Information collected from the Workshop questionnaire

1. General information about the Numerical Method

a) Code Designation

Ecole Centrale de Nantes, ECN	ISIS
FLOWTECH International AB	CHAPMAN
École Polytechnique de Montréal, EPM	CADYF
West Virginia University, WVU	FLUENT
Analisis-DSC CEHIPAR	ANSYS CFX
National Maritime Research Institute, NRMI	SURF
Instituto Superior Técnico, IST Maritime Research Institute Netherlands, MARIN	PARNASSOS

b) Mathematical Formulation

ECN	Strong Conservation Form
FLOWTECH	Steady-state RANS with artificial time step
EPM	Generalized Galerkin FEM
WVU	Reynolds Averaged Navier-Stokes equations
DSC/CEHIPAR	Strong Conservation Form
NRMI	Artificial-compressibility
IST/MARIN A	Contravariant form, weak formulation
IST/MARIN B	Strong Conservation Form

c) Discretization Technique

ECN	Finite Volume
FLOWTECH	Finite Volume
EPM	Finite Elements
WVU	Finite Volume
DSC/CEHIPAR	Finite Volume
NRMI	Finite Volume
IST/MARIN A	Finite Differences
IST/MARIN B	Finite Volume

d) Linearization Procedure

ECN	Picard
FLOWTECH	Roe split
EPM	Newton
WVU	Picard
DSC/CEHIPAR	
NRMI	Quasi-Newton
IST/MARIN A	Newton
IST/MARIN B	Newton

e) Method of solution of the linear systems of equations

ECN	CGSTAB+ ILU preconditioner
FLOWTECH	ADI
EPM	LU Decomposition
WVU	Algebraic Multigrid + Gauss-Seidel
DSC/CEHIPAR	Algebraic Multigrid + ILU preconditioner
NRMI	Symmetric Gauss-Seidel
IST/MARIN A	GMRES + ILU preconditioner
IST/MARIN B	GMRES + ILU preconditioner

f) Convergence Criteria (Details given below)

ECN	Residuals reduced to machine zero
FLOWTECH	Forces and residuals check
EPM	Residuals reduced to machine zero
WVU	Residuals reduced to machine zero
DSC/CEHIPAR	Maximum residual < 10^{-4}
NRMI	Residuals reduced to machine zero
IST/MARIN A	L_{max} norm of variable variation reduced to machine accuracy + check of L_{max} of normalized residuals
IST/MARIN B	L_{max} norm of variable variation reduced to machine accuracy + check of L_{max} of normalized residuals

2. Detailed information about the calculation procedure

a) Order of accuracy (p) of the discretization of the continuity and momentum equations

ECN	Continuity: 1<p<2, Momentum: p=2 on Cartesian grid
FLOWTECH	Between first and second order
EPM	Third order accurate for velocity components Second order accurate for p + stabilization
WVU	First and second order
DSC/CEHIPAR	Second order
NRMI	Second order
IST/MARIN A	Second order
IST/MARIN B	Second order

b) Order of accuracy (p) of the discretization of the turbulent quantities transport equations

ECN	p=2 on Cartesian grid
FLOWTECH	Between first and second order
EPM	Third-order + stabilization
WVU	First and second order
DSC/CEHIPAR	First order
NRMI	First order
IST/MARIN A	First and second order
IST/MARIN B	First and second order

c) Order of accuracy of the interpolation schemes applied in the post-processing of the data

ECN	Fourth order
FLOWTECH	Second order
EPM	Third order
WVU	First order
DSC/CEHIPAR	Second order
NRMI	First order
IST/MARIN A	Third order
IST/MARIN B	Third order

d) Order of accuracy of the integration schemes applied in the post-processing of the data

ECN	Second order
FLOWTECH	Second order
EPM	Sixth order accurate for volume integrals and fourth order accurate for boundary integrals
WVU	Second order
DSC/CEHIPAR	Second order
NRMI	First order
IST/MARIN A	Second order
IST/MARIN B	Second order

3. Boundary Conditions

3.1. Manufactured Solution

MS stands for a value taken from the Manufactured Solution. $\tilde{\nu}$ is the dependent variable of the one-equation turbulence model of Spalart & Allmaras.

a) Bottom wall

	u_x	u_y	C_p	$\tilde{\nu}$	K	ω/ε
ECN	MS	MS		MS		
FLOWTECH	MS	MS	$\partial C_p/\partial y$MS		MS	MS(2nodes)
EPM	MS	MS	MS		MS	MS
WVU	MS	MS		MS		
DSC/CEHIPAR						
NRMI	MS	MS	$\partial C_p/\partial y$MS	MS		
IST/MARIN A	MS	MS	$\partial C_p/\partial y$MS	MS	MS	MS(2nodes)
IST/MARIN B	MS	MS	$\partial C_p/\partial y$MS	MS	MS	MS(2nodes)

b) Top

	u_x	u_y	C_p	$\tilde{\nu}$	k	ω/ε
ECN	MS	MS	MS	MS		
FLOWTECH	MS	MS	MS	MS	MS	MS
EPM	MS	MS	MS		MS	MS
WVU	MS	MS		MS		
DSC/CEHIPAR						
NRMI	$\partial u_x/\partial y$ MS	$\partial u_y/\partial y$ MS	MS	$\partial \tilde{\nu}/\partial y$MS		
IST/MARIN A	MS		MS	MS	MS	MS
IST/MARIN B	MS	$\partial^2 u_y/\partial y^2$ MS	MS	MS	MS	MS

c) Inlet

	u_x	u_y	C_p	$\tilde{\nu}$	K	ω/ε
ECN	MS	MS	MS	MS		
FLOWTECH	MS	MS	MS	MS	MS	MS
EPM	MS	MS	MS		MS	MS
WVU	MS	MS				
DSC/CEHIPAR	MS	MS	MS		MS	MS
NRMI	MS	MS	$\partial C_p/\partial x$MS	MS		
IST/MARIN A	MS	MS	$\partial C_p/\partial x$MS	MS	MS	MS
IST/MARIN B	MS	MS	$\partial C_p/\partial x$MS	MS	MS	MS

d) Outlet

	u_x	u_y	C_p	$\tilde{\nu}$	k	ω/ε
ECN	$\partial u_x/\partial x$ MS	$\partial u_y/\partial x$ MS	$\partial C_p/\partial x$MS	$\partial\tilde{\nu}/\partial x=0$		
FLOWTECH	$\partial u_x/\partial x$ MS	$\partial u_y/\partial x$ MS	C_p MS	$\tilde{\nu}$ MS	$\partial k/\partial x$MS	$\partial\omega/\partial x$MS
EPM	$\partial u_x/\partial x$ MS	$\partial u_y/\partial x$ MS	$\partial C_p/\partial x$MS		$\partial k/\partial x$MS	$\partial\varepsilon/\partial x$MS
WVU	MS	MS				
DSC/CEHIPAR						
NRMI	$\partial u_x/\partial x$ MS	$\partial u_y/\partial x$ MS	$\partial C_p/\partial x$MS	$\partial\tilde{\nu}/\partial x$MS		
IST/MARIN A	$\partial u_x/\partial x$ MS	$\partial u_y/\partial x$ MS	MS	$\partial\tilde{\nu}/\partial x$MS	$\partial k/\partial x$MS	$\partial\omega/\partial x$MS
IST/MARIN B	$\partial u_x/\partial x$ MS	$\partial u_y/\partial x$ MS	MS	$\partial\tilde{\nu}/\partial x$MS	$\partial k/\partial x$MS	$\partial\omega/\partial x$MS

3.2. Backward Facing Step

PW stands for the values given by the inlet profiles generated by the organizers of the Workshop for the flow over a backward facing step. $\tilde{\nu}$ is the dependent variable of the one-equation turbulence model of Spalart & Allmaras. W_S is the near-wall ω solution.

a) Walls

	u_x	u_y	C_p	$\tilde{\nu}$	k	ω/ε
ECN	0	0		0		
FLOWTECH	0	0	$\partial C_p/\partial y=0$	0	0	
EPM	Wall funct.	Wall funct	Wall funct		Wall funct	Wall funct
WVU	0	0		0		
DSC/CEHIPAR	0	0				
NRMI	0	0	$\partial C_p/\partial y=0$	0		
IST/MARIN A	0	0		0	0	W_S(2nodes)
IST/MARIN B	0	0	$\partial^2 C_p/\partial y^2=0$	0	0	W_S(2nodes)

b) Inlet

	u_x	u_y	C_p	$\tilde{\nu}$	k	ω/ε
ECN	PW	PW		PW		
FLOWTECH	PW	PW	$\partial C_p/\partial x$=0	PW	PW	PW
EPM	PW	PW	PW			
WVU	PW	PW				
DSC/CEHIPAR	PW	PW			PW	PW
NRMI	PW	PW	$\partial C_p/\partial x$=0	PW		
IST/MARIN A	PW	PW	$\partial C_p/\partial x$=0	PW	PW	PW
IST/MARIN B	PW	PW	$\partial C_p/\partial x$=0	PW	PW	PW

c) Outlet

	u_x	u_y	C_p	$\tilde{\nu}$	k	ω/ε
ECN	$\partial u_x/\partial x$ =0	$\partial u_y/\partial x$=0	C_p=0	$\partial \tilde{\nu}/\partial x=0$		
FLOWTECH	Zero flux	Zero flux	C_p=0		$\partial k/\partial x$=0	$\partial \omega/\partial x$=0
EPM	$\partial u_x/\partial x$ =0	$\partial u_y/\partial x$ =0	$\partial C_p/\partial x$=0		$\partial k/\partial x$=0	$\partial \varepsilon/\partial x$=0
WVU			C_p=0			
DSC/CEHIPAR			C_p=0			
NRMI	$\partial u_x/\partial x$ =0	$\partial u_y/\partial x$=0	C_p=0	$\partial \tilde{\nu}/\partial x=0$		
IST/MARIN A	$\partial^2 u_x/\partial x^2$ =0	$\partial^2 u_y/\partial x^2$=0	C_p=0	$\partial \tilde{\nu}/\partial x=0$	$\partial k/\partial x$=0	$\partial \omega/\partial x$=0
IST/MARIN B	$\partial^2 u_x/\partial x^2$ =0	$\partial^2 u_y/\partial x^2$=0	C_p=0	$\partial \tilde{\nu}/\partial x=0$	$\partial k/\partial x$=0	$\partial \omega/\partial x$=0

4. Uncertainty estimation method

ECN	GCI with Grid Triplets
FLOWTECH	GCI with Least squares method and data range
EPM	Zhu-Zienkiewicz for integral, Wiberg for local quantities
WVU	ERE, GCI, ERE_{cv2}
DSC/CEHIPAR	
NRMI	GCI with Least squares method
IST/MARIN A	GCI with Least squares method and data range
IST/MARIN B	GCI with Least squares method and data range

GCI – Grid Convergence Index

ERE – Extrapolated Relative Error

5. Calculations performed

	Manufactured Solution	C-30, Backward facing step
ECN	MS2, SA with $f_{v1}=1$	SA
FLOWTECH	MS4, BSL	BSL
EPM	$MS4_{mod}$, SKE	SKE with wall functions
WVU	"Laminar", D1 and D2	SA, D1 and D2
DSC/CEHIPAR		SST and SST with re-attachment modification
NRMI	MS1, SA,MS2 fixed ν_t	SA
IST/MARIN A	MS2, SA and MS4, BSL	SA, BSL
IST/MARIN B	MS2, SA and MS4, BSL	SA, BSL

MS1 – Manufactured solution with $\tilde{\nu}$ varying with y at the wall
MS2 – Manufactured solution with $\tilde{\nu}$ varying with y^2 at the wall
MS4 – Manufactured solution with ν_t varying with y^4 at the wall
$MS4_{mod}$ – MS4 with constants added to k and ε
SA – Spalart & Allmaras one-equation model
BSL – Baseline k-ω two-equation model
SKE – Standard k-ε two-equation model
SST – Shear Stress Transport k-ω two-equation model
f_{v1} – Damping function of the Spalart & Allmaras model
D1 – First order discretization
D2 – Second order discretization

6. Results submitted

6.1 General information

	Round-off error	Iterative error	Convergence Criteria
ECN	Negligible	Negligible	Residuals to machine precision
FLOWTECH			
EPM	Negligible	Negligible	Residuals to machine precision
WVU	Negligible	Negligible	Residuals to machine precision
DSC/CEHIPAR			Max Residual < 10^{-4}
NRMI	Negligible	Negligible	Residuals to machine precision
IST/MARIN A	Negligible, Double P.	< 10^{-10}	$L_{max}(\Delta\phi)<10^{-12}$, $L_{max}(res)<10^{-10}$
IST/MARIN B	Negligible, Double P.	< 10^{-9}	$L_{max}(\Delta\phi)<10^{-10}$, $L_{max}(res)<10^{-9}$

All the flow variables are non-dimensional. The reference length, L_{ref}, is the step height for the bakcward facing step. The reference velocity, U_{ref}, is the uniform incoming flow for the backward facing step.

For the backward facing step, the pressure coefficient is defined in the usual way $C_p=(p-p_{ref})/(1/2\ \rho U^2_{ref})$, where the p_{ref} is the pressure at the outlet boundary. On the other hand, $C_p=p/(\rho U^2_{ref})$ for the manufactured solution.

The eddy-viscosity value is made non-dimensional by the product $L_{ref}U_{ref}$. Friction and pressure resistance coefficients are obtained using $\rho U^2_{ref}L_{ref}$ as the reference force.

6.2 Manufactured Solution

a) Calculations performed

		MS	Turbulence Model	Grid
1	ECN	MS2	SA with $f_{v1}=1$	Cartesian, CB, 193×385
2	FLOWTECH	MS4	BSL	Cartesian, CB, 289×289
3	EPM	$MS4_{mod}$	SKE	Unstructured, adaptive
4	WVU	Laminar		Cartesian, D1, CB, 120×120
5	WVU	Laminar		Cartesian, D2, CB, 120×120
6	NMRI	MS2	Fixed ν_t	Cartesian, CB
7	NRMI	MS1	SA	Cartesian, CB
8	IST/MARIN A	MS2	SA	Curvilinear, CB, 401×401
9	IST/MARIN A	MS4	BSL	Cartesian, CB, 401×401
10	IST/MARIN A	MS4	BSL	Curvilinear, CB, NO, 401×401
11	IST/MARIN B	MS2	SA	Cartesian, CB, 401×401
12	IST/MARIN B	MS4	BSL	Cartesian, CB, 401×401
13	IST/MARIN B	MS4	BSL	Curvilinear, CB, NO, 401×401
14	IST/MARIN A	MS2	SA	Curvilinear, CB, 201×201
15	IST/MARIN A	MS4	BSL	Cartesian, CB, 201×201
16	IST/MARIN A	MS4	BSL	Curvilinear, CB, NO, 201×201
17	IST/MARIN B	MS2	SA	Cartesian, CB, 201×201
18	IST/MARIN B	MS4	BSL	Cartesian, CB, 201×201
19	IST/MARIN B	MS4	BSL	Curvilinear, CB, NO, 201×201

MS1 – Manufactured solution with $\tilde{\nu}$ varying with y at the wall
MS2 – Manufactured solution with $\tilde{\nu}$ varying with y^2 at the wall
MS4 – Manufactured solution with ν_t varying with y^4 at the wall
$MS4_{mod}$ – MS4 with constants added to k and ε
EQ – Equally-spaced
CB – Clustered nodes at the bottom
NO – Non-orthogonal
SA – Spalart & Allmaras one-equation model
BSL – Baseline k-ω two-equation model
SKE – Standard k-ε two-equation model
f_{v1} – Damping function of the Spalart & Allmaras model
D1 – First order discretization
D2 – Second order discretization

