख्यात्मक सिमुलेशन का उपयोग करके किया गया है ANSYS CFX 15.0 सिमुलेशन पर रखे SFSEs का उपयोग करके किया गया है स्थानों और बल प्रतिबन्ध के आधार पर उनके चलना / समय की दर के अनुसार उनके वेग को अद्यतन करना एसएफएसएस पर प्लेट्स और के बीच बातचीत यूआईडी दो तरह से है, अर्थात् कारण की कार्रवाई यूआईडी बलों, प्लेट की वेग बदल रही है और गति के कारण प्लेट की प्लेट के चारों ओर ओउ ओल्ड भी बदल रहा है। दोनों के रूप में चलती का प्रयोग अच्छी तरह से स्थिर meshes बना दिया गया है और यह दिखाया गया है कि जब ओउ पूरी तरह से विकसित हो जाता है, दोनों चलती और स्थिर meshes द्वारा दिए गए परिणाम हैं बराबर। सुधार की सटीकता और क्रियान्वयन में आसानी के लिए, इसे बनाने का निर्णय लिया गया स्थानों पर एसएफएसएस के साथ स्थिर मेष का उपयोग और उनके वेग अद्यतन में थीसिस के आरएसटी भाग, रेनॉल्ड्स एवरेज्ड नेवीर-स्टोक्स (रान) सिमुलेशन में हैं प्रस्तुत किया गया जो कार्यान्वयन के अनुकूलन का अध्ययन करते हैं, दूसरे भाग में, बड़े एडी सिमुलेशन (एलईएस) सिमुलेशन के परिणामों को समझने के लिए चर्चा की जाती है घटना के भौतिकी 2-डी और 3-डी रेन सिमुलेशन का उपयोग करके प्रदर्शन किया गया एक अशांत चैनल के लिए कतरनी तनाव परिवहन (एसएसटी) अशांति मॉडल ओउ और ये सिमुलेशन का उपयोग आकार, आकार, प्लेसमेंट और एसएफएसएस की संख्या को अनुकूलित करने के लिए किया जाता है। खींचें की गणना चैनल के छोर पर कुल दबाव ड्रॉप के साथ किया जाता है और इस प्रकार एसएफएसएस स्वयं के कारण किसी भी खींचें भी शामिल है इस प्रकार कोई अतिरिक्त नहीं है दंड या तो सिमुलेशन में या वास्तविक स्थितियों में विचार किया जाना चाहिए। यह किया गया है पाया कि ड्रैग कटौती की मात्रा दृढ़ता से संख्या, आकार, आकार पर निर्भर करती है और एसएफएसएस का स्थान प्लेटों की कई संख्याओं का उपयोग करना भी बढ़ गया था ड्रैग रिडक्शन सिग्नल कैन्टली एकता से कम के एसएफएसएस के सॉलिडिटी अनुपात में इष्टतम हैं पार्श्व दिशा, जबकि सॉलिडिटी अनुपात को 50% तक कम कर देता है ओउ दिशा क्या करता है नहीं सिगनी ड्रैग कटौती को प्रभावित कर सकते हैं। इस घटना के लिए शासित होने की संभावना है एक 'धीमी गति से' अशांत समय पैमाने पर इसके

