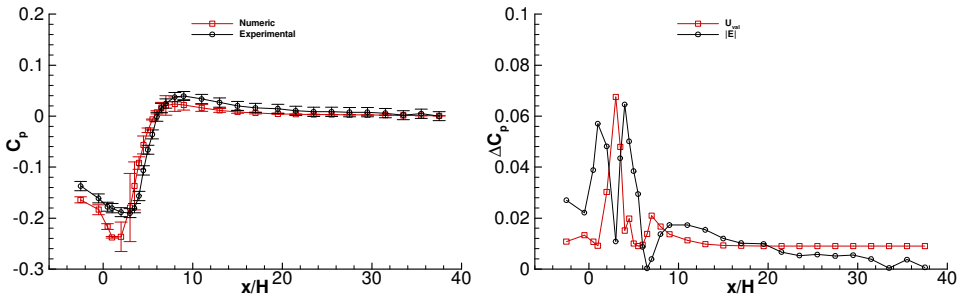
6. Validation
Backward Facing Step

a) Calculations performed

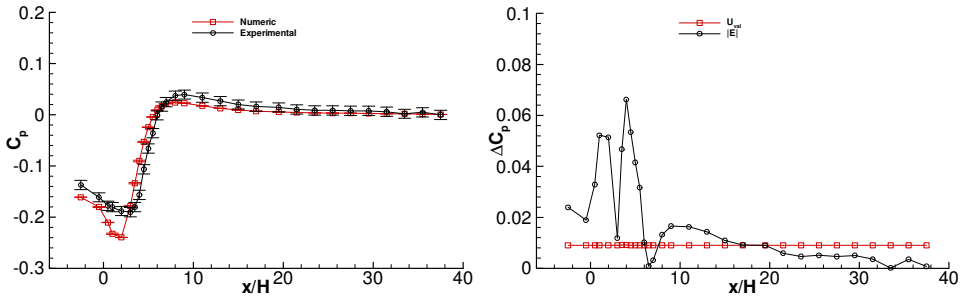
		T. Model	Observations
A	FLUENT	SA	2nd-order convection
B	ISIS	SA	Multiblock grid
C	OpenFOAM	SA	Multiblock grid
D	CFL3D	SA	1st-order convection for $\tilde{\nu}$
E	FUN3D	SA	1st-order convection for $\tilde{\nu}$
F	PARNASSOS	SA	2nd-order convection for $\tilde{\nu}$
G	FLUENT	SKE	2nd-order convection, Wall Functions
H	CADYF	SKE	Wall functions
I	CHAPMAN	BSL	Set A
J	PARNASSOS	BSL	2nd-order convection for k and ω
K	PARNASSOS	STT	2nd-order convection for k and ω

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

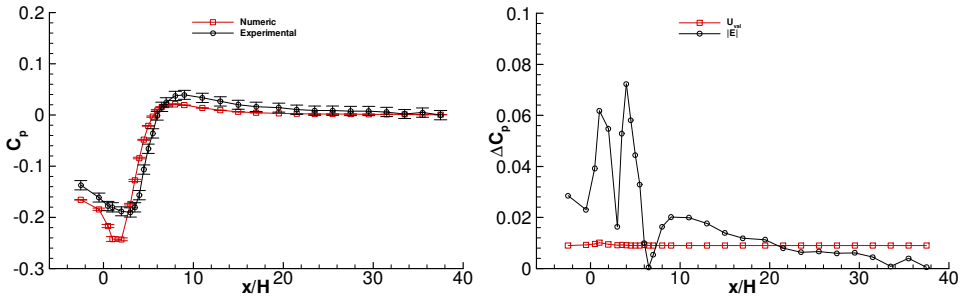
b) Pressure coefficient along bottom wall, $C_p = (p - p_{outlet})/(1/2\,\rho U_{ref}^2)$



A


Numeric
Experimental
C_p
x/H
U_{val}
$|E|$
ΔC_p

B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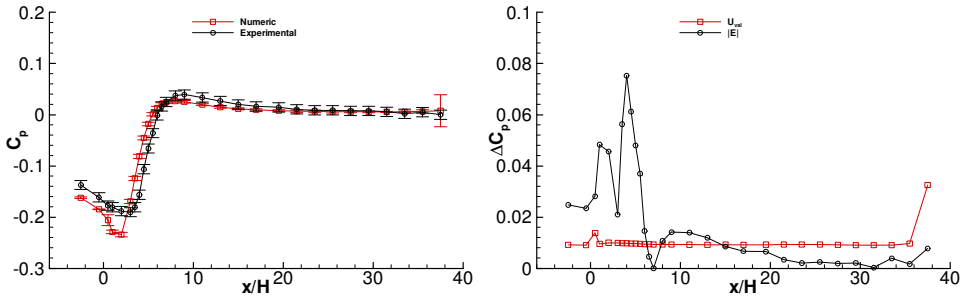
Experimental
C_p
x/H
U_{val}
$|E|$
ΔC_p