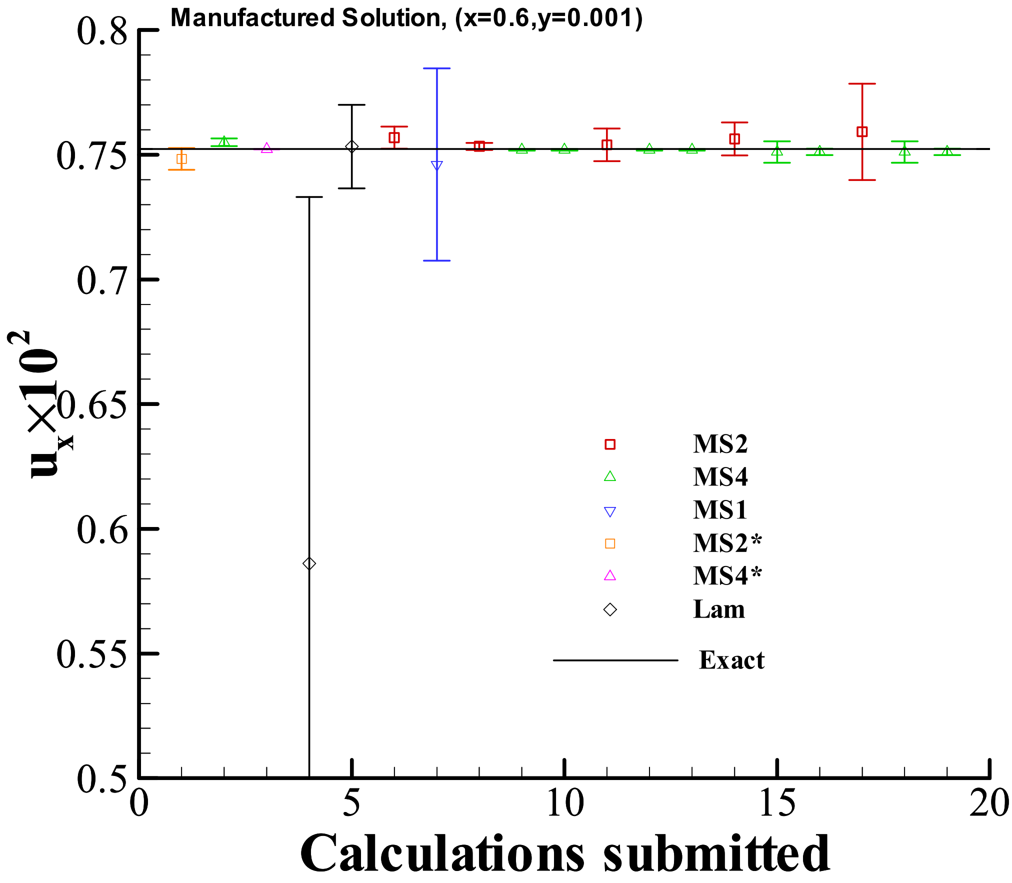
b) Global Convergence

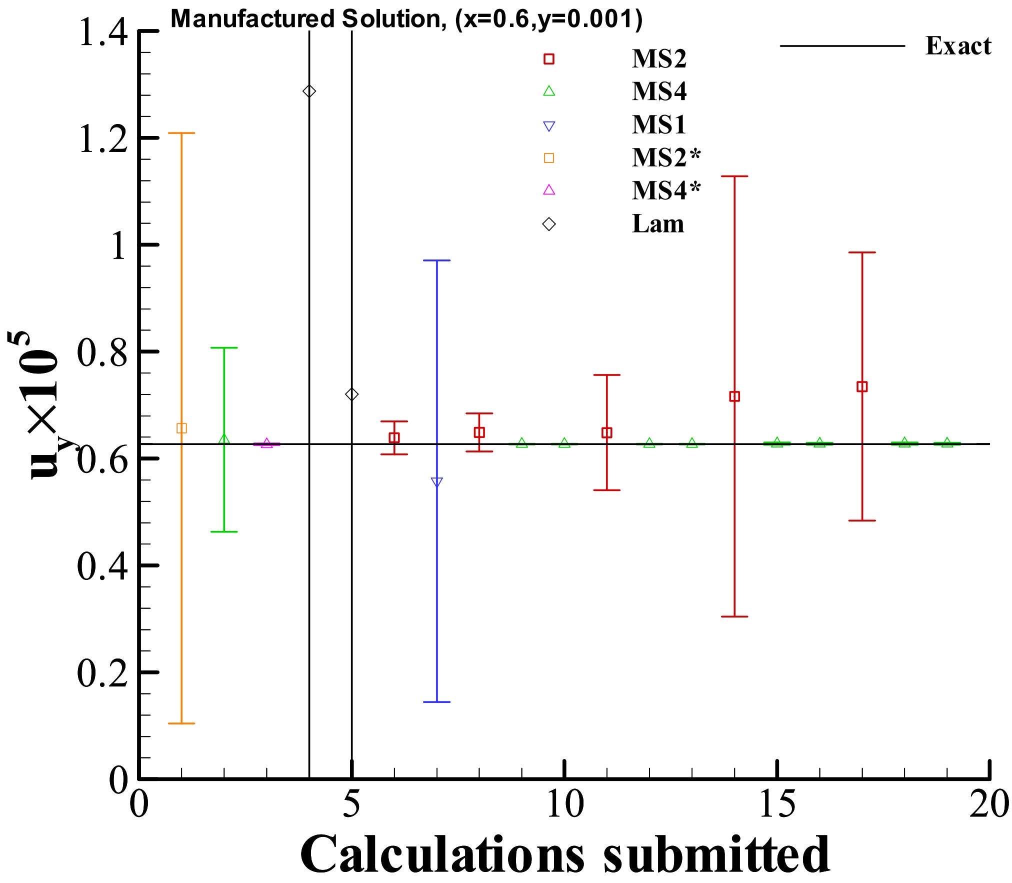
Observed order of accuracy		u_x	u_y	C_p	ν_t
1	ECN	1.96	1.92	2.12	1.92
2	FLOWTECH	1.9	1.5	1-1.5	1.5
3	EPM	2.273	2.273	1.902	3.122
4	WVU	1	1	1	—
5	WVU	2	2	2	—
6	NMRI				
7	NRMI				
8	IST/MARIN A	1.3	1.1	1.1	1.5
9	IST/MARIN A	2.0	2.0	2.0	2.0
10	IST/MARIN A	2.0	2.0	2.0	2.0
11	IST/MARIN B	2.3	2.3	2.3	2.1
12	IST/MARIN B	2.0	2.0	2.0	1.9
13	IST/MARIN B	2.0	2.0	2.0	1.9
14	IST/MARIN A	1.2	1.1	1.0	1.7
15	IST/MARIN A	2.0	2.0	2.0	1.7
16	IST/MARIN A	2.0	2.0	2.0	1.7
17	IST/MARIN B	1.1	0.8	0.2	1.7
18	IST/MARIN B	2.0	2.0	2.3	1.8
19	IST/MARIN B	2.0	2.0	2.0	1.7

c) Local flow quantities

u_x and u_y velocity component at $x=0.6, y=0.001$

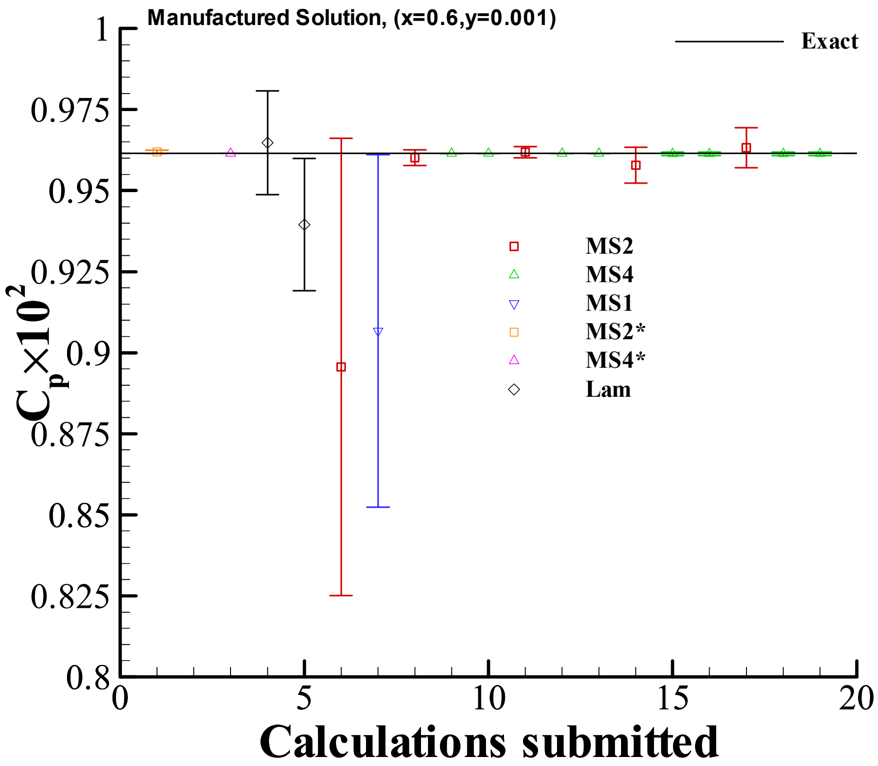
		$u_x \times 10^2$	$U(u_x) \times 10^2$	$u_y \times 10^5$	$U(u_y) \times 10^5$
0	Exact Solution	0.7522416	—	0.6268634	—
1	ECN	0.74833	0.0044	0.6568	0.5524
2	FLOWTECH	0.755	0.00151	0.635	0.172
3	EPM	0.752228	0.000010	0.626501	0.00149948
4	WVU	0.58609	0.14690	1.2876	12.4
5	WVU	0.75327	0.01679	0.72024	3.208
6	NMRI	0.75683	0.0043999	0.63893	0.030814
7	NRMI	0.74605	0.03855	0.55774	0.41320
8	IST/MARIN A	0.7533748	0.0014222	0.6489389	0.0354791
9	IST/MARIN A	0.7519672	0.0003395	0.6272104	0.0006187
10	IST/MARIN A	0.7519821	0.0003221	0.6271870	0.0005932
11	IST/MARIN B	0.7539756	0.0065323	0.6484401	0.1078513
12	IST/MARIN B	0.7519672	0.0003395	0.6272104	0.0006187
13	IST/MARIN B	0.7519821	0.0003221	0.6271870	0.0005932
14	IST/MARIN A	0.7563530	0.0065557	0.7164684	0.4119779
15	IST/MARIN A	0.7511301	0.0043210	0.6279529	0.0022973
16	IST/MARIN A	0.7511931	0.0012928	0.6278668	0.0019458
17	IST/MARIN B	0.7592015	0.0193059	0.7347211	0.2510066
18	IST/MARIN B	0.7511301	0.0043210	0.6279529	0.0022973
19	IST/MARIN B	0.7511931	0.0012928	0.6278668	0.0019458

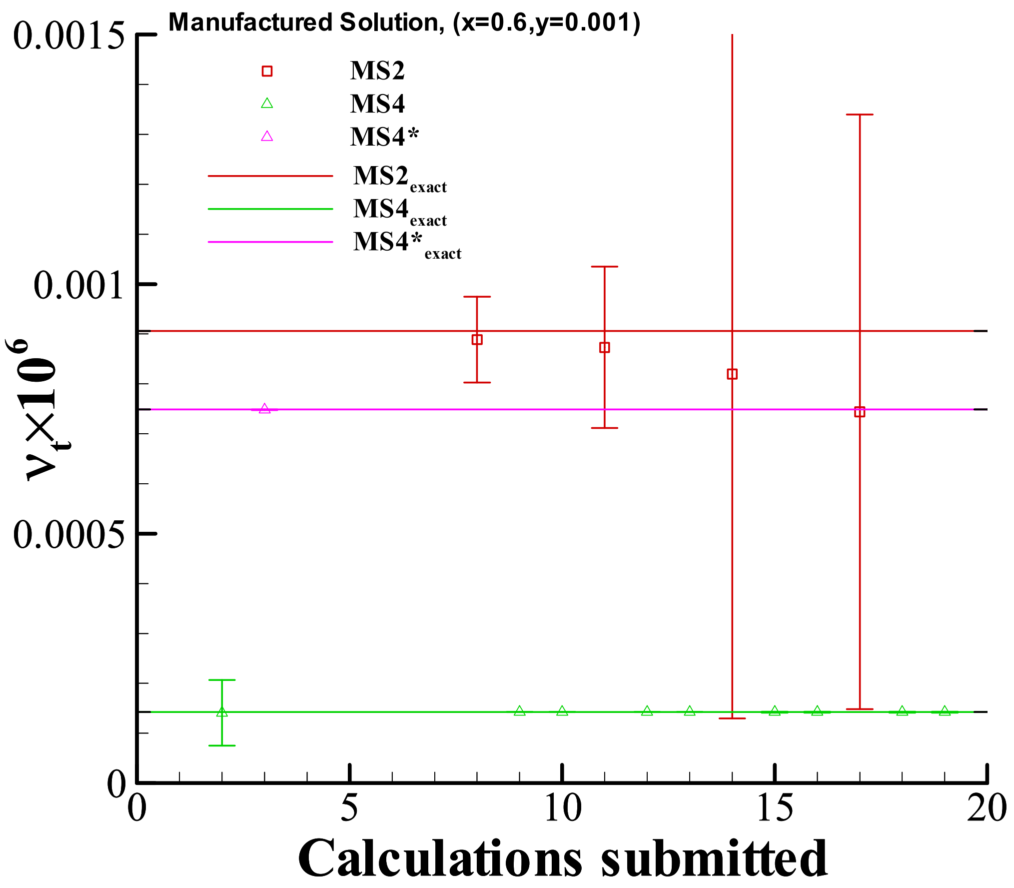

Manufactured Solution, (x=0.6,y=0.001)
$u_x \times 10^2$
0.8
0.75
0.7
0.65
0.6
0.55
0.5
MS2
MS4
MS1
MS2*
MS4*
Lam
Exact
0
5
10
15
20
Calculations submitted

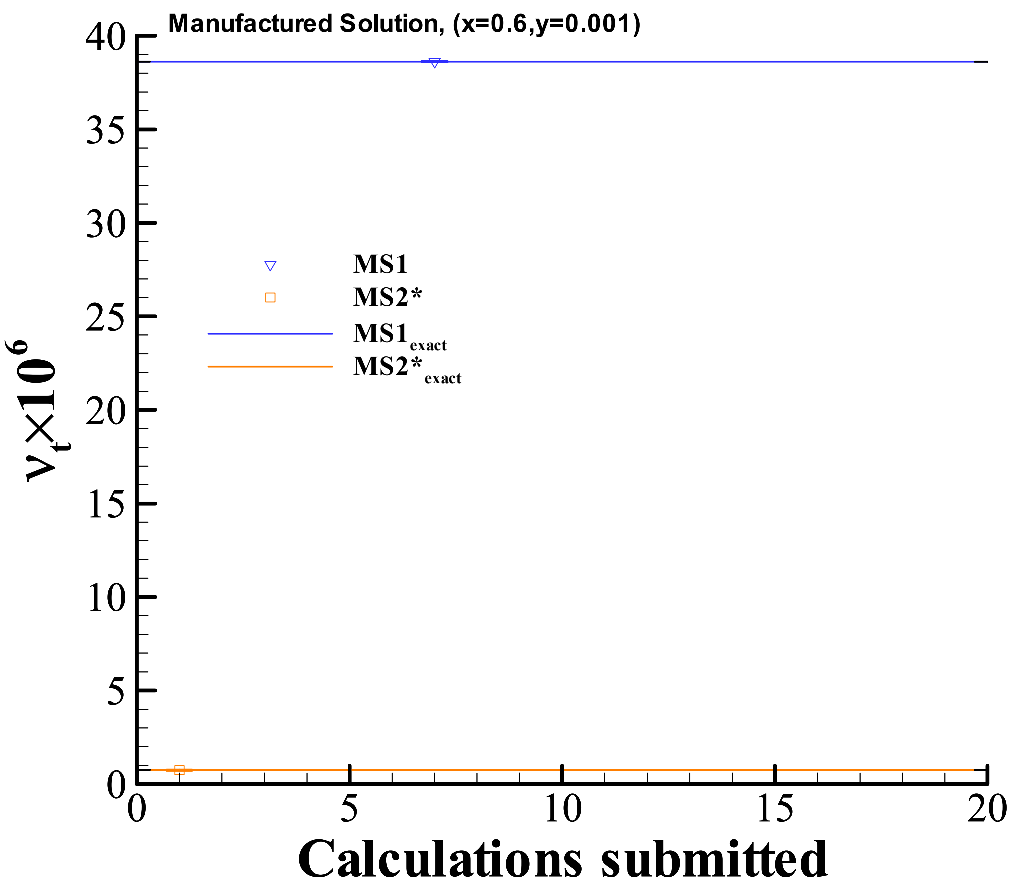

Manufactured Solution, (x=0.6,y=0.001)
$u_y \times 10^5$
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Exact
MS2
MS4
MS1
MS2*
MS4*
Lam
0
5
10
15
20
Calculations submitted

C_p and v_t velocity component at $x=0.6, y=0.001$

		$C_p \times 10^2$	$U(C_p) \times 10^2$	$v_t \times 10^6$	$U(v_t) \times 10^6$
0	Exact Solution	0.9614895	—	MS4 0.0001425 MS4* 0.000749 MS2 0.0009061 MS2* 0.7548687 MS1 38.61424	—
1	ECN	0.96195	0.00052	MS2* 0.7429	0.0318
2	FLOWTECH	—	—	MS4 0.000141	0.0000658
3	EPM	0.961490	0.00000038	MS4* 0.00074814	0.00000078
4	WVU	0.96480	0.01601	—	—
5	WVU	0.93950	0.02038	—	—
6	NRMI	0.89561	0.07054	—	—
7	NRMI	0.90671	0.054378	MS1 38.613	0.033251
8	IST/MARIN A	0.9601494	0.0023903	MS2 0.0008887	0.0000862
9	IST/MARIN A	0.9614547	0.0000430	MS4 0.0001425	0.0000000
10	IST/MARIN A	0.9614572	0.0000401	MS4 0.0001425	0.0000000
11	IST/MARIN B	0.9618739	0.0017280	MS2 0.0008732	0.0001615
12	IST/MARIN B	0.9614547	0.0000430	MS4 0.0001425	0.0000000
13	IST/MARIN B	0.9614572	0.0000401	MS4 0.0001425	0.0000000
14	IST/MARIN A	0.9578317	0.0055508	MS2 0.0008197	0.0006897
15	IST/MARIN A	0.9613484	0.0005493	MS4 0.0001425	0.0000008
16	IST/MARIN A	0.9613580	0.0005132	MS4 0.0001425	0.0000008
17	IST/MARIN B	0.9632563	0.0061701	MS2 0.0007440	0.0005958
18	IST/MARIN B	0.9613484	0.0005493	MS4 0.0001425	0.0000008
19	IST/MARIN B	0.9613580	0.0005132	MS4 0.0001425	0.0000008