अलावा, विधि की प्रभावकारिता को इसके आधार पर देखा जाता है दो बार तराजू का अनुपात - एक एडवेक्शन टाइम-स्केल, जो निकट 'निवासी समय' को दर्शाता है एक एसएफएस और अशांत समय-स्तर इसके अलावा, यह पाया जाता है कि एसएफएसएस में रखा गया है अधिकतम गतिज ऊर्जा उत्पादन का क्षेत्र सबसे बड़ा प्रभाव पड़ता है, जबकि एसएफएसएस ने रखा है धुरी के साथ थोड़ा असर पड़ता है। बड़े एडी सिमुलेशन (एलईएस) सिमुलेशन भी हैं उसी के लिए प्रदर्शन किया गतिशील Smagorinsky मॉडल का उपयोग कर ओउ। लेस डेटा दिया गया है पोस्ट की गई प्रक्रिया और अशांत गतिज ऊर्जा और रेनॉल्ड्स पर जोर दिया गया है बजट का विश्लेषण किया गया है। संतुलन से टिप्पणियों को समझने के लिए उपयोग किया जाता है रेन सिमुलेशन और प्रयोग शर्तों के संतुलन पर एसएफएसएस का प्रभाव क्वांटि एड है एसएफएसएस के पास अशांति उत्पादन लगभग पूरी तरह से दबा हुआ है अधिकतम उत्पादन के क्षेत्रों में रखा गया है, और यह समग्र अशांति को कम कर देता है में ओउ, जिससे खींचने में कमी आती है समय सीमा लागू और छूट की घटना का विश्लेषण किया जाता है और 'धीमी' अशांत समय के तराजू पाए जाते हैं। एक सरल स्थिरता विश्लेषण से पता चलता है कि एसएफएस को समांतर चलती है ओव स्थिर है निहितार्थ इस घटना के व्यावहारिक कार्यान्वयन के लिए सिमुलेशन के बारे में चर्चा की गई है।

# Contents

<b>Certificate</b>	<b>i</b>
<b>Acknowledgements</b>	<b>ii</b>
<b>Abstract</b>	<b>iv</b>
<b>List of Figures</b>	<b>xiv</b>
<b>List of Tables</b>	<b>xv</b>
<b>List of Symbols</b>	<b>xvi</b>
<b>1 Introduction and Literature Review</b>	<b>1</b>
1.1 Introduction . . . . .	1
1.2 Literature Survey . . . . .	2
1.2.1 Active Drag Control Techniques . . . . .	2
1.2.2 Passive Drag Control Techniques . . . . .	4
<b>2 The mechanism of the present approach and the objectives of the thesis</b>	<b>11</b>
2.1 Introduction . . . . .	11
2.2 Mechanism Involved in drag reduction process using SFSEs . . . . .	14
2.3 Objectives of the present work . . . . .	17
<b>3 2D and 3D RANS simulations</b>	<b>19</b>
3.1 Introduction . . . . .	19
3.2 2D RANS Simulations . . . . .	20
3.2.1 Results of 2-D RANS simulations . . . . .	26
3.2.2 Effect of the Reynolds number and the time scales of the phenomenon	31
3.2.3 Summary of 2-D simulations . . . . .	39
3.3 3-D RANS Simulations . . . . .	39
3.3.1 Results of 3-D RANS Simulations . . . . .	41
3.3.2 Summary of 3-D RANS simulations . . . . .	56

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<b>4</b>	<b>Large Eddy Simulations (LES)</b>	<b>59</b>
4.1	Introduction . . . . .	59
4.2	Mean profiles and kinetic energy balance . . . . .	60
4.3	Balance of the Reynolds Stresses . . . . .	75
4.4	Consistency of LES simulations . . . . .	77
4.4.1	Estimation of dissipation . . . . .	77
4.5	Integral Balances . . . . .	79
4.6	Flow evolution and time scales . . . . .	84
4.6.1	Relaxation . . . . .	84
4.6.2	Imposition . . . . .	90
4.7	Stability of the SFSES . . . . .	95
<b>5</b>	<b>Conclusions and Future Work</b>	<b>99</b>
	<b>References</b>	<b>101</b>
<b>A</b>	<b>Appendix</b>	<b>106</b>
A.1	Details of SST turbulence model . . . . .	106
A.2	Details of Large Eddy Simulations model . . . . .	108
A.3	Publications from the present work . . . . .	111
	<b>Author's Biography</b>	<b>112</b>

# List of Figures

1.1	Sketch of a tandem arrangement of an LEBU (Gad-El-Hak [17]) . . . . .	4
1.2	Diagram of compliant wall, (a) single layer and (b) double layer (Dixon et al. [15]) . . . . .	5
1.3	Spherical Micelle [37] . . . . .	8
3.1	Equivalence of moving and stationary mesh problems. See text for boundary conditions.(a) Geometry and boundary conditions for the Moving Mesh Problem. (b) Geometry and boundary conditions for the equivalent stationary-mesh problem with SFSes ‘fixed’ at particular locations . . . . .	21
3.2	Schematics for various cases considered in table 3.1. Flow comes in from left side of channel and goes out of right side. Upper and lower surfaces are walls of the channel. . . . .	21
3.3	Grid Independence study using 11 different meshes with 1 <sup>st</sup> mesh being most coarse and 11 <sup>th</sup> mesh being the finest mesh. . . . .	26
3.4	Comparison of velocity profiles at Re = 10000 for moving mesh cases (10m long channel) having one SFS along the centreline, the case without SFS and the stationary mesh case (3 SFSes along the centreline of the channel 2m long). The profiles correspond to a distance of 0.05m from the exit. . . . .	27
3.5	Velocity profiles for moving mesh cases (2m, 4m, 6m, 8m and 10m long channel) having 1 SFS along centreline and the case without any SFS (10m long channel). The profiles correspond to a distance of 0.05m from the exit. . . . .	27
3.6	Schematics for various cases considered in Table 3.2. Flow comes in from left side and goes out of right side. Upper and lower surfaces are walls of the channel. . . . .	29
3.7	Comparison of velocity profiles at a location 0.2m from exit for the cases considered in figure 3.6 and table 3.2 (Case 1 to Case 5). Velocity profiles become more and more peakier with additional SFSes. . . . .	30
3.8	Comparison of turbulent kinetic energy at a location 0.2m from exit for the cases considered in figure 3.6 and table 3.2 (Case 1 to Case 5). Kinetic energy decreases more and more in the entire channel with additional SFSes. . . . .	30

3.9	Velocity profiles scaled by the mean velocity ( $U_{avg} = 1.5\text{m/s}$ , $0.5\text{m/s}$ and $0.05\text{m/s}$ respectively for figures (a), (b) and (c)) at a location $0.2\text{m}$ from exit at $\text{Re}$ around $30000$ for the cases considered in figure 3.6 and Table 3.3 (Case 1 to Case 5). The scaled velocity profiles are identical. . . . .	32
3.10	Turbulent kinetic energy scaled by $U_{avg}^2$ at a location $0.2\text{m}$ from exit at $\text{Re}$ around $30000$ corresponding to the cases considered in figure 3.6 and table 3.3 (Case 1 to Case 5). $U_{avg} = 1.5\text{m/s}$ , $0.5\text{m/s}$ and $0.05\text{m/s}$ respectively for figures (a), (b) and (c). The scaled turbulent kinetic energy profiles are identical. . . . .	33
3.11	Velocity profiles scaled by the average velocity ( $U_{avg} = 0.5\text{m/s}$ ) at a location $0.2\text{m}$ from exit at $\text{Re}$ around $10000$ for the cases considered in figure 3.6 and table 3.3. (Case 1 to Case 5). . . . .	34
3.12	Turbulent kinetic energy scaled by $U_{avg}^2$ at a location $0.2\text{m}$ from exit at $\text{Re}$ around $10000$ for the cases considered in figure 3.6 and table 3.3. (Case 1 to Case 5). $U_{avg} = 0.5\text{m/s}$ . . . . .	34
3.13	Velocity profiles scaled by the average velocity ( $U_{avg} = 0.75\text{m/s}$ ) at a location $0.2\text{m}$ from exit at $\text{Re}$ around $30000$ for the cases considered in figure 3.6 and table 3.3. (Case 1 to Case 5) Peakiness of the profiles has decreased from figure 3.9. . . . .	34
3.14	Velocity profiles scaled by the average velocity ( $U_{avg} = 3.0\text{m/s}$ ) at a location $0.2\text{m}$ from exit at $\text{Re}$ around $30000$ for the cases considered in figure 3.6 and table 3.3. (Case 1 to Case 5) Peakiness of the profiles has increased from figure 3.9. . . . .	34
3.15	Turbulent kinetic energy scaled by $U_{avg}^2$ a location $0.2\text{m}$ from exit at $\text{Re}$ around $30000$ for the cases considered in figure 3.6 and table 3.3 (Case 1 to Case 5). $U_{avg} = 0.75\text{m/s}$ . The scaled $k$ profiles show a slight increase compared to figure 3.10. . . . .	35
3.16	Turbulent kinetic energy scaled by $U_{avg}^2$ a location $0.2\text{m}$ from exit at $\text{Re}$ around $30000$ for the cases considered in figure 3.6 and table 3.3 (Case 1 to Case 5). $U_{avg} = 3.0\text{m/s}$ . The scaled $k$ profiles show a slight decrease compared to figure 3.10. . . . .	35
3.17	Schematic for the cases considered in table 3.4 . . . . .	37
3.18	Schematic of the region simulated (cross section) . . . . .	40
3.19	Schematic for cases 1, 2 and 3 in table 3.6 . . . . .	42
3.20	Schematic for case 4 in table 3.6 . . . . .	42
3.21	Schematic for case 5 in table 3.6 . . . . .	42
3.22	Velocity Profiles ( $U_{avg}$ ) at $0.2\text{m}$ from exit for Cases (1) to (5) in table 3.6 ( $\text{Re}=10000$ ). . . . .	45
3.23	Turbulent K.E. ( $k$ ) at $0.2\text{m}$ from exit for Cases (1) to (5) in table 3.6 ( $\text{Re}=10000$ ). . . . .	45
3.24	Velocity Profiles ( $U_{avg}$ ) at $0.2\text{m}$ from exit for Cases (1) to (5) in table 3.6 ( $\text{Re}=30000$ ). . . . .	46