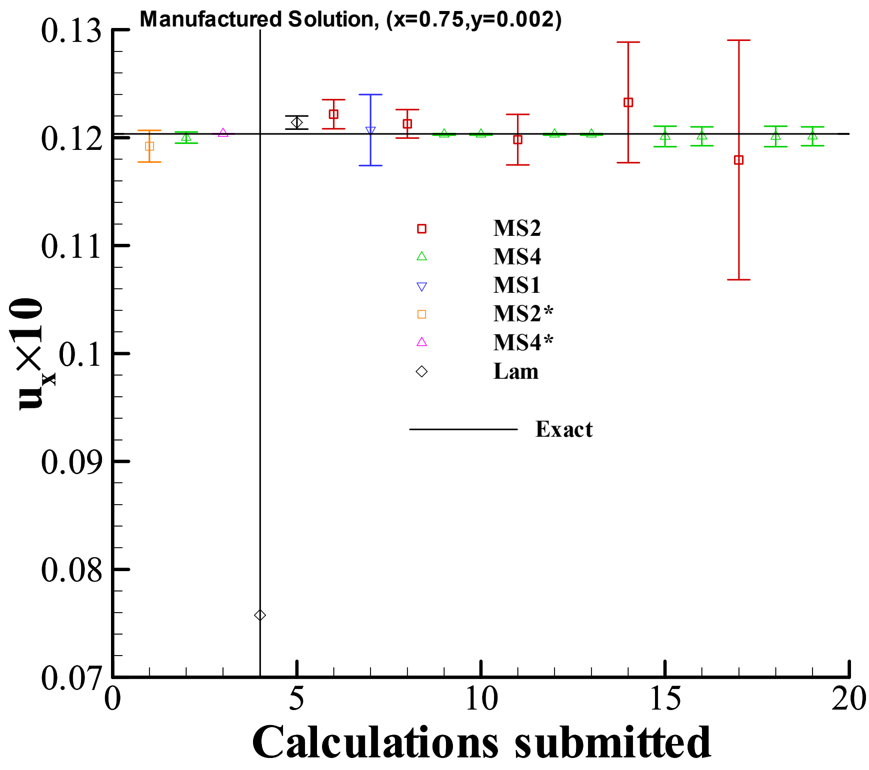


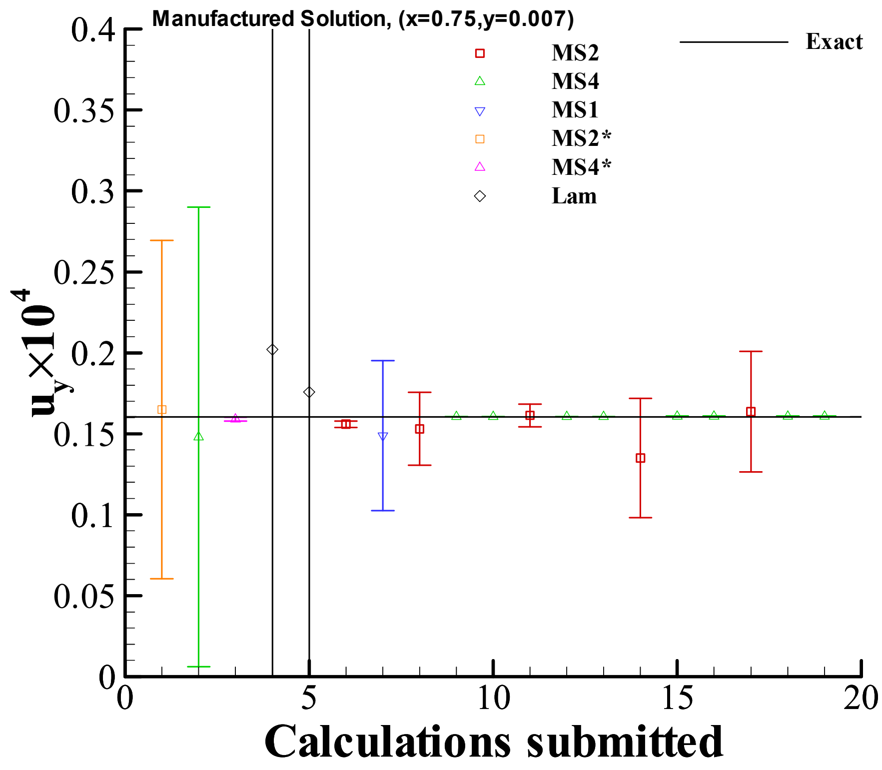

Manufactured Solution, (x=0.6,y=0.001)
0.0015
0.001
0.0005
0
$\nu_t \times 10^6$
MS2
MS4
MS4*
$MS2_{exact}$
$MS4_{exact}$
$MS4^*_{exact}$
0
5
10
15
20
Calculations submitted


Manufactured Solution, (x=0.6,y=0.001)
40
35
30
25
20
15
10
5
0
$\nu_t \times 10^6$
MS1
MS2*
$MS1_{exact}$
$MS2^*_{exact}$
0
5
10
15
20
Calculations submitted

u_x and u_y velocity component at $x=0.75, y=0.002$

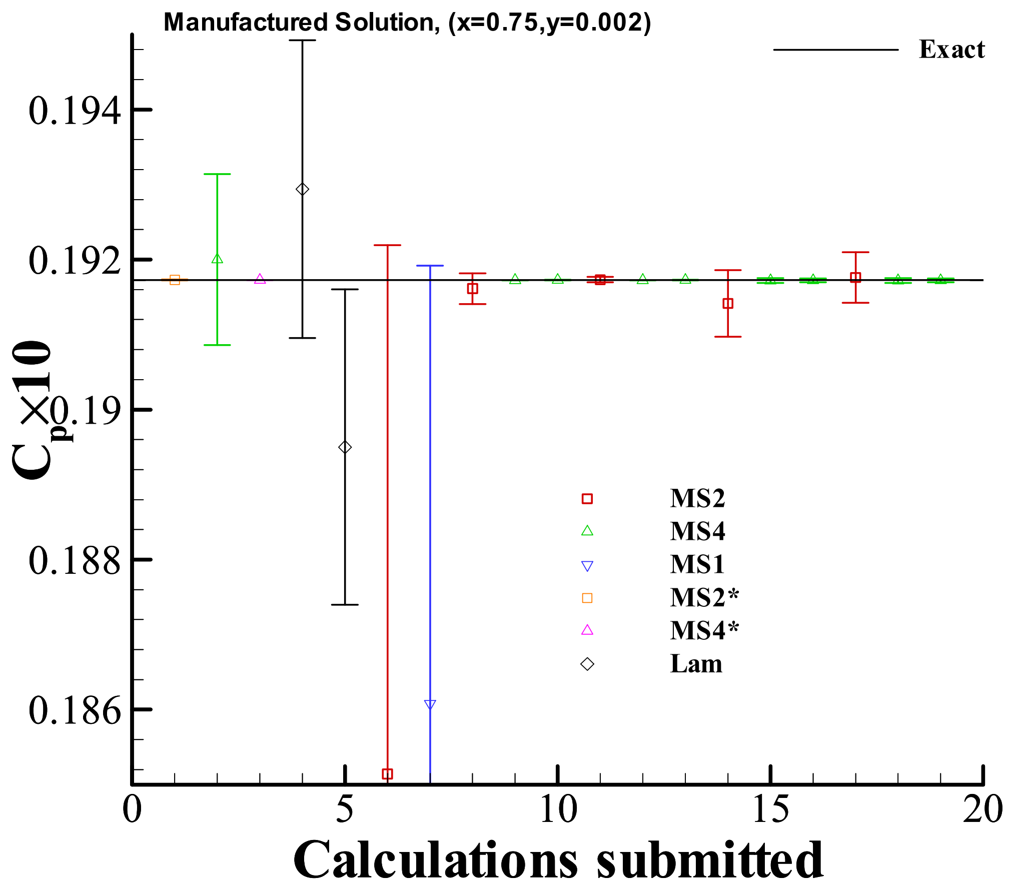
		u_x×10	$U(u_x)$ ×10	u_y×10^4	$U(u_y)$ ×10^4
0	Exact Solution	0.1203559	—	0.1604715	—
1	ECN	0.11921	0.00146	0.16496	0.1044
2	FLOWTECH	0.120	0.000512	0.148	0.142
3	EPM	0.120354	0.00000168	0.159042	0.00116034
4	WVU	0.075754	0.05677	0.20205	8.626
5	WVU	0.12140	0.0005948	0.17572	0.5306
6	NRMI	0.12216	0.0013426	0.15591	0.0020487
7	NRMI	0.12070	0.0032793	0.14886	0.046307
8	IST/MARIN A	0.1212881	0.0013119	0.1530320	0.0225063
9	IST/MARIN A	0.1202960	0.0000740	0.1605349	0.0000845
10	IST/MARIN A	0.1202999	0.0000694	0.1605270	0.0000756
11	IST/MARIN B	0.1198071	0.0023426	0.1613666	0.0070144
12	IST/MARIN B	0.1202960	0.0000740	0.1605349	0.0000845
13	IST/MARIN B	0.1202999	0.0000694	0.1605270	0.0000756
14	IST/MARIN A	0.1232623	0.0055849	0.1350270	0.0368091
15	IST/MARIN A	0.1201128	0.0009482	0.1607099	0.0003722
16	IST/MARIN A	0.1201289	0.0008791	0.1606774	0.0003511
17	IST/MARIN B	0.1179330	0.0110992	0.1637047	0.0372039
18	IST/MARIN B	0.1201128	0.0009482	0.1607099	0.0003722
19	IST/MARIN B	0.1201289	0.0008791	0.1606774	0.0003511

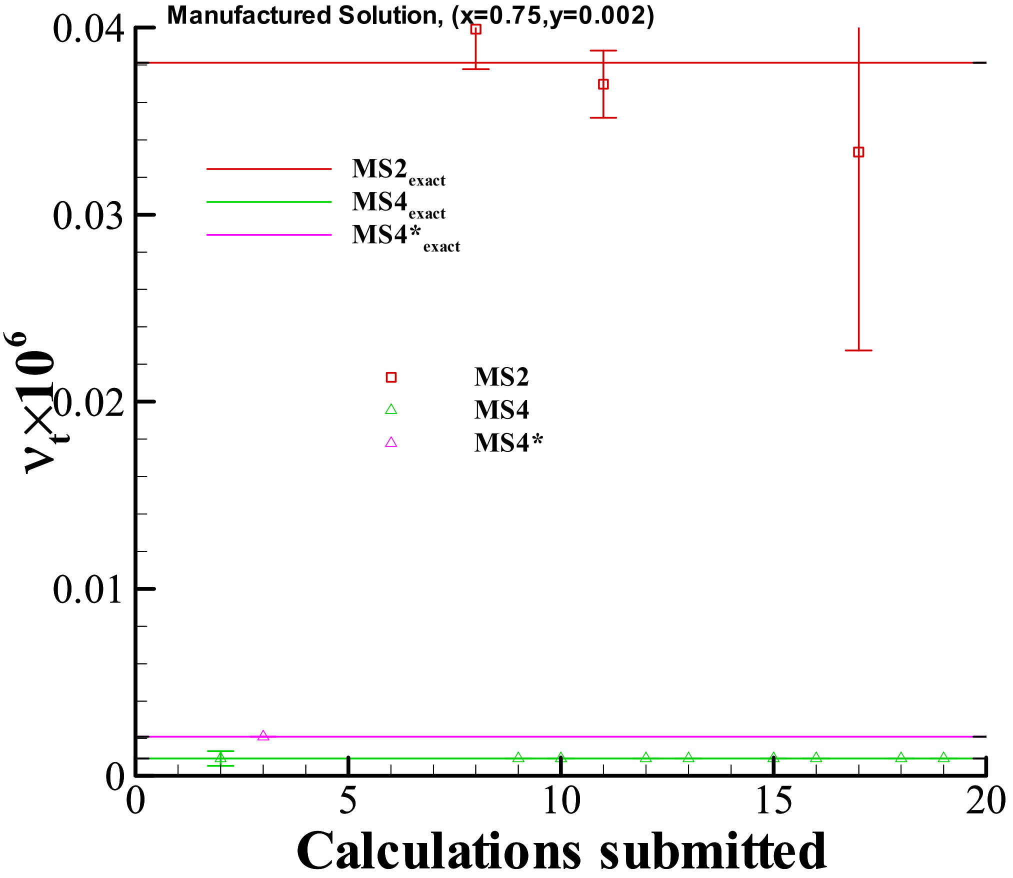


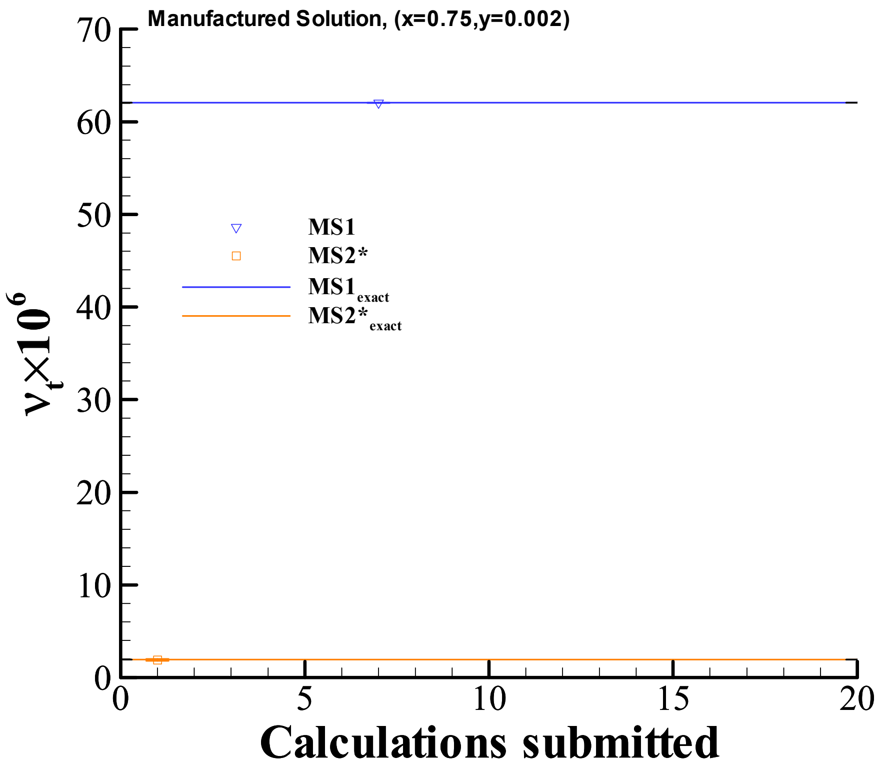


C_p and ν_t velocity component at $x=0.75, y=0.002$

		$C_p \times 10$	$U(C_p) \times 10$	$\nu_t \times 10^6$	$U(\nu_t) \times 10^6$
0	Exact Solution	0.1917282	—	MS4 0.0009335 MS4* 0.0020920 MS2 0.0381293 MS2* 1.931626 MS1 62.04040	—
1	ECN	0.19173	0.0000083	MS2* 1.8948	0.0995
2	FLOWTECH	0.192	0.00114	MS4 0.000925	0.000390
3	EPM	0.191728	0.00000008	MS4* 0.00209155	0.00000068
4	WVU	0.19294	0.001987	—	—
5	WVU	0.18950	0.002103	—	—
6	NRMI	0.18514	0.0070539	—	—
7	NRMI	0.18608	0.0058413	MS1 62.041	0.0049746
8	IST/MARIN A	0.1916133	0.0002053	MS2 0.0399194	0.0021415
9	IST/MARIN A	0.1917262	0.0000025	MS4 0.0009335	0.0000000
10	IST/MARIN A	0.1917266	0.0000060	MS4 0.0009335	0.0000000
11	IST/MARIN B	0.1917326	0.0000365	MS2 0.0369786	0.0017950
12	IST/MARIN B	0.1917262	0.0000025	MS4 0.0009335	0.0000000
13	IST/MARIN B	0.1917266	0.0000060	MS4 0.0009335	0.0000000
14	IST/MARIN A	0.1914159	0.0004422	MS2 0.0437822	0.0108154
15	IST/MARIN A	0.1917201	0.0000315	MS4 0.0009334	0.0000014
16	IST/MARIN A	0.1917218	0.0000253	MS4 0.0009334	0.0000014
17	IST/MARIN B	0.1917619	0.0003360	MS2 0.0333499	0.0106059
18	IST/MARIN B	0.1917201	0.0000315	MS4 0.0009334	0.0000014
19	IST/MARIN B	0.1917218	0.0000253	MS4 0.0009334	0.0000014

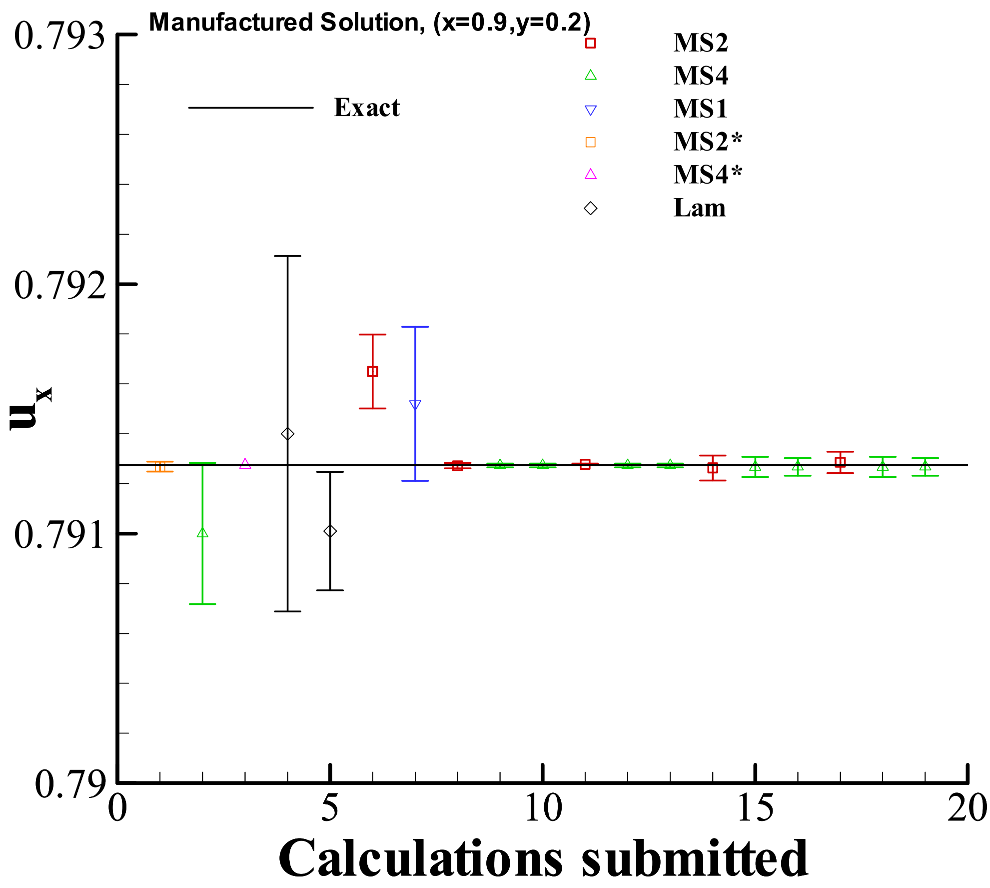

Manufactured Solution, (x=0.75,y=0.002)
Exact
0.194
0.192
0.19
0.188
0.186
$C_p \times 10$
MS2
MS4
MS1
MS2*
MS4*
Lam
0
5
10
15
20
Calculations submitted

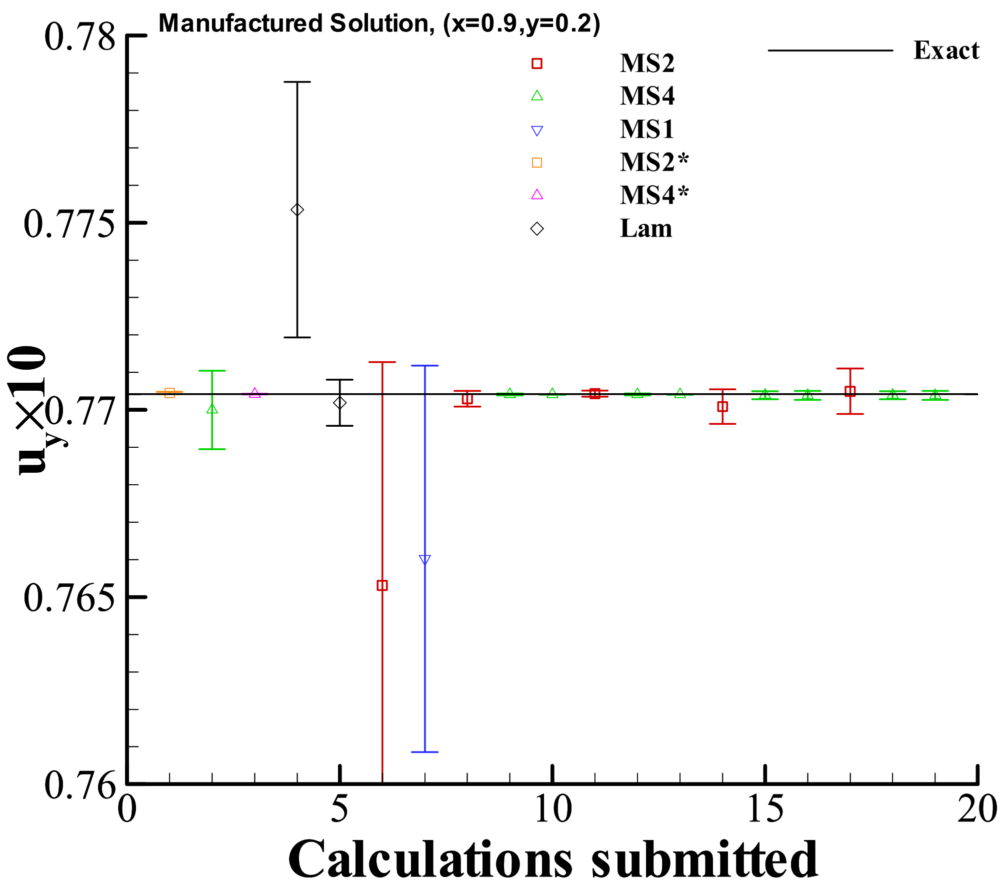

Manufactured Solution, (x=0.75,y=0.002)
0.04
0.03
0.02
0.01
0
$\nu_t \times 10^6$
$MS2_{exact}$
$MS4_{exact}$
$MS4^*_{exact}$
MS2
MS4
MS4*
0
5
10
15
20
Calculations submitted



u_x and u_y velocity component at $x=0.9,\ y=0.2$

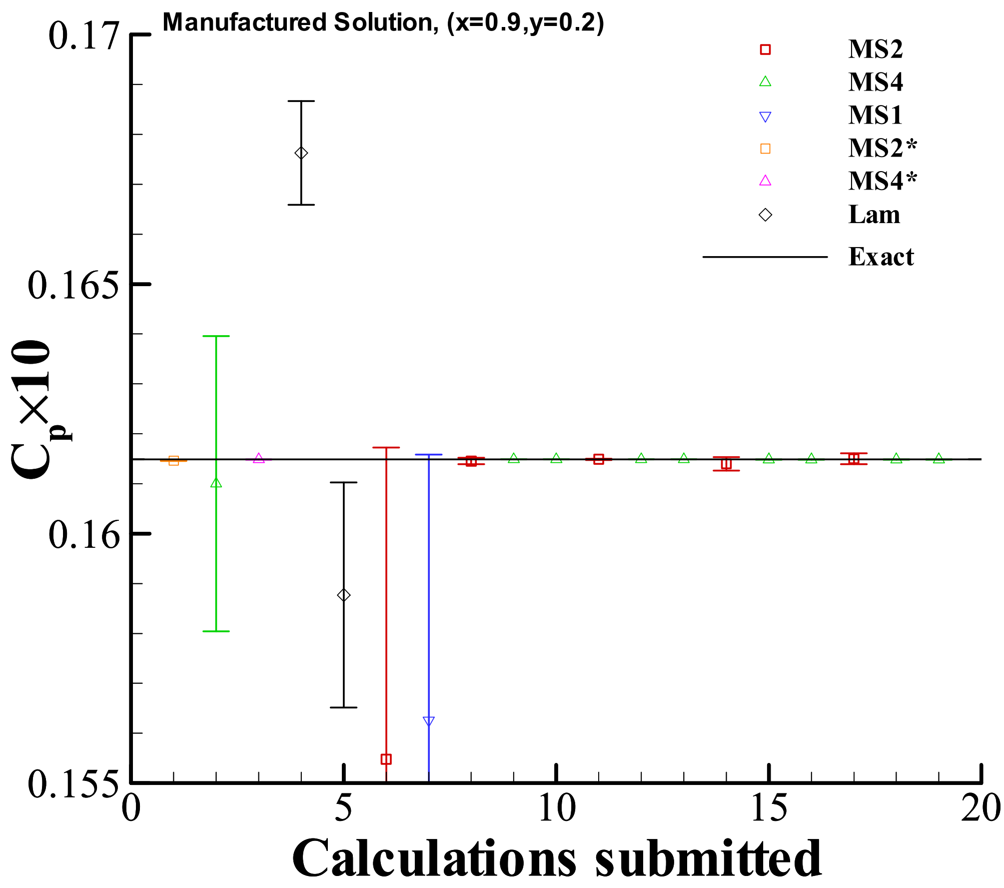
		u_x	$U(u_x)$	$u_y{\times}10$	$U(u_y)\ {\times}10$
	Exact Solution	0.7912749	—	0.7704167	—
1	ECN	0.79126867	0.00001933	0.770449	0.0000277
2	FLOWTECH	0.791	0.000283	0.770	0.00105
3	EPM	0.791275	0.00000009	0.770422	0.00000629
4	WVU	0.79140	0.0007122	0.77535	0.003411
5	WVU	0.79101	0.0002373	0.77019	0.0006161
6	NRMI	0.79165	0.00014824	0.76531	0.0059640
7	NRMI	0.79152	0.00030876	0.76602	0.0051586
8	IST/MARIN A	0.7912722	0.0000108	0.7702967	0.0002107
9	IST/MARIN A	0.7912732	0.0000077	0.7704107	0.0000239
10	IST/MARIN A	0.7912732	0.0000071	0.7704094	0.0000090
11	IST/MARIN B	0.7912776	0.0000034	0.7704322	0.0000811
12	IST/MARIN B	0.7912732	0.0000077	0.7704107	0.0000239
13	IST/MARIN B	0.7912732	0.0000071	0.7704094	0.0000090
14	IST/MARIN A	0.7912635	0.0000499	0.7700882	0.0004643
15	IST/MARIN A	0.7912671	0.0000407	0.7703916	0.0001057
16	IST/MARIN A	0.7912675	0.0000347	0.7703872	0.0001168
17	IST/MARIN B	0.7912859	0.0000430	0.7704971	0.0006062
18	IST/MARIN B	0.7912671	0.0000407	0.7703916	0.0001057
19	IST/MARIN B	0.7912675	0.0000347	0.7703872	0.0001168

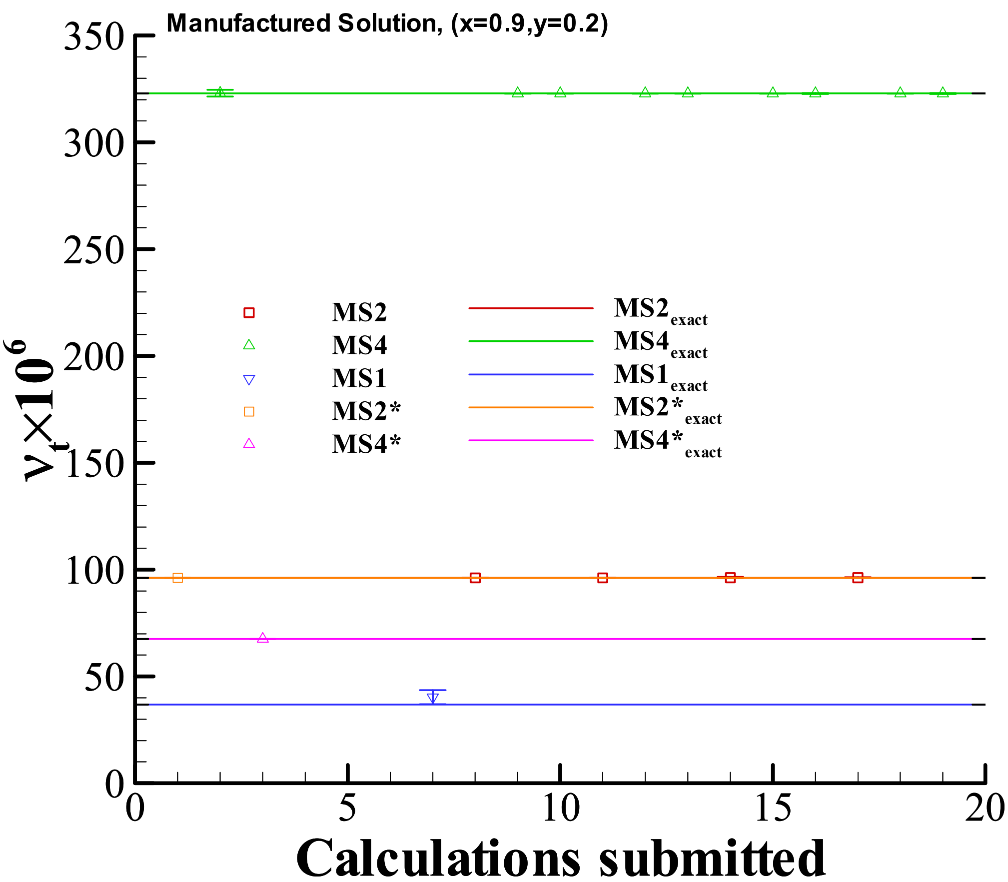

Manufactured Solution, (x=0.9,y=0.2)
Exact
MS2
MS4
MS1
MS2*
MS4*
Lam
0.793
0.792
0.791
0.79
u_x
0
5
10
15
20
Calculations submitted


Manufactured Solution, (x=0.9,y=0.2)
Exact
MS2
MS4
MS1
MS2*
MS4*
Lam
0.78
0.775
0.77
0.765
0.76
u_y×10
0
5
10
15
20
Calculations submitted

C_p and v_t velocity component at ***x=0.9, y=0.2***

		$C_p \times 10$	$U(C_p) \times 10$	$v_t \times 10^6$	$U(v_t) \times 10^6$
0	Exact Solution	0.1614870	—	MS4 322.8604 MS4* 67.60059 MS2 96.16805 MS2* 96.20670 MS1 36.87745	—
1	ECN	0.1614631	0.00000428	MS2* 96.1796	0.0322
2	FLOWTECH	0.161	0.00296	MS4 323	1.57
3	EPM	0.161486	0.00000311	MS4* 67.6005	0.0018989
4	WVU	0.16763	0.001039	—	—
5	WVU	0.15877	0.002254	—	—
6	NRMI	0.15548	0.0062467	—	—
7	NRMI	0.15626	0.0053214	MS1 40.342	3.2911
8	IST/MARIN A	0.1614534	0.0000648	MS2 96.17909	0.0566165
9	IST/MARIN A	0.1614862	0.0000011	MS4 322.8571	0.0295656
10	IST/MARIN A	0.1614864	0.0000009	MS4 322.8579	0.0305867
11	IST/MARIN B	0.1614890	0.0000138	MS2 96.18911	0.0816875
12	IST/MARIN B	0.1614862	0.0000011	MS4 322.8571	0.0295656
13	IST/MARIN B	0.1614864	0.0000009	MS4 322.8579	0.0305867
14	IST/MARIN A	0.1613985	0.0001330	MS2 96.22439	0.3017610
15	IST/MARIN A	0.1614840	0.0000048	MS4 322.8334	0.0766775
16	IST/MARIN A	0.1614841	0.0000045	MS4 322.8334	0.1889472
17	IST/MARIN B	0.1615000	0.0001110	MS2 96.25446	0.1373631
18	IST/MARIN B	0.1614840	0.0000048	MS4 322.8334	0.0766775
19	IST/MARIN B	0.1614841	0.0000045	MS4 322.8334	0.1889472

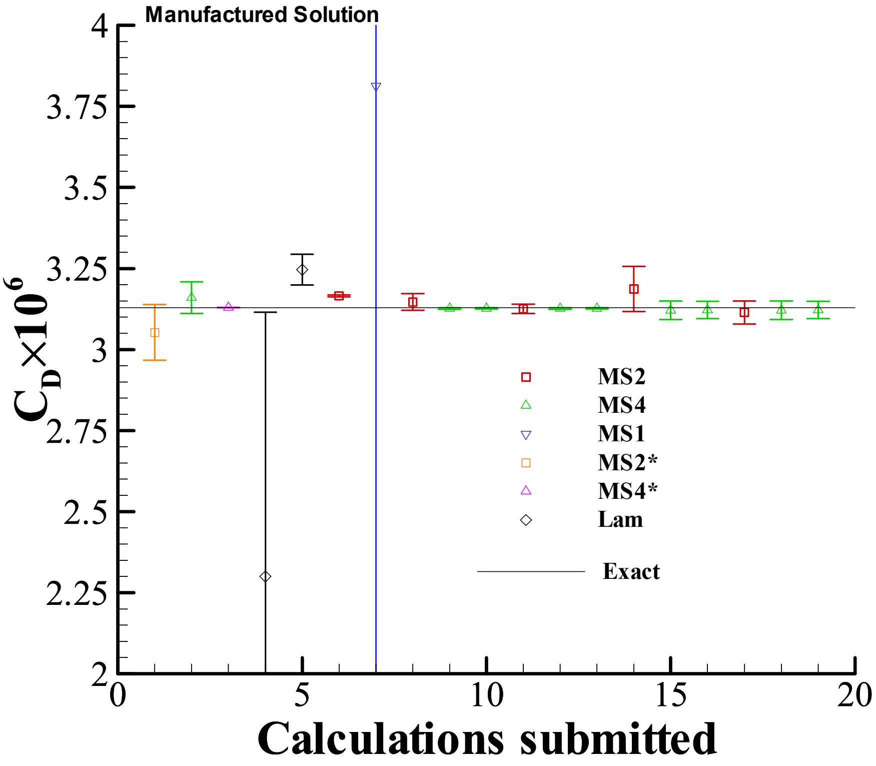

Manufactured Solution, (x=0.9,y=0.2)
MS2
MS4
MS1
MS2*
MS4*
Lam
Exact
$C_p \times 10$
0.17
0.165
0.16
0.155
0
5
10
15
20
Calculations submitted