3.25	Turbulent K.E. ( $k$ ) at 0.2m from exit for Cases (1) to (5) in table 3.6 (Re =30000). . . . .	46
3.26	Plot of $U_{avg}$ v/s $y$ at $z = 0.008$ m for $w = 0.0018$ m (Cases 1-5), in table 3.6 (Re =10,000). . . . .	47
3.27	Schematics of front view for the various cases considered in table 3.7. . .	48
3.28	Side view schematics for various cases considered in table 3.7 . . . . .	48
3.29	Velocity profiles ( $U_{avg}$ ) at 0.2m from exit for Cases (1) to (3) in table 3.7 (Re =30000). The lateral stability ratio decreases from 0.23 to 0.80 in each figure. Also compare the 100% solidity ratio case (figure 3.24). . . .	50
3.30	Turbulent K.E. ( $k$ ) at 0.2m from exit for Cases (1) to (3) in table 3.7 (Re =30000). Also compare with the 100% solidity ratio case (figure 3.25). . .	50
3.31	Schematics of front view for the various cases considered in table 3.8. . .	52
3.32	Side view schematics for various cases considered in table 3.8. . . . .	52
3.33	Front view for case with 12 horizontal and 12 vertical plates in one quarter of a channel. . . . .	52
3.34	Velocity profiles ( $U_{avg}$ ) at 0.2m from exit for Cases (1) to (3) in table 3.8. Compare with figure 3.29. . . . .	54
3.35	Turbulent K.E. ( $k$ ) at 0.2m from exit for Cases (1) to (3) in table 3.8. Compare with figure 3.30. . . . .	54
3.36	(a) Velocity profile and (b) Turbulent kinetic energy profiles at 0.2m from exit of channel for Case 4 in table 3.8. . . . .	55
3.37	Schematic of front view for case with multiple, small SFSEs of size 0.004m x 0.004m with an axial separation of 0.004m placed in one group near the exit of the channel. . . . .	56
3.38	Sectioned side view for case with multiple, small SFSEs of size 0.004m x 0.004m with an axial separation of 0.004m placed in one group near the exit of the channel. . . . .	57
3.39	(a) Comparison of velocity profiles at various locations along $x$ -direction for case with large SFSEs only (b) Comparison of velocity profiles at various locations along $x$ -direction for case with one group of small SFSEs each 0.004m x 0.004m placed near the exit of the channel. The profiles in (a) and (b) are remarkably similar. . . . .	57
3.40	(a) Comparison of turbulence kinetic energy ( $k$ ) profiles at various locations along $x$ -direction for case with large SFSEs only (b) Comparison of turbulence kinetic energy ( $k$ ) at various locations along $x$ -direction for case with one group of small SFSEs each 0.004m x 0.004m placed near the exit of the channel. The profiles in (a) and (b) are remarkably similar. . .	58
4.1	Schematic of front view for case with 3 SFSEs placed along the centreline of the channel, side view is same as in figure 3.1b. . . . .	61
4.2	Schematic of front view for case with three SFSEs placed at a distance of 0.001m from both the upper and lower walls of the channel, side view is same as in figure 3.17. . . . .	61