Manufactured Solution, (x=0.9,y=0.2)
MS2
MS4
MS1
MS2*
MS4*
$MS2_{exact}$
$MS4_{exact}$
$MS1_{exact}$
$MS2*_{exact}$
$MS4*_{exact}$
$\nu_t \times 10^6$
350
300
250
200
150
100
50
0
0
5
10
15
20
Calculations submitted

d) Integral quantities

Friction resistance of the bottom wall

		$C_D \times 10^6$	$U(C_D) \times 10^6$
0	Exact Solution	3.128531	—
1	ECN	3.0526	0.0858
2	FLOWTECH	3.16	0.0486
3	EPM	3.12938	0.0000488755
4	WVU	2.29995	0.815
5	WVU	3.2463	0.047395
6	NRMI	3.1655	0.0028666
7	NRMI	3.8125	2.0846
8	IST/MARIN A	3.1465176	0.0255210
9	IST/MARIN A	3.1267246	0.0022316
10	IST/MARIN A	3.1268387	0.0020982
11	IST/MARIN B	3.1258496	0.0142844
12	IST/MARIN B	3.1267246	0.0022316
13	IST/MARIN B	3.1268387	0.0020982
14	IST/MARIN A	3.1865395	0.0697526
15	IST/MARIN A	3.1211923	0.0287206
16	IST/MARIN A	3.1216665	0.0266437
17	IST/MARIN B	3.1144221	0.0356216
18	IST/MARIN B	3.1211923	0.0287206
19	IST/MARIN B	3.1216665	0.0266437



6.3 Backward Facing Step

a) Calculations performed

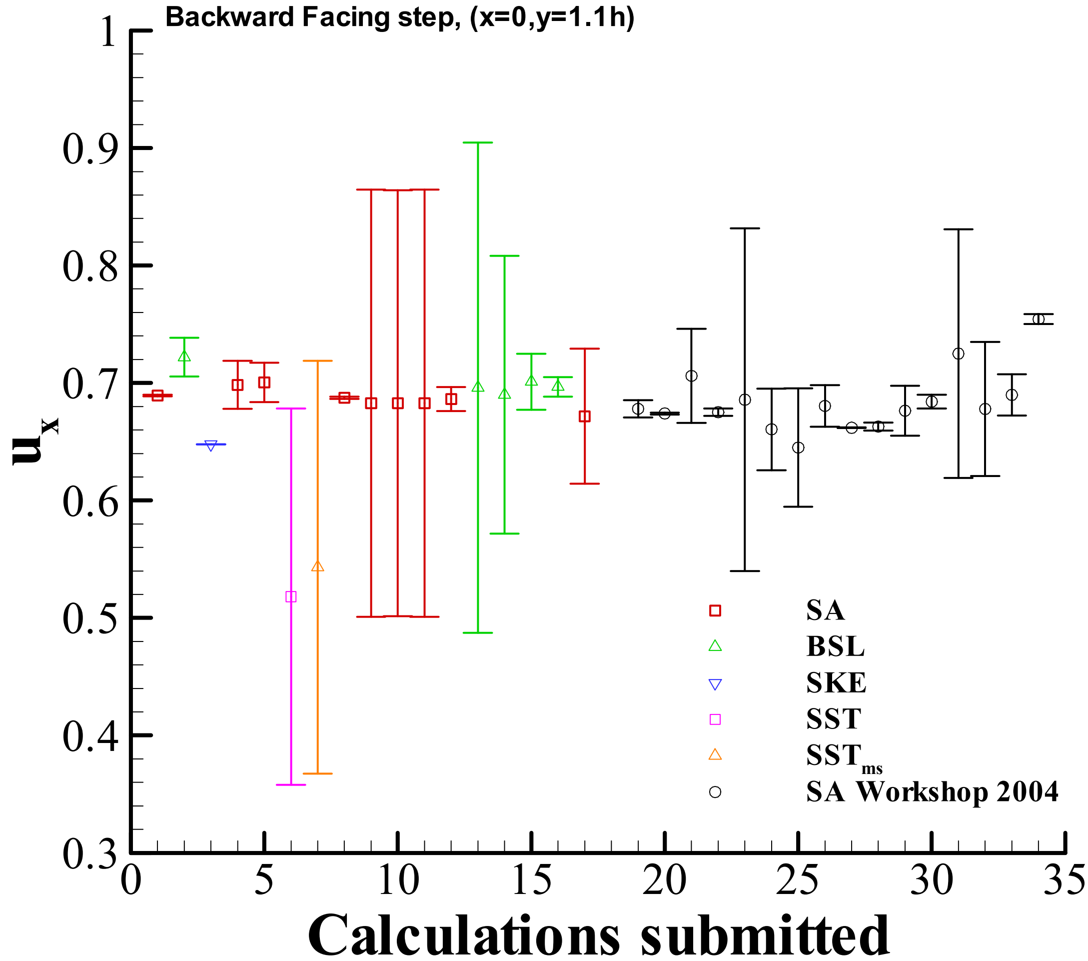
		Turbulence Model	Grid
1	ECN	SA	Unstructured, 95500 cells
2	FLOWTECH	SST	Single block, Structured
3	EPM	SKE	Unstructured adaptive triangular
4	WVU	SA	Structured, D1
5	WVU	SA	Structured, D2
6	DSC/CEHIPAR	SST	Unstructured
7	DSC/CEHIPAR	SST_{rm}	Unstructured
8	NRMI	SA	Multi-block, Structured
9	IST/MARIN A	SA	Single block, Structured, NOC1, 241×241
10	IST/MARIN A	SA	Single block, Structured, NOC3, 241×241
11	IST/MARIN A	SA	Single block, Structured, NOS1, 241×241
12	IST/MARIN A	SA	Single block, Structured, NOS3, 241×241
13	IST/MARIN A	BSL	Single block, Structured, NOC1, 241×241
14	IST/MARIN A	BSL	Single block, Structured, NOC3, 241×241
15	IST/MARIN A	BSL	Single block, Structured, NOS1, 241×241
16	IST/MARIN A	BSL	Single block, Structured, NOS3, 241×241
17	IST/MARIN B	SA	Single block, Structured, NOCL, 401×201

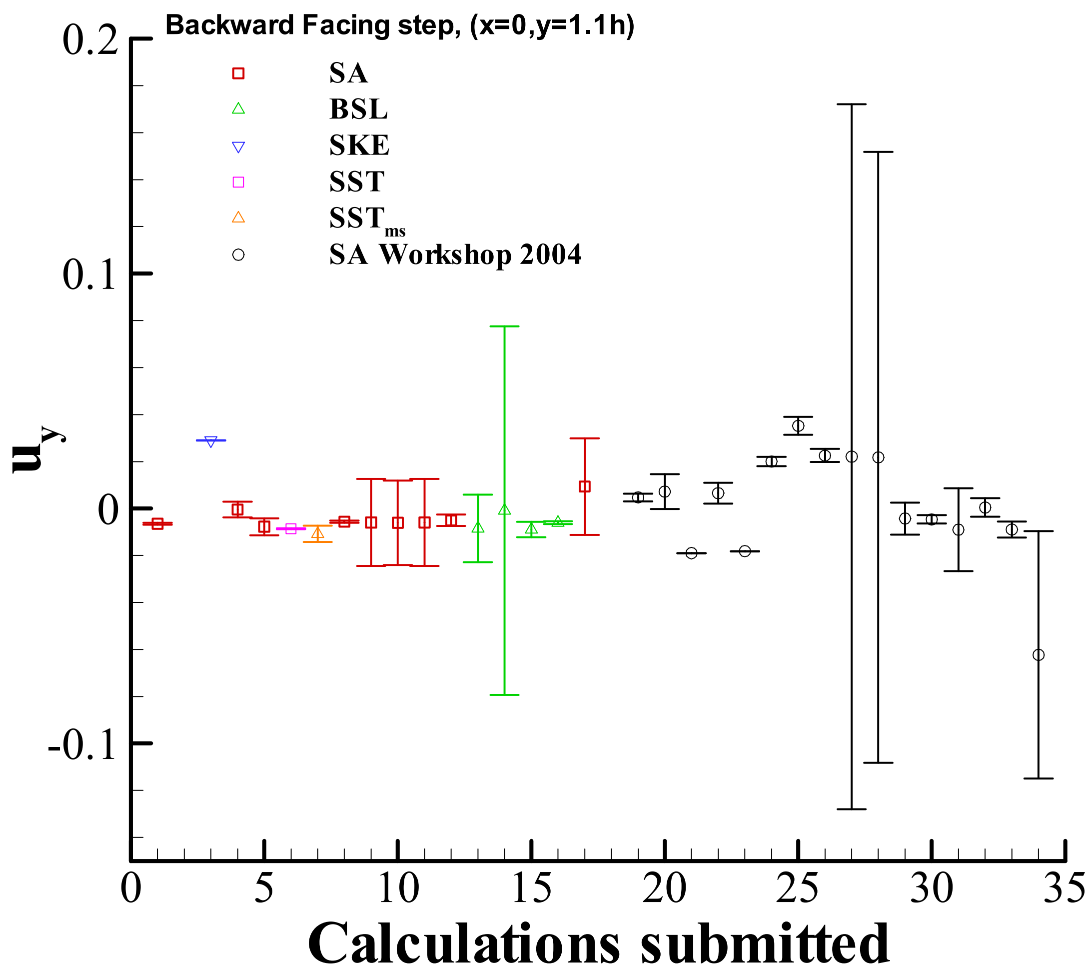
SA – Spalart & Allmaras one-equation model
BSL – Baseline k-ω two-equation model
SKE – Standard k-ε two-equation model
SST – Shear-Stress transport k-ω two-equation model
SST_{rm} – SST with reattachement modification
D1 – First order discretization
D2 – Second order discretization
NOC1 – Non-orthogonal curvilinear, first-order convection turbulence quantities
NOC3 – Non-orthogonal curvilinear, third-order convection turbulence quantities
NOS1 – Non-orthogonal straight lines, first-order convection turbulence quantities
NOS3 – Non-orthogonal straight lines, third-order convection turbulence quantities
NOCL – Non-orthogonal curvilinear, third-order with limiters all convective terms

b) Local flow quantities

u_x and u_y velocity component at $x=0$, $y=1.1h$

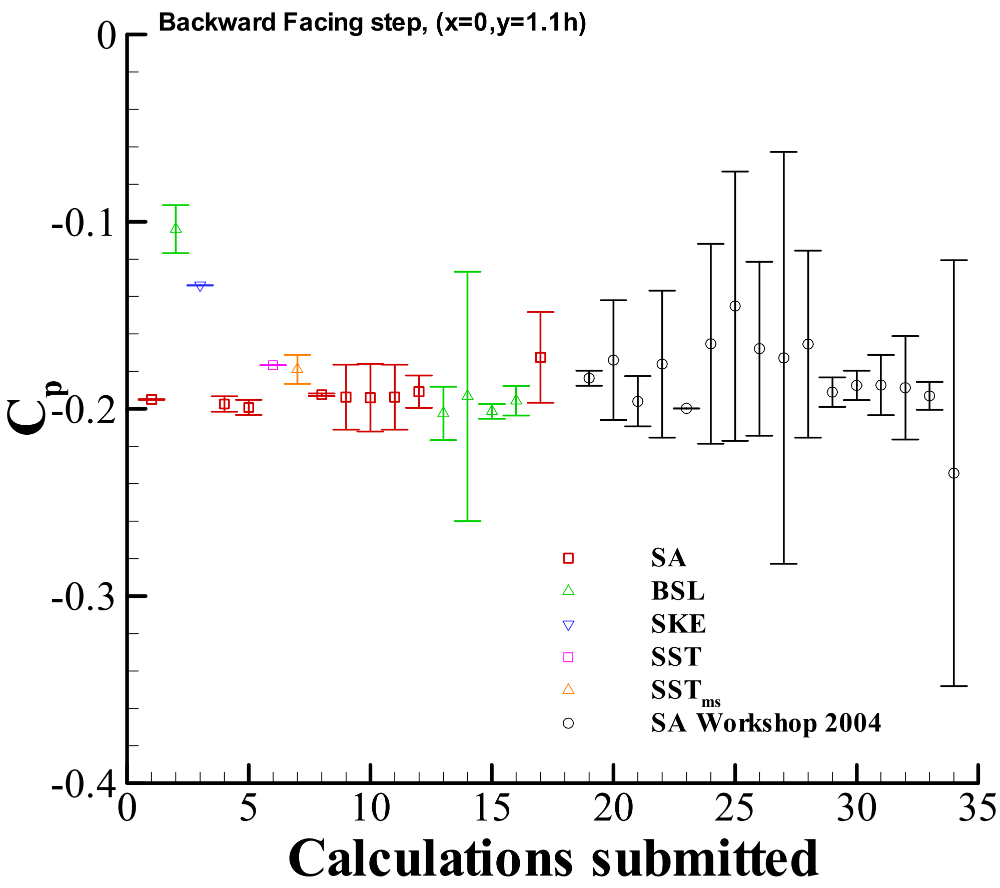
		u_x	$U(u_x)$	u_y	$U(u_y)$
1	ECN	0.689202	0.000684	-0.006496	0.000457
2	FLOWTECH	0.722	0.0165	-0.418	0.011909
3	EPM	0.647700	0.00003965	0.0289958	0.00010219
4	WVU	0.69837	0.020462	-0.00047	0.0033346
5	WVU	0.700446	0.01688	-0.00773	0.003608
6	DSC/CEHIPAR	0.51808	0.16029	-0.0085967	0.00024197
7	DSC/CEHIPAR	0.54321	0.17565	-0.01082	0.003438
8	NRMI	0.68738	0.00091788	-0.0056080	0.00044706
9	IST/MARIN A	0.6828014	0.1818082	-0.0059755	0.0185447
10	IST/MARIN A	0.6827631	0.1813002	-0.0060770	0.0179746
11	IST/MARIN A	0.6828014	0.1818082	-0.0059755	0.0185447
12	IST/MARIN A	0.6862671	0.0101388	-0.0050294	0.0024578
13	IST/MARIN A	0.6960053	0.2087002	-0.0084815	0.0143728
14	IST/MARIN A	0.6899527	0.1182354	-0.0009477	0.0784919
15	IST/MARIN A	0.7010954	0.0238234	-0.0089417	0.0032683
16	IST/MARIN A	0.6967075	0.0082530	-0.0060689	0.0005750
17	IST/MARIN B	0.6716300	0.0574440	0.0093455	0.0205416



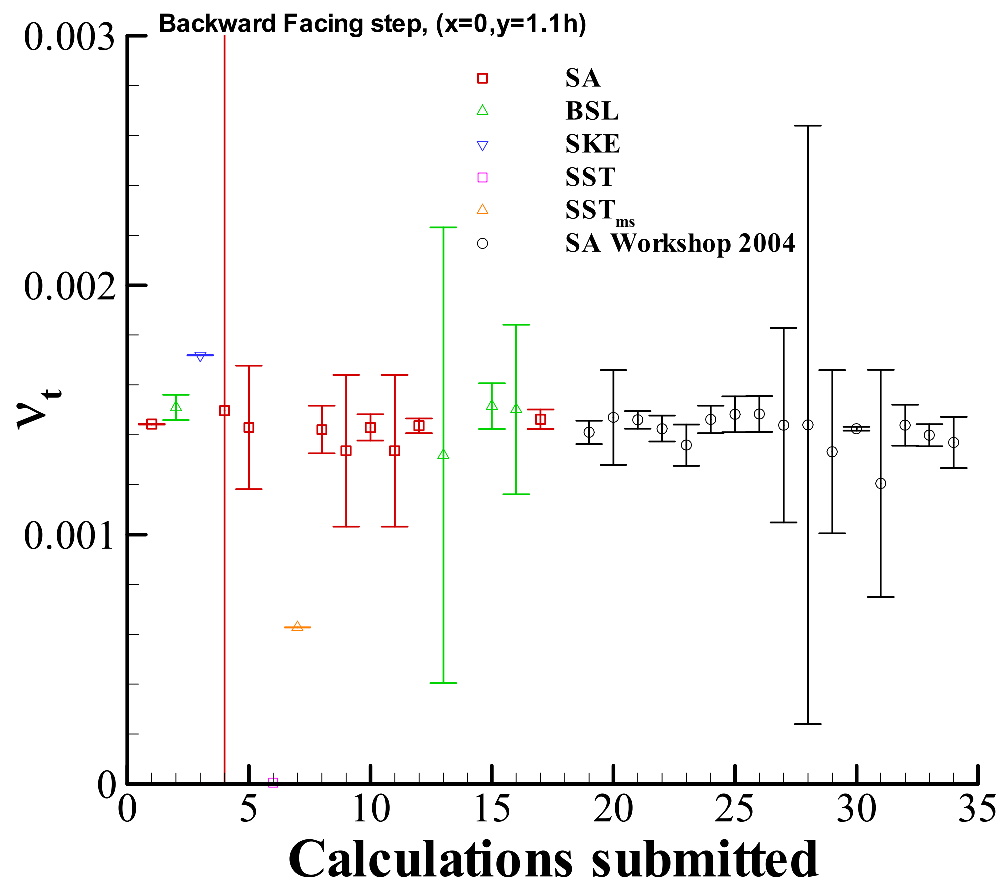


Cp and ν_t velocity component at ***x=0, y=1.1h***

		C_p	$U(C_p)$	ν_t	$U(\nu_t)$
1	ECN	-0.194975	0.000166	0.00144293	0.0000015
2	FLOWTECH	-0.104	0.0128	0.00151	0.00005
3	EPM	-0.133953	0.00003394	0.00171898	0.00000031
4	WVU	-0.197411	0.0041279	0.00149738	0.00186244
5	WVU	-0.19925	0.00402485	0.00143	0.0002481
6	DSC/CEHIPAR	-0.17672	—	0.00000523	—
7	DSC/CEHIPAR	-0.17897	0.00768	0.0006279	—
8	NRMI	-0.19245	0.00065478	0.0014211	0.0000958
9	IST/MARIN A	-0.1937565	0.0173310	0.0013363	0.0003043
10	IST/MARIN A	-0.1940392	0.0180163	0.0014292	0.0000527
11	IST/MARIN A	-0.1937565	0.0173310	0.0013363	0.0003043
12	IST/MARIN A	-0.1908241	0.0086205	0.0014364	0.0000296
13	IST/MARIN A	-0.2024341	0.0142606	0.0013181	0.0009133
14	IST/MARIN A	-0.1933648	0.0666990	0.0034740	0.0356488
15	IST/MARIN A	-0.2013730	0.0039197	0.0015150	0.0000918
16	IST/MARIN A	-0.1957108	0.0078837	0.0015019	0.0003399
17	IST/MARIN B	-0.1724570	0.0241387	0.0014626	0.0000391