4.3	Comparison of the present simulations with the DNS data of Zhu [49]; ( $u^+$ $v/s$ $y^+$ ) . . . . .	63
4.4	Comparison of the present simulations with the DNS data of Zhu [49]; ( $v_{r.m.s}/u^*$ $v/s$ $y^+$ ) . . . . .	63
4.5	Comparison of the present simulations with the DNS data of Zhu [49]; ( $u_{r.m.s}/u^*$ $v/s$ $y/h$ ) . . . . .	64
4.6	Comparison of the present simulations with the DNS data of Zhu [49]; ( $w_{r.m.s}/u^*$ $v/s$ $y^+$ ) . . . . .	64
4.7	Energy Spectra . . . . .	64
4.8	Scaled $U_{mean}$ $v/s$ $y/h$ for the case with 3 plates placed at $y/h = 0.1$ . . . . .	65
4.9	$v_{r.m.s}/U_{avg}$ $v/s$ $y/h$ for the case with 3 plates placed at $y/h = 0.1$ . . . . .	65
4.10	$u_{r.m.s}/U_{avg}$ $v/s$ $y/h$ for the case with 3 plates placed at $y/h = 0.1$ . . . . .	65
4.11	$w_{r.m.s}/U_{avg}$ $v/s$ $y/h$ for the case with 3 plates placed at $y/h = 0.1$ . . . . .	65
4.12	$\langle uv \rangle / U_{avg}^2$ $v/s$ $y/h$ for the case with 3 plates placed at $y/h = 0.1$ . . . . .	66
4.13	Scaled turbulent production, $P/(U_{avg}^3/l)$ $v/s$ $y/h$ for the case with 3 plates placed at $y/h = 0.1$ , $l$ is taken as $100k_1$ to make the scaled quantities of order one. . . . .	66
4.14	Scaled dissipation, $\epsilon/(U_{avg}^3/l)$ $v/s$ $y/h$ for the case with 3 plates placed at $y/h = 0.1$ , $l$ is taken as $100k_1$ to make the scaled quantities of order one. . . . .	66
4.15	$k/U_{avg}^2$ $v/s$ $y/h$ for the case with 3 plates placed at $y/h = 0.1$ . . . . .	66
4.16	Scaled $U_{mean}$ $v/s$ $y/h$ for case with plates along centreline of channel. . . . .	67
4.17	$v_{r.m.s}/U_{avg}$ $v/s$ $y/h$ for case with plates along centreline of channel. . . . .	67
4.18	$u_{r.m.s}/U_{avg}$ $v/s$ $y/h$ for case with plates along centreline of channel. . . . .	67
4.19	$w_{r.m.s}/U_{avg}$ $v/s$ $y/h$ for case with plates along centreline of channel. . . . .	67
4.20	$\langle uv \rangle$ $v/s$ $y/h$ for case with plates along centreline of channel. . . . .	68
4.21	Scaled turbulent production, $P/(U_{avg}^3/l)$ $v/s$ $y/h$ for case with plates along centreline of channel, $l$ is taken as $100k_1$ to make the scaled quantities of order one. . . . .	68
4.22	Scaled dissipation, $\epsilon/(U_{avg}^3/l)$ $v/s$ $y/h$ for case with plates along centreline of channel, $l$ is taken as $100k_1$ to make the scaled quantities of order one. . . . .	68
4.23	$k/U_{avg}^2$ $v/s$ $y/h$ for case with plates along centreline of channel. . . . .	68
4.24	$v_{r.m.s}/U_{avg}$ $v/s$ $y/h$ at $z/w$ values of 0.0667, 0.0833, 0.1, 0.14, 0.58, 0.97 and 1 from the wall along the $z$ - <i>direction</i> for the case of 3 SFSEs at 0.001m from the walls. The effect of the SFS is mostly complete by $z/w \approx 0.58$ . . . . .	69
4.25	$u_{r.m.s}/U_{avg}$ $v/s$ $y/h$ at $z/w$ values of 0.0667, 0.0833, 0.1, 0.14, 0.58, 0.97 and 1 from the wall along the $z$ -direction for the case of 3 SFSEs at 0.001m from the walls. The effect of the SFS is not as rapid as in case of $v_{r.m.s}$ (figure 4.24). . . . .	70
4.26	$w_{r.m.s}/U_{avg}$ $v/s$ $y/h$ at $z/w$ values of 0.0667, 0.0833, 0.1, 0.14, 0.58, 0.97 and 1 from the wall along the $z$ -direction for the case of SFSEs at 0.001m from the walls. The profiles are not affected as quickly as the $w_{r.m.s}$ profiles (figure 4.24). . . . .	70

4.27	$\langle uv \rangle / U_{avg}^2$ $v/s$ $y/h$ at $z/w$ values of 0.0667, 0.0833, 0.1, 0.14, 0.58, 0.97 and 1 from the wall along the $z$ -direction for the case of SFSEs at 0.001m from the walls. . . . .	71
4.28	Scaled turbulent production ( $P/(U_{avg}^3/l)$ $v/s$ $y/h$ ) at $z/w$ values of 0.0667, 0.0833, 0.1, 0.14, 0.58, 0.97 and 1 from the wall along the $z$ -direction for the case of SFSEs at 0.001m from the walls. . . . .	71
4.29	Scaled dissipation ( $\epsilon/(U_{avg}^3/l)$ $v/s$ $y/h$ ) at $z/w$ values of 0.0667, 0.0833, 0.1, 0.14, 0.58, 0.97 and 1 from the wall along the $z$ -direction for the case of SFSEs at 0.001m from the walls. . . . .	72
4.30	$k/U_{avg}^2$ $v/sy/h$ at $z/w$ values of 0.0667, 0.0833, 0.1, 0.14, 0.58, 0.97 and 1 from the wall along the $z$ -direction for the case of SFSEs at 0.001m from the walls. . . . .	72
4.31	$U_{mean}/0.75$ $v/sy/h$ at $z/w$ values of 0.0667, 0.0833, 0.1, 0.14, 0.58, 0.97 and 1 from the wall along the $z$ -direction for the case of SFSEs at 0.001m from the walls. . . . .	73
4.32	Production term ( $P_{12}$ ) plotted in the axial plane, for the case of SFSEs at 0.001m from the walls. . . . .	73
4.33	Dissipation term ( $\epsilon_{12}$ ), plotted in the axial plane, for the case of SFSEs at 0.001m from the walls. . . . .	73
4.34	Pressure transport ( $\partial_k T_{kij}^p$ ) for the case of SFSEs at 0.001m from the walls.	74
4.35	Transport due to velocity ( $\partial_k T_{kij}^u$ ) for the case of SFSEs at 0.001m from the walls. . . . .	74
4.36	Viscous transport ( $\partial_k T_{kij}^v$ ) for the case of SFSEs at 0.001m from the walls.	74
4.37	Comparison of the different estimates of the dissipation. . . . .	78
4.38	Difference between LHS and RHS of the $\langle uu \rangle$ eq. (i.e. eq. A.15 with $i=1$ and $j=1$ with both time and space averaging). . . . .	80
4.39	Difference between LHS and RHS of the $\langle uv \rangle$ eq. (i.e. eq. A.15 with $i=1$ and $j=2$ with both time and space averaging). . . . .	80
4.40	Difference between LHS and RHS of the $\langle uw \rangle$ eq. (i.e. eq. A.15 with $i=1$ and $j=3$ with both time and space averaging). . . . .	81
4.41	Difference between LHS and RHS of the $\langle vv \rangle$ eq. (i.e. eq. A.15 with $i=2$ and $j=2$ with both time and space averaging). . . . .	81
4.42	Difference between LHS and RHS of the $\langle vw \rangle$ eq. (i.e. eq. A.15 with $i=2$ and $j=3$ with both time and space averaging). . . . .	82
4.43	Difference between LHS and RHS of the $\langle ww \rangle$ eq. (i.e. eq. A.15 with $i=3$ and $j=3$ with both time and space averaging). . . . .	82
4.44	Schematic showing the region considered for evaluating the relaxation and re-imposition effects. . . . .	85
4.45	$Sk/\epsilon$ $v/s$ $y/h$ at 0.01m before leading edge of $2^{nd}$ SFS, at the leading edge, 0.002m, 0.004m, 0.006m, 0.01m, 0.05m and 0.09m after leading edge of $2^{nd}$ SFS. Large values near the wall and the SFS, but small values in the bulk, indicating rapid evolution near the solid boundaries and slow evolution in the bulk. The labelled distances are from the leading edge of the $2^{nd}$ SFS.	86