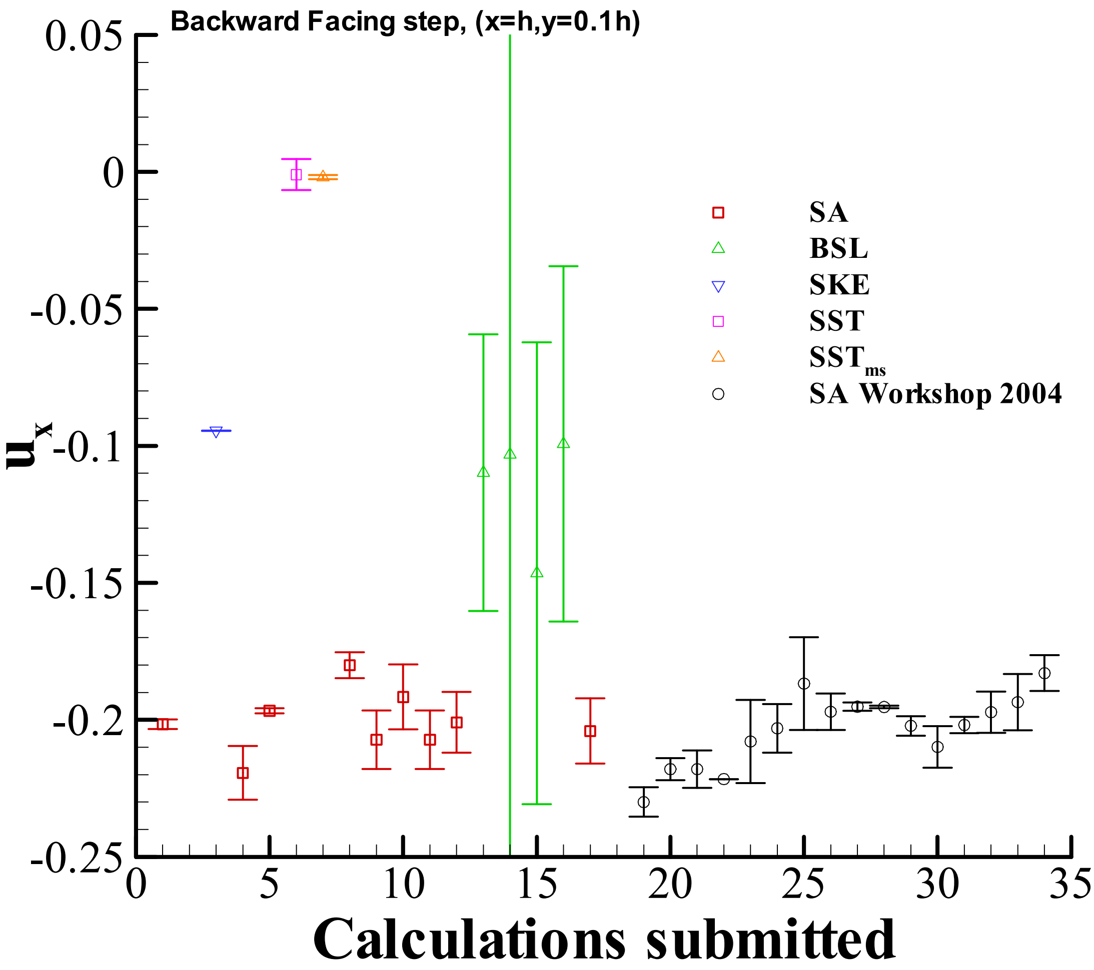
Backward Facing step, (x=0,y=1.1h)
0
-0.1
-0.2
-0.3
-0.4
C_p
0
5
10
15
20
25
30
35
Calculations submitted
SA
BSL
SKE
SST
SST_{ms}
SA Workshop 2004

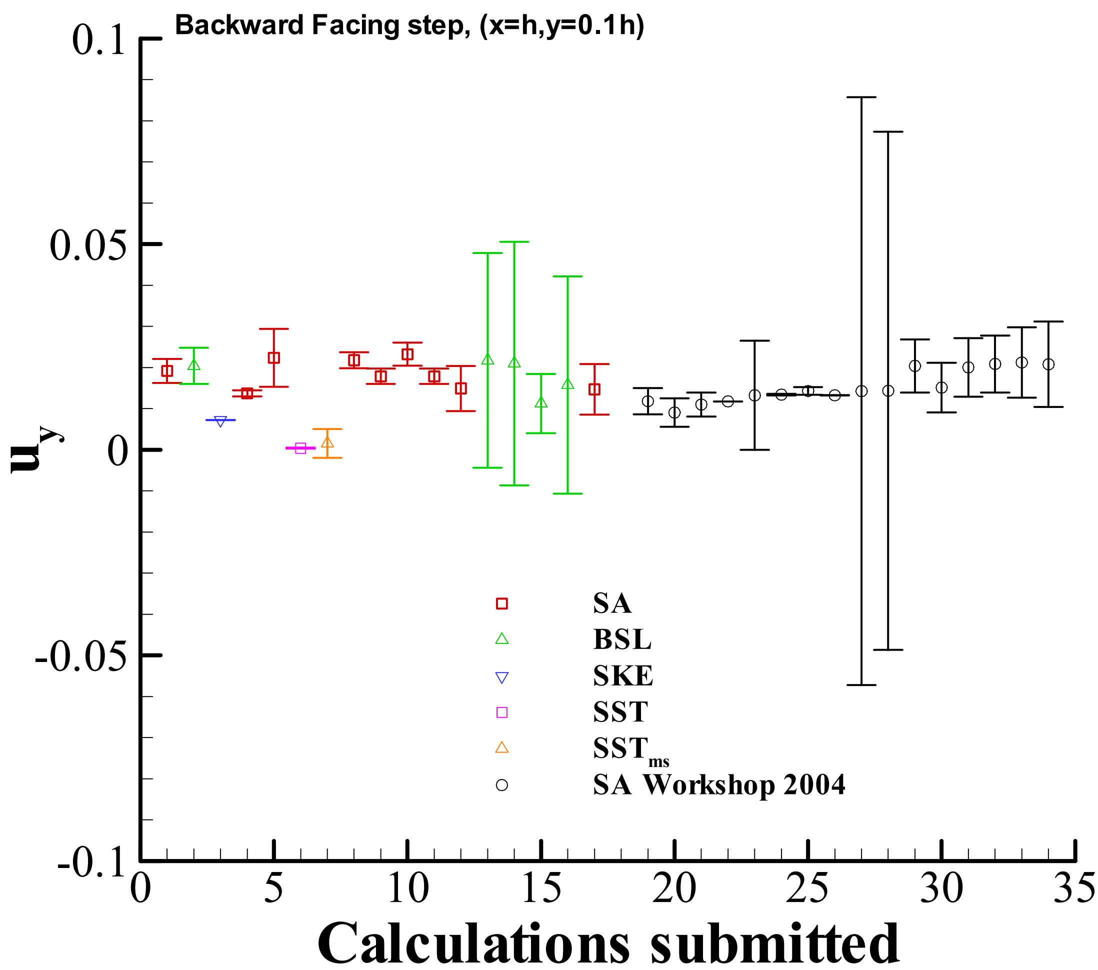


Backward Facing step, (x=0,y=1.1h)
0.003
0.002
0.001
0
ν_t
0
5
10
15
20
25
30
35
Calculations submitted
SA
BSL
SKE
SST
SST_{ms}
SA Workshop 2004

u_x and u_y velocity component at $x=h, y=0.1h$

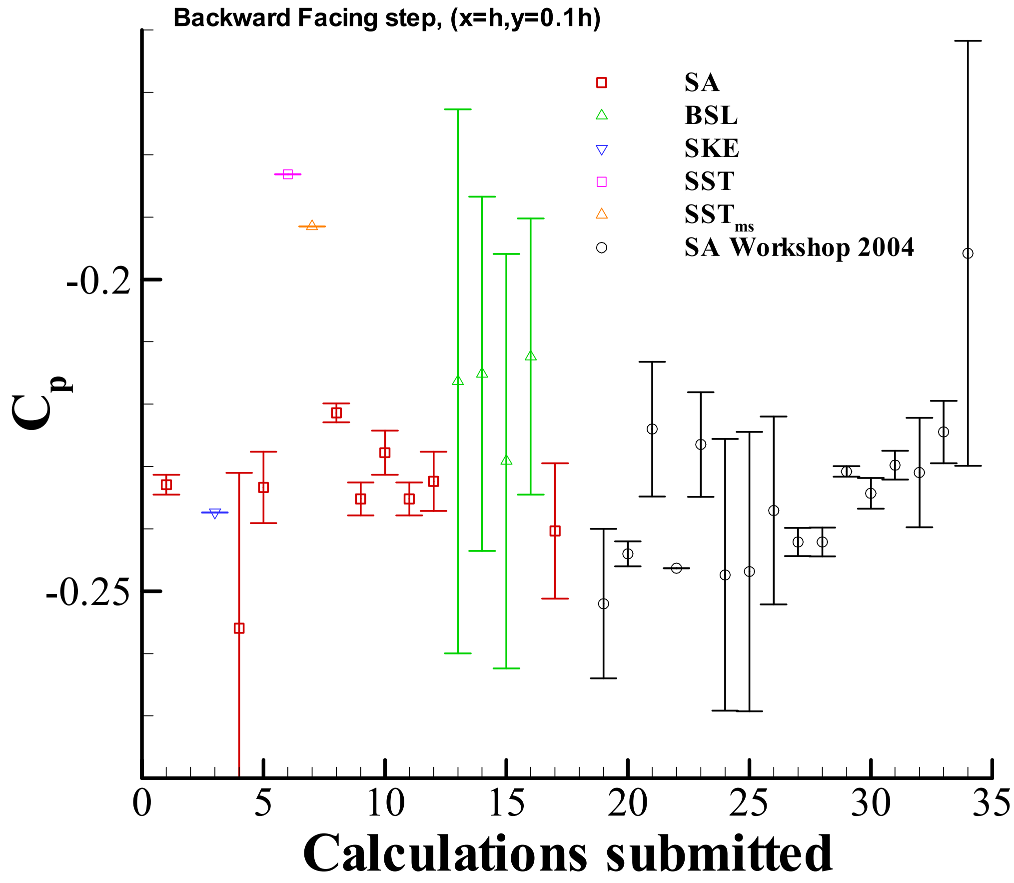
		u_x	$U(u_x)$	u_y	$U(u_y)$
1	ECN	-0.201609	0.001721	0.019145	0.00294
2	FLOWTECH	—	—	0.0204	0.00437
3	EPM	-0.0944773	0.00003712	0.00721732	0.00001106
4	WVU	-0.2193704	0.0097839	0.0136924	0.00072432
5	WVU	-0.1966764	0.00092437	0.0223564	0.0070668
6	DSC/CEHIPAR	-0.001011	0.0056547	0.00038371	0.00012766
7	DSC/CEHIPAR	-0.001929	0.0007516	0.0015279	0.0035079
8	NRMI	-0.180050	0.0047425	0.021778	0.0019691
9	IST/MARIN A	-0.2072513	0.0106927	0.0178586	0.0018735
10	IST/MARIN A	-0.1916504	0.0118797	0.0232240	0.0028006
11	IST/MARIN A	-0.2072513	0.0106927	0.0178586	0.0018735
12	IST/MARIN A	-0.2009371	0.0110845	0.0149110	0.0054793
13	IST/MARIN A	-0.1098003	0.0505233	0.0217237	0.0261174
14	IST/MARIN A	-0.1031532	0.1757845	0.0209797	0.0296381
15	IST/MARIN A	-0.1465352	0.0843015	0.0112529	0.0071966
16	IST/MARIN A	-0.0992850	0.0648635	0.0157557	0.0264283
17	IST/MARIN B	-0.2040980	0.0119031	0.0146845	0.0061536

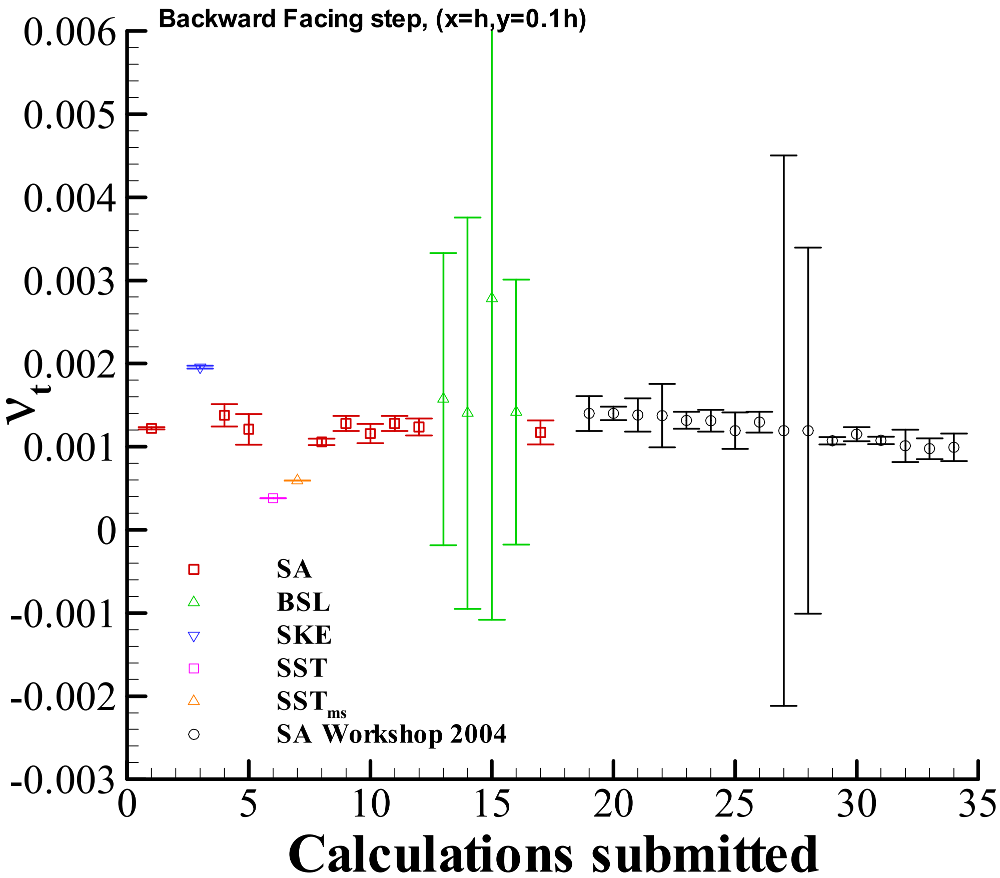




Cp and ν_t velocity component at ***x=h, y=0.1h***

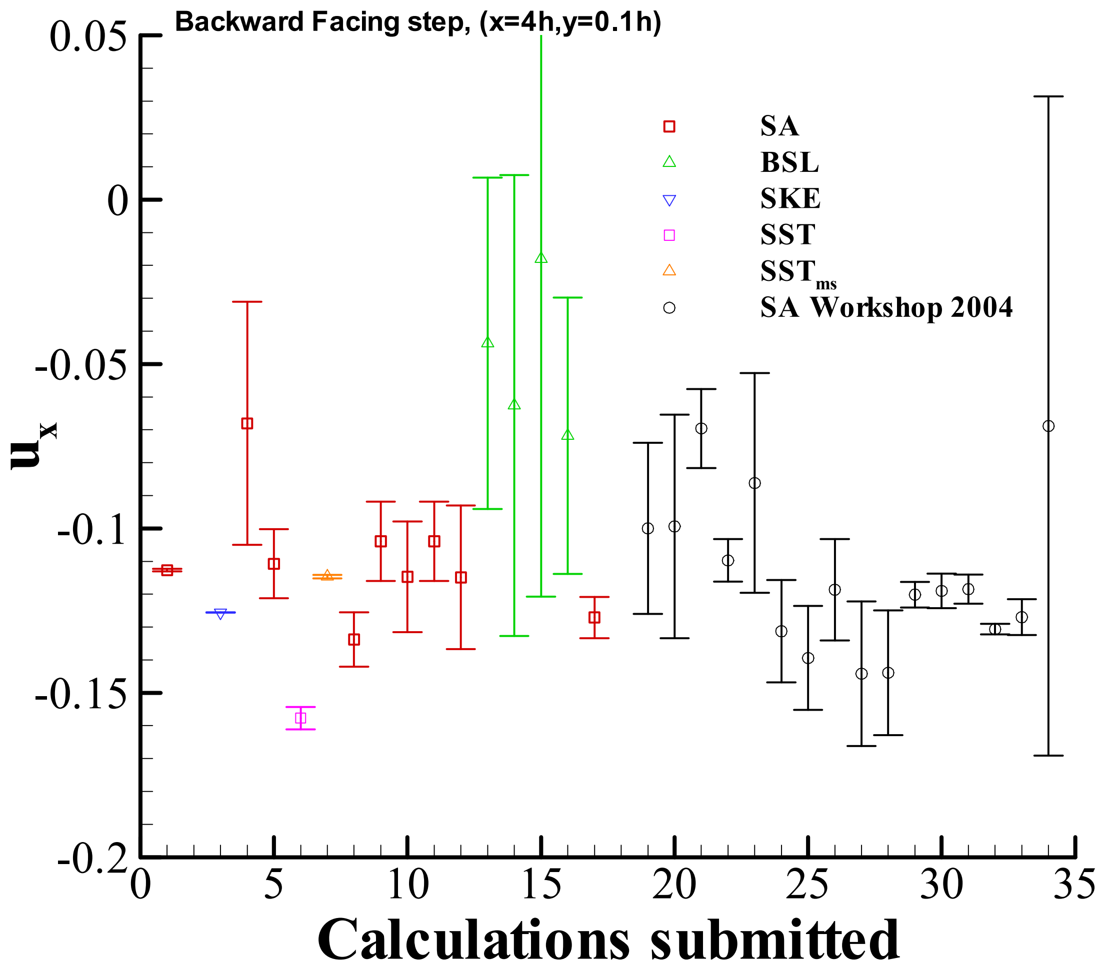
		C_p	$U(C_p)$	ν_t	$U(\nu_t)$
1	ECN	-0.232923	0.001602	0.0012209	0.0000136
2	FLOWTECH	—	—	—	—
3	EPM	-0.237365	0.00000227	0.00195559	0.0000175
4	WVU	-0.2559408	0.024903	0.0013771	0.0001359
5	WVU	-0.2333627	0.0057173	0.0012094	0.00018588
6	DSC/CEHIPAR	-0.18313	—	0.00038	—
7	DSC/CEHIPAR	-0.19149	—	0.0005914	—
8	NRMI	-0.22140	0.0015124	0.0010582	0.0000381
9	IST/MARIN A	-0.2352008	0.0026281	0.0012789	0.0000893
10	IST/MARIN A	-0.2277730	0.0035468	0.0011586	0.0001156
11	IST/MARIN A	-0.2352008	0.0026281	0.0012789	0.0000893
12	IST/MARIN A	-0.2323870	0.0047343	0.0012372	0.0001027
13	IST/MARIN A	-0.2163524	0.0436151	0.0015732	0.0017580
14	IST/MARIN A	-0.2151362	0.0284299	0.0014028	0.0023537
15	IST/MARIN A	-0.2291382	0.0332378	0.0027816	0.0038636
16	IST/MARIN A	-0.2123768	0.0221444	0.0014163	0.0015939
17	IST/MARIN B	-0.2403250	0.0108462	0.0011719	0.0001437

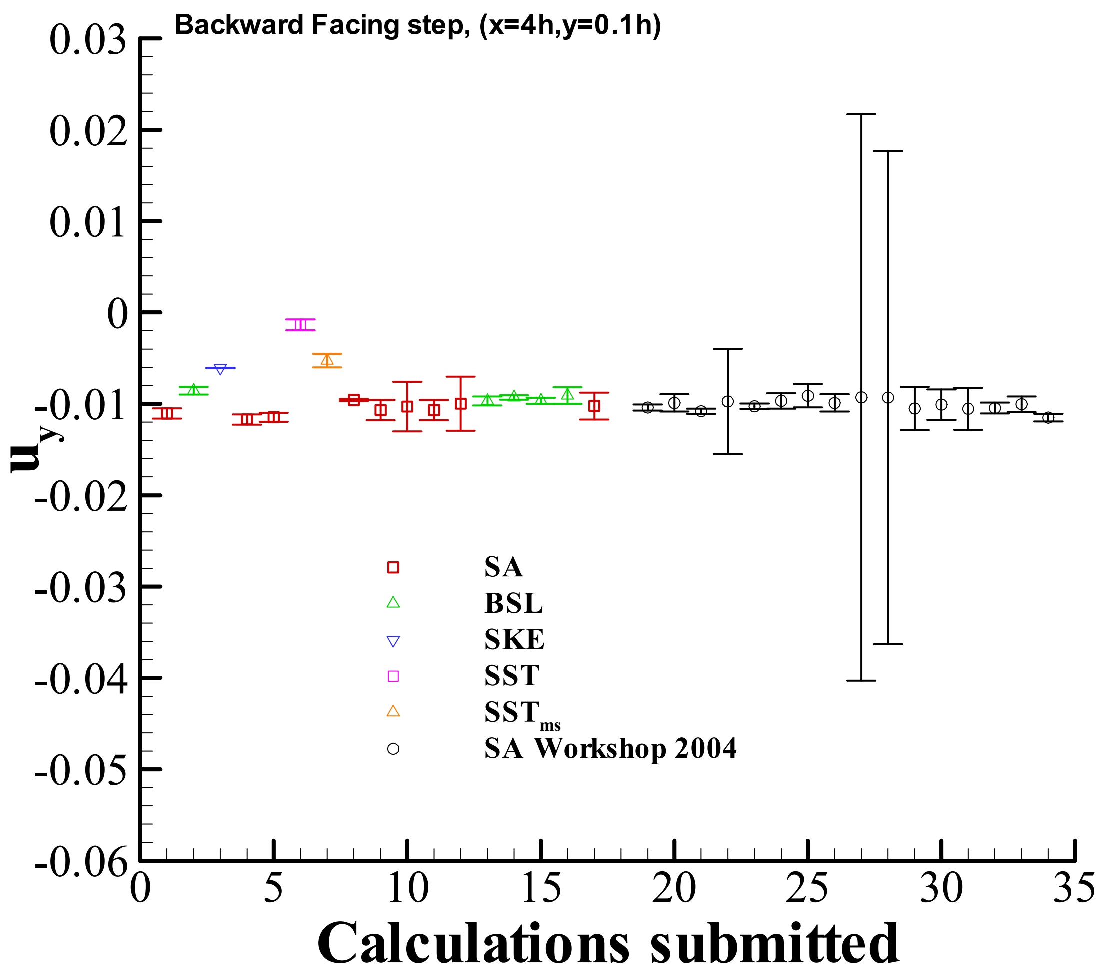

Backward Facing step, (x=h,y=0.1h)
SA
BSL
SKE
SST
SST$_{ms}$
SA Workshop 2004
-0.2
-0.25
C_p
0
5
10
15
20
25
30
35
Calculations submitted


Backward Facing step, (x=h,y=0.1h)
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
ν_t
SA
BSL
SKE
SST
SST$_{ms}$
SA Workshop 2004
0
5
10
15
20
25
30
35
Calculations submitted

u_x and u_y velocity component at $x=4h, y=0.1h$

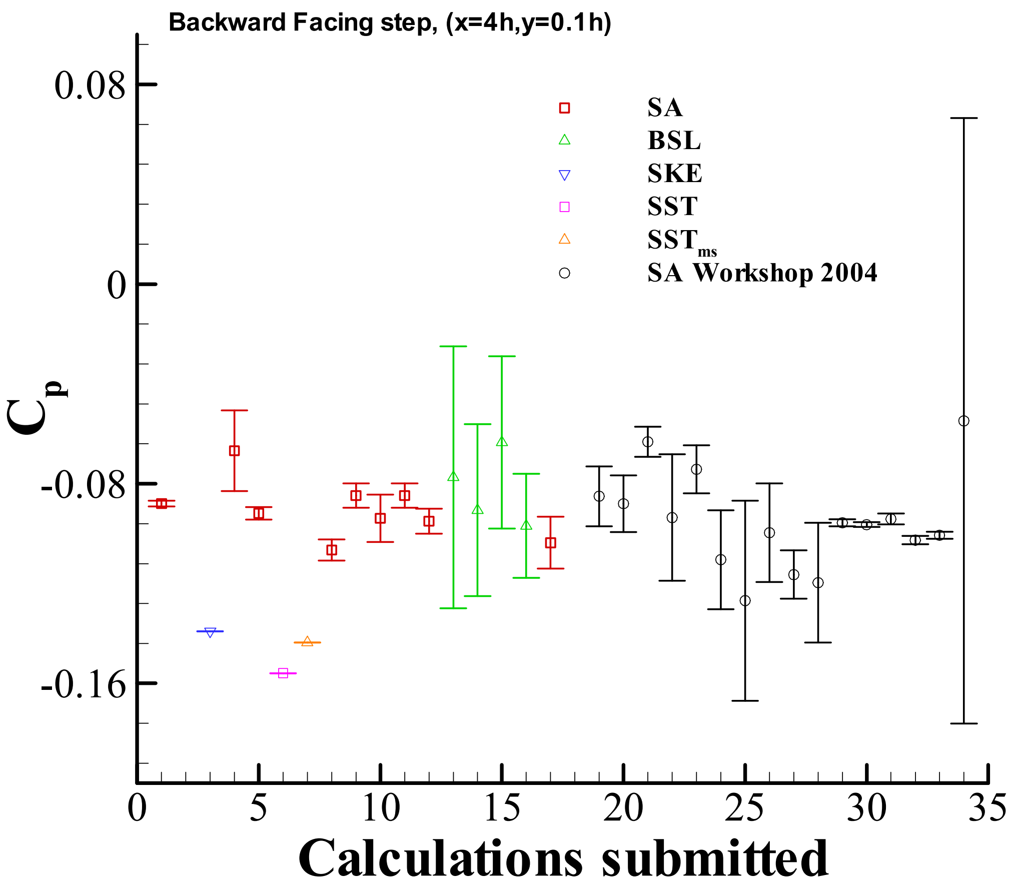
		u_x	$U(u_x)\times10^2$	$u_y\times10^5$	$U(u_y)\times10^5$
1	ECN	-0.112696	0.000388	-0.011053	0.000560
2	FLOWTECH	-0.420	0.0474	-0.00856	0.000418
3	EPM	-0.125582	0.00001095	-0.00608819	0.00000080
4	WVU	-0.06803701	0.0369713	-0.01170795	0.00056549
5	WVU	-0.1107796	0.010502	-0.0114692	0.00048285
6	DSC/CEHIPAR	-0.1577	0.003406	-0.00135	0.00060716
7	DSC/CEHIPAR	-0.11463	0.0005257	-0.0052601	0.00073755
8	NRMI	-0.13378	0.0082435	-0.0095751	0.00009634
9	IST/MARIN A	-0.1039419	0.0120763	-0.0106849	0.0010921
10	IST/MARIN A	-0.1147244	0.0168190	-0.0102934	0.0027041
11	IST/MARIN A	-0.1039419	0.0120763	-0.0106849	0.0010921
12	IST/MARIN A	-0.1149021	0.0218446	-0.0099844	0.0029575
13	IST/MARIN A	-0.0437002	0.0504088	-0.0096850	0.0004966
14	IST/MARIN A	-0.0626273	0.0701217	-0.0093073	0.0002557
15	IST/MARIN A	-0.0180654	0.1026454	-0.0096559	0.0003305
16	IST/MARIN A	-0.0717989	0.0420207	-0.0090899	0.0009149
17	IST/MARIN B	-0.1270890	0.0062700	-0.0102360	0.0014757



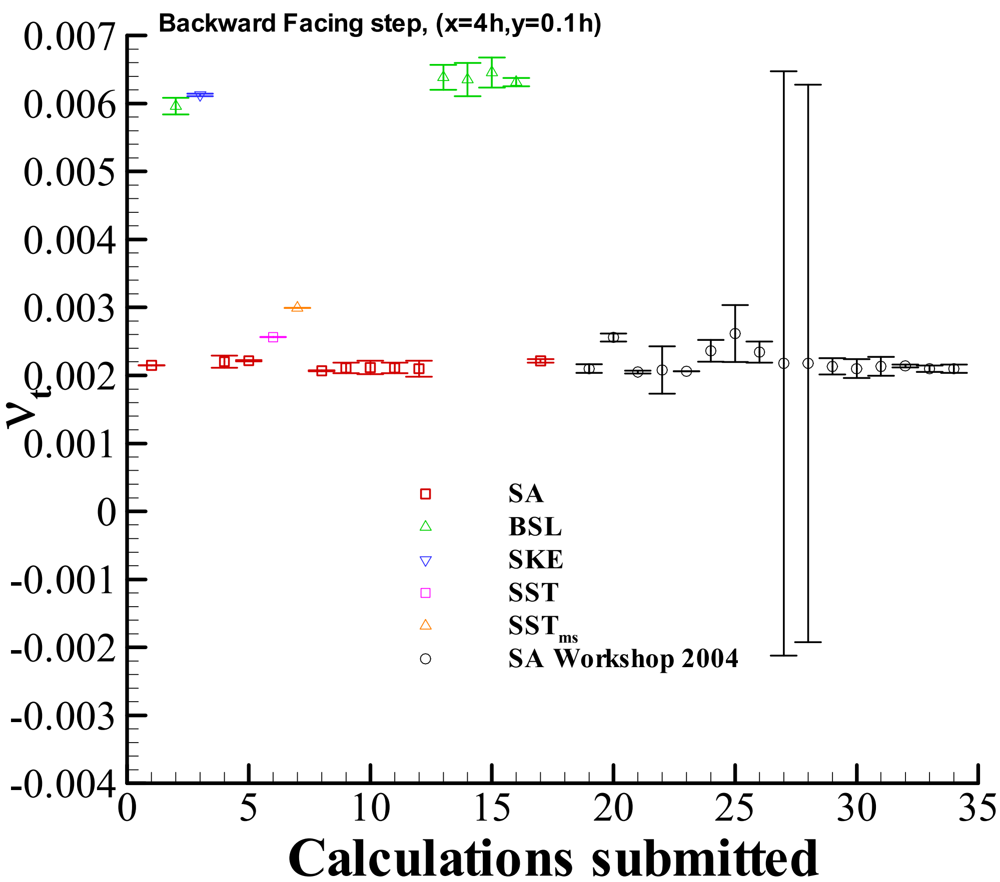


Cp and v_t velocity component at ***x=4h, y=0.1h***

		C_p	$U(C_p)$	v_t	$U(v_t)$
1	ECN	-0.087934	0.00118	0.0021476	0.00000322
2	FLOWTECH	—	—	0.00596	0.000123
3	EPM	-0.139171	0.00000484	0.00612614	0.00001852
4	WVU	-0.06681666	0.0161696	0.00220131	0.00008959
5	WVU	-0.0918282	0.0024793	0.0022154	0.00000953
6	DSC/CEHIPAR	-0.15592	—	0.0025621	—
7	DSC/CEHIPAR	-0.14363	—	0.0029909	—
8	NRMI	-0.10656	0.0042588	0.0020681	0.00000870
9	IST/MARIN A	-0.0847148	0.0048667	0.0021098	0.0000087
10	IST/MARIN A	-0.0938294	0.0095043	0.0021163	0.0000984
11	IST/MARIN A	-0.0847148	0.0048667	0.0021098	0.0000780
12	IST/MARIN A	-0.0949953	0.0050297	0.0020972	0.0001177
13	IST/MARIN A	-0.0774073	0.0524790	0.0063843	0.0001826
14	IST/MARIN A	-0.0905928	0.0344202	0.0063527	0.0002455
15	IST/MARIN A	-0.0634222	0.0344873	0.0064566	0.0002203
16	IST/MARIN A	-0.0969122	0.0208686	0.0063123	0.0000613
17	IST/MARIN B	-0.1036550	0.0103860	0.0022140	0.0000238