4.46	Evolution of $u_{r.m.s}/U_{avg}$ $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.45. . . . .	86
4.47	Evolution of $v_{r.m.s}/U_{avg}$ $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.45. . . . .	87
4.48	Evolution of $w_{r.m.s}/U_{avg}$ $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.45. . . . .	87
4.49	Evolution of $\langle uv \rangle / U_{avg}^2$ $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.45. . . . .	88
4.50	Evolution of scaled turbulent production ( $P/(U_{avg}^3/l)$ ) $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.45. . . . .	88
4.51	Evolution of scaled dissipation ( $\epsilon/(U_{avg}^3/l)$ ) $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.45. . . . .	89
4.52	Evolution of the scaled mean velocity profiles, $U_{mean}/U_{avg}$ $v/s$ $y/h$ . Locations correspond to those in figure 4.45. The profile adjusts rapidly near the walls, but slowly away from them. . . . .	89
4.53	$Sk/\epsilon$ $v/s$ $y/h$ at 0.01m before trailing edge of 3 <sup>rd</sup> SFS, at the trailing edge, 0.002m, 0.004m, 0.006m, 0.01m, 0.05m and 0.09m after trailing edge of 3 <sup>rd</sup> SFS. Large values near the wall and the SFS, but small values in the bulk, indicating rapid evolution near the solid boundaries and slow evolution in the bulk. The labelled distances are from the trailing edge of the 3 <sup>rd</sup> SFS. . . . .	91
4.54	Evolution of $u_{r.m.s}/U_{avg}$ $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.53. . . . .	91
4.55	Evolution of $v_{r.m.s}/U_{avg}$ $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.53. . . . .	92
4.56	Evolution of $w_{r.m.s}/U_{avg}$ $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.53. . . . .	92
4.57	Evolution of $\langle uv \rangle / U_{avg}^2$ $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.53. . . . .	93
4.58	Evolution of scaled turbulent production ( $P/(U_{avg}^3/l)$ ) $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.53. . . . .	93

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4.59	Evolution of scaled dissipation ( $\epsilon/(U_{avg}^3/l)$ ) $v/s$ $y/h$ . Rapid evolution near the solid boundaries, but slow evolution in the bulk and overall. Plots at the same distances as in figure 4.53. . . . .	94
4.60	Evolution of the scaled mean velocity profiles, $U_{mean}/U_{avg}$ $v/s$ $y/h$ . Locations correspond to those in figure 4.53. The profile adjusts rapidly near the walls, but slowly away from them. . . . .	94
4.61	Multiple small SFSes placed in maximum shear production region close to upper wall of the channel. The configuration is neutrally stable. . . . .	95
4.62	One wide SFS placed in maximum shear production region close to upper wall of the channel. . . . .	96
4.63	Effect of pressure forces on the stability of the SFS. The SFS tends to tilt away from the wall as shown; but is prevented by the x-momentum gradient of the flow in the $y$ -direction. This is a stable situation. . . . .	96
4.64	Plots of force difference between upper and lower sides of SFS, moment on the SFS and the difference $\Delta x_c$ (i.e difference between the centres of pressure on upper and lower side of SFS) over time for an SFS placed in the maximum shear production region close to upper wall of the channel. . . . .	98