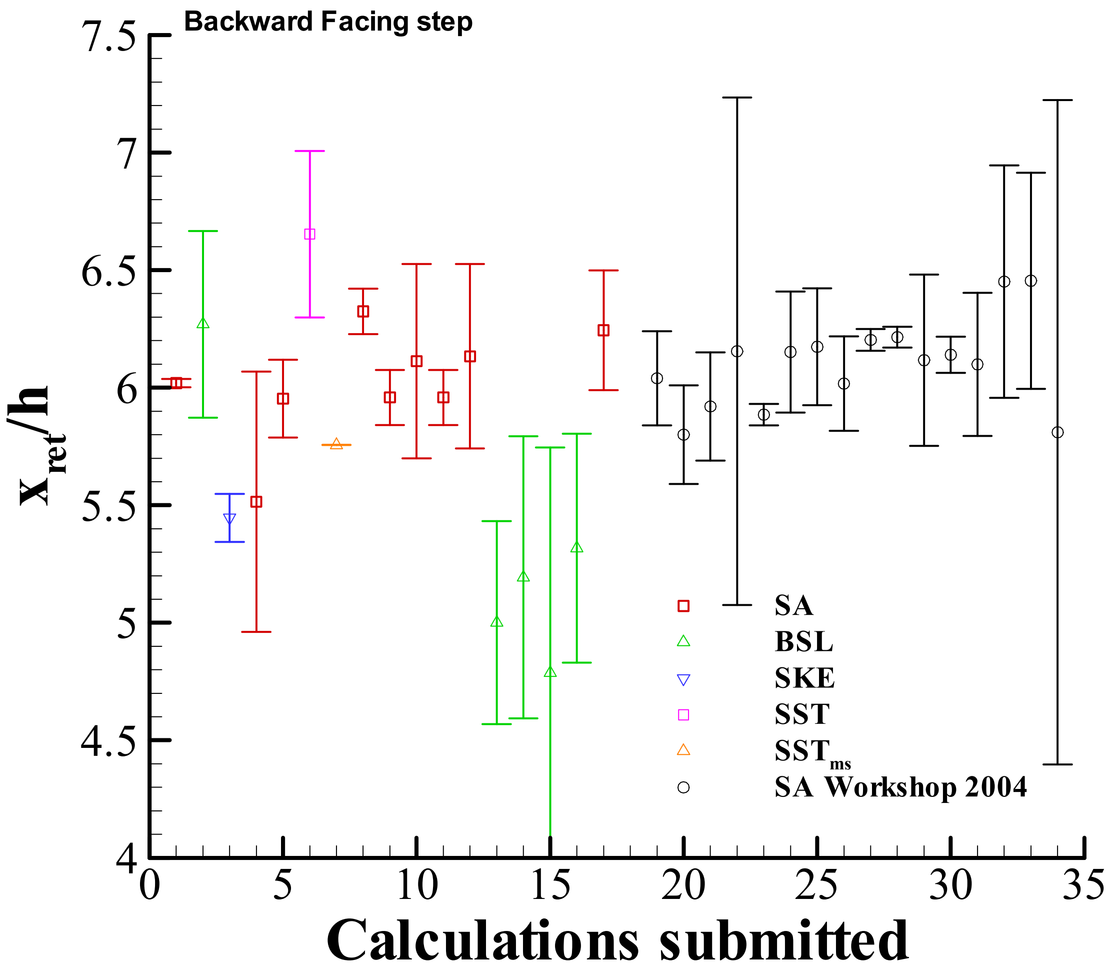
Backward Facing step, (x=4h,y=0.1h)
0.08
0
-0.08
-0.16
C_p
SA
BSL
SKE
SST
SST_{ms}
SA Workshop 2004
0
5
10
15
20
25
30
35
Calculations submitted



Backward Facing step, (x=4h,y=0.1h)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
ν_t
SA
BSL
SKE
SST
SST_{ms}
SA Workshop 2004
0
5
10
15
20
25
30
35
Calculations submitted

Re-attachment point

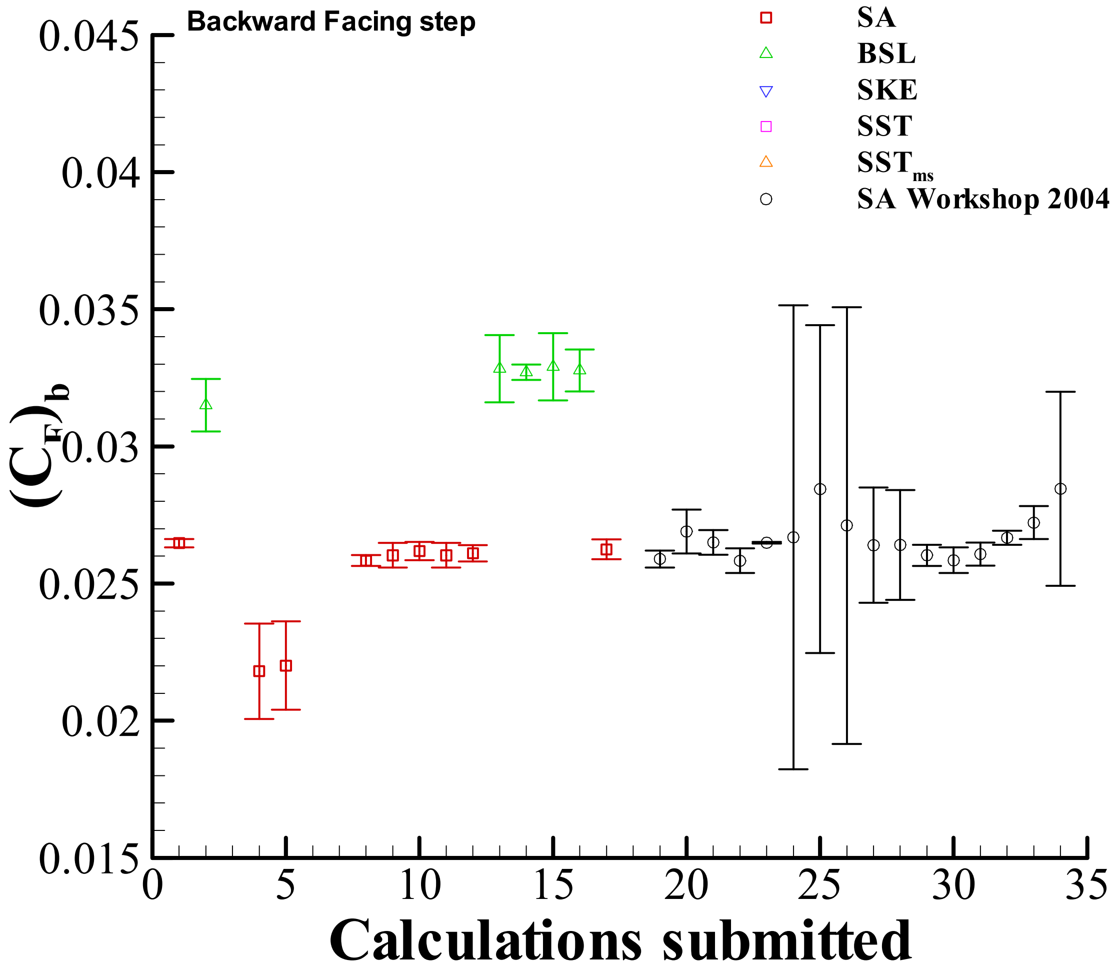
		x_{ret}/h	$U(x_{ret}/h)$
1	ECN	6.0191	0.0181
2	FLOWTECH	6.27	0.397
3	EPM	5.446644	0.102065
4	WVU	5.51486	0.55369
5	WVU	5.95309985	0.1649
6	DSC/CEHIPAR	6.653	0.354
7	DSC/CEHIPAR	5.756	—
8	NRMI	6.3242	0.09651
9	IST/MARIN A	5.9581597	0.1173911
10	IST/MARIN A	6.1124440	0.4132124
11	IST/MARIN A	5.9581597	0.1173911
12	IST/MARIN A	6.1336971	0.3926113
13	IST/MARIN A	5.0003953	0.4316598
14	IST/MARIN A	5.1927959	0.5997766
15	IST/MARIN A	4.7863401	0.9594897
16	IST/MARIN A	5.3170328	0.4869708
17	IST/MARIN B	6.2440000	0.2550000

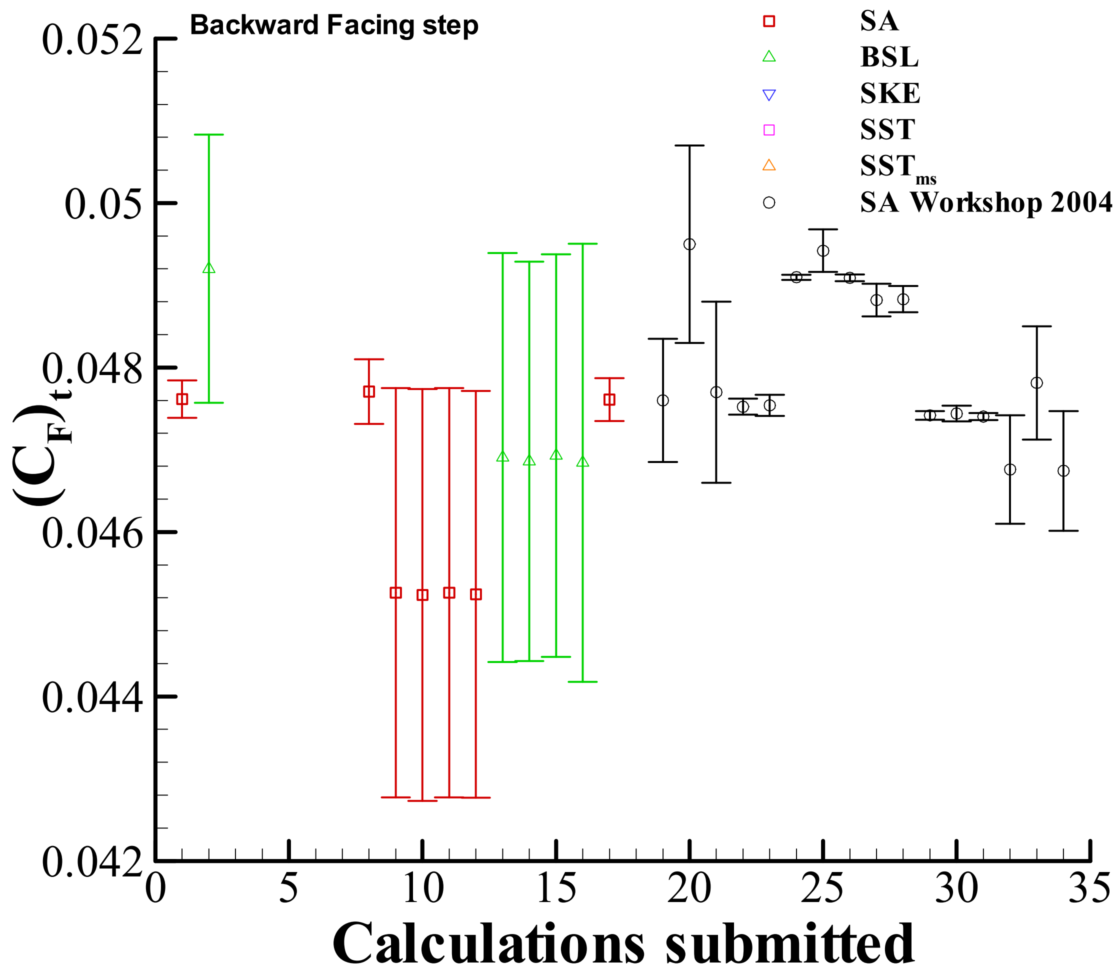


c) Integral flow quantities

Friction resistance of the bottom and top walls

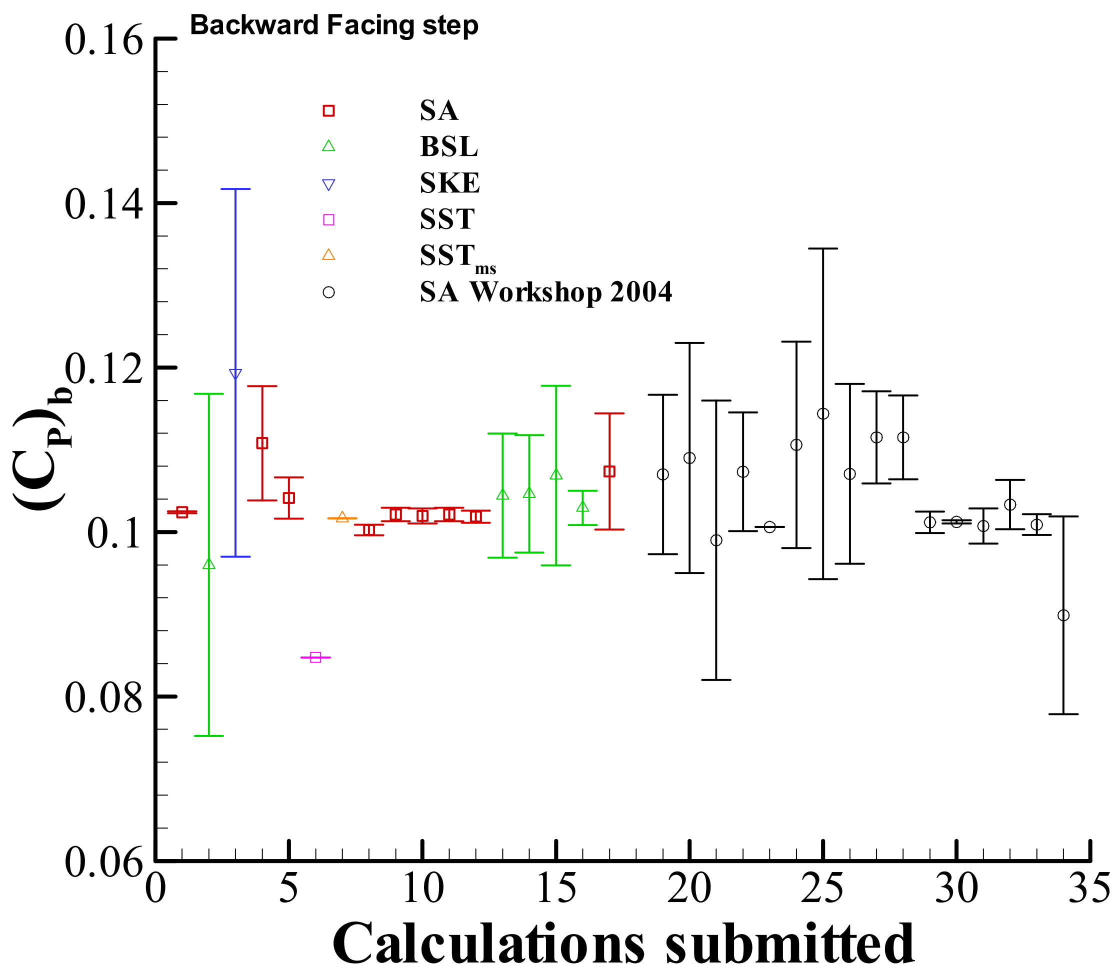
		$(C_F)_b$	$U((C_F)_b)$	$(C_F)_t$	$U((C_F)_t)$
1	ECN	0.026475	0.000154	0.047616	0.000226
2	FLOWTECH	0.031500	0.000958	0.049200	0.001630
3	EPM	0.0526499	0.009936	0.0672544	0.0253363
4	WVU	0.021805	0.00174	0.033164	0.01369
5	WVU	0.022008	0.0016109	0.032922	0.01303
6	DSC/CEHIPAR	0.003123	—	0.0048852	—
7	DSC/CEHIPAR	0.003861	—	0.0058640	—
8	NRMI	0.025837	0.00020147	0.047708	0.0003918
9	IST/MARIN A	0.0260309	0.0004490	0.0452609	0.0024890
10	IST/MARIN A	0.0261818	0.0003322	0.0452352	0.0025043
11	IST/MARIN A	0.0260309	0.0004490	0.0452609	0.0024890
12	IST/MARIN A	0.0261015	0.0002944	0.0452427	0.0024733
13	IST/MARIN A	0.0328305	0.0012281	0.0469058	0.0024856
14	IST/MARIN A	0.0327052	0.0002806	0.0468576	0.0024277
15	IST/MARIN A	0.0329024	0.0012270	0.0469272	0.0024473
16	IST/MARIN A	0.0327708	0.0007654	0.0468419	0.0026638
17	IST/MARIN B	0.0262450	0.0003625	0.0476100	0.0002624





Pressure resistance of the bottom wall

		$(C_P)_b$	$U((C_P)_b)$
1	ECN	0.102395	0.000104
2	FLOWTECH	0.096	0.020800
3	EPM	0.119342	0.0223481
4	WVU	0.11080	0.006947
5	WVU	0.10413	0.002499
6	DSC/CEHIPAR	0.084744	—
7	DSC/CEHIPAR	0.101673	—
8	NRMI	0.10024	0.0006339
9	IST/MARIN A	0.1021319	0.0008151
10	IST/MARIN A	0.1019543	0.0009021
11	IST/MARIN A	0.1021319	0.0008151
12	IST/MARIN A	0.1018643	0.0007440
13	IST/MARIN A	0.1044333	0.0075395
14	IST/MARIN A	0.1046360	0.0071591
15	IST/MARIN A	0.1068583	0.0109098
16	IST/MARIN A	0.1029322	0.0020867
17	IST/MARIN B	0.1073500	0.0070625


Backward Facing step
SA
BSL
SKE
SST
SST$_{ms}$
SA Workshop 2004
$(C_P)_b$
0.16
0.14
0.12
0.1
0.08
0.06
0
5
10
15
20
25
30
35
Calculations submitted