# List of Tables

3.1	2-D Simulations performed with SFSES placed only along the centreline of the channel in a single row (also see figure 3.2). . . . .	23
3.2	2-D simulations performed with SFSES placed along the height as well as along the length of the channel (also see figure 3.6). . . . .	23
3.3	Summary of simulations at Re=30000, showing the effect of the ratio of resident and turbulent time scales. This ratio remains constant for cases A-C, and the drag reduction and the profiles remain identical. The ratio doubles for case D, increasing the drag reduction, and the ratio is halved for case E, reducing the drag reduction. . . . .	25
3.4	Effect of variation of distance of SFS from wall of the channel. . . . .	38
3.5	Effect of turbulence intensity at the inlet on the drag reduction . . . . .	38
3.6	Simulations run to study the effect of width of SFSES on drag reduction obtained. . . . .	43
3.7	Various simulations run at Reynolds number of around 30000 to study the effect of changes in width of SFSES on drag reduction obtained. The drag reduction percentage in brackets are for the corresponding 100% solidity ratio cases in table 3.6. . . . .	49
3.8	Various simulations run at Reynolds number of around 30000 to study the effect of the removal of the SFSES in the axial plane(s). . . . .	53
4.1	Approximations for balance between LHS and RHS of the Reynolds stress equations . . . . .	79
4.2	Mean and standard deviations of forces and moment acting on the SFS placed near the upper wall of the channel . . . . .	98

# List of Symbols

$C_f$	Skin friction coefficient
$F$	Force acting on the plate along the direction of flow
$h$	Half height of the channel
$K_1$	a constant
$k$	Turbulent kinetic energy
$L$	Scales as the length of a shear free surface (SFS)
$l$	A large scale of turbulence
$m$	Mass of the plate
$P$	Production of turbulent kinetic energy
$p$	Pressure
$P_{ij}$	Production of $\langle u_i u_j \rangle$
$p$	Gap between consecutive SFSes along the width (in section 3.3.1)
$R_{ij}$	Pressure-rate-of-strain tensor
$S$	Shear strain rate
$T_{adv}$	Advection time scale
$T_{kij}$	Flux of Reynolds stress
$T_{kij}^p$	Flux of Reynolds stress (due to fluctuating pressure)
$T_{kij}^u$	Flux of Reynolds stress (due to turbulent convection)
$T_{kij}^\nu$	Flux of Reynolds stress (Diffusive)
$T_{turb}, \tau$	Turbulent time scale
$t$	Size of the time step
$U_{avg}$	Average velocity in $x$ -direction

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$U$	Velocity at previous iteration
$u'$	$x$ -component of the fluctuating velocity
$u^+$	Mean velocity normalized by friction velocity
$u_{r.m.s}$	r.m.s. velocity fluctuation in $x$ -direction
$u^*$	Friction velocity
$V$	Velocity at current iteration
$v'$	$y$ -component of the fluctuating velocity
$v_{r.m.s}$	r.m.s. velocity fluctuation in $y$ -direction
$w$	Width of SFS
$w'$	$z$ -component of the fluctuating velocity
$w_{r.m.s}$	r.m.s. velocity fluctuation in $z$ -direction
$x$	Cartesian coordinate (along direction of flow)
$y$	Cartesian coordinate (transverse direction)
$y^+$	Distance from the wall normalized by the viscous length scale
$z$	Cartesian coordinate (transverse direction)
$\nu$	Kinematic viscosity
$\rho$	Density
$\eta$	Kolmogorov length scale
$\epsilon$	Dissipation of turbulent kinetic energy
$\epsilon_{ij}$	Dissipation tensor
$\mu_t$	Eddy Viscosity