C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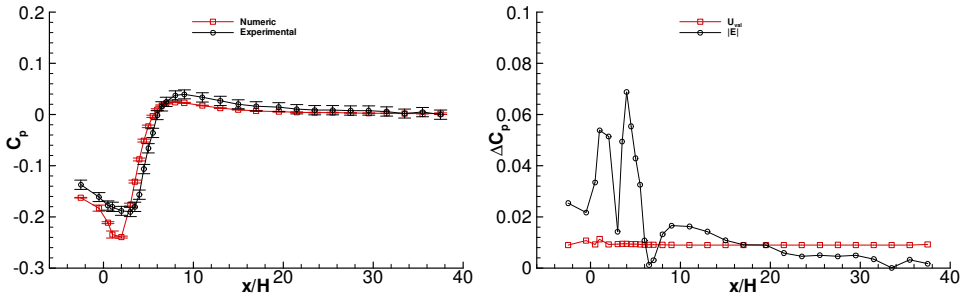
Experimental
C_p
x/H
U_{val}
$|E|$
ΔC_p

D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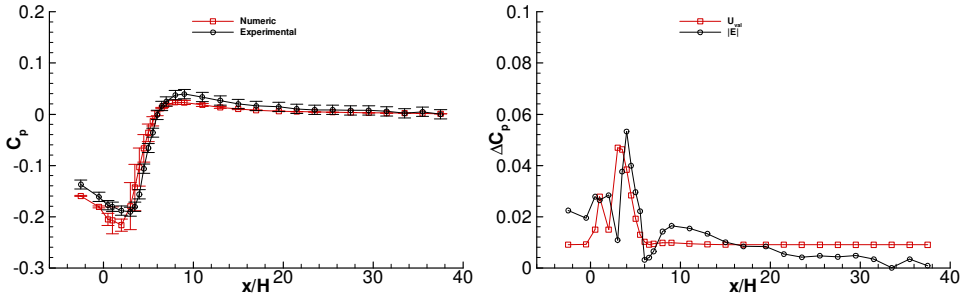
Experimental
C_p
x/H
U_{val}
$|E|$
ΔC_p

E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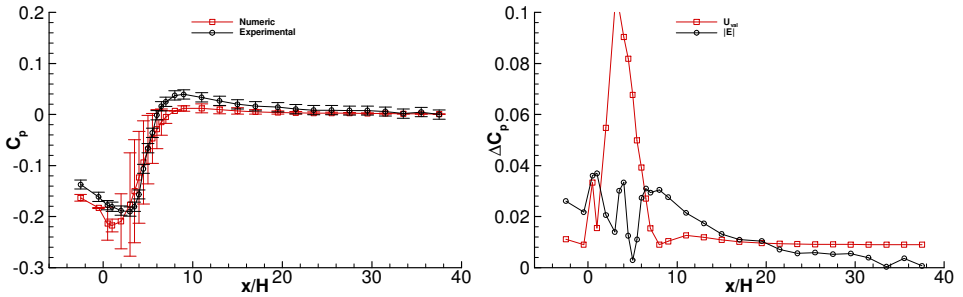
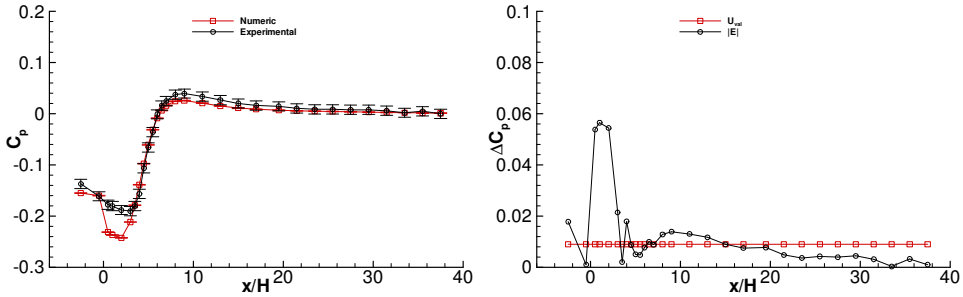
Experimental
C_p
x/H
U_{val}
$|E|$
ΔC_p

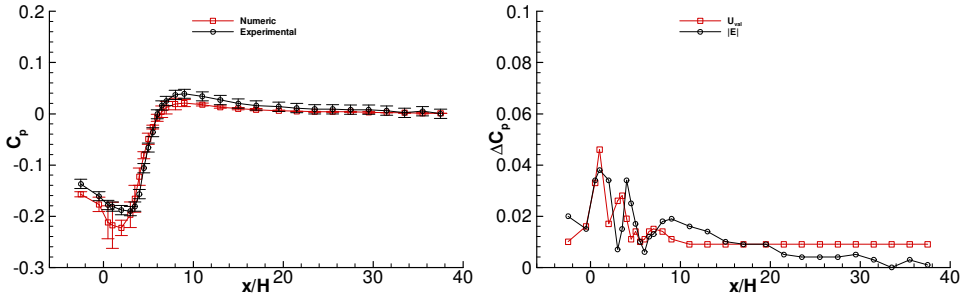
F


Numeric
Experimental
C_p
x/H
U_{val}
|E|
ΔC_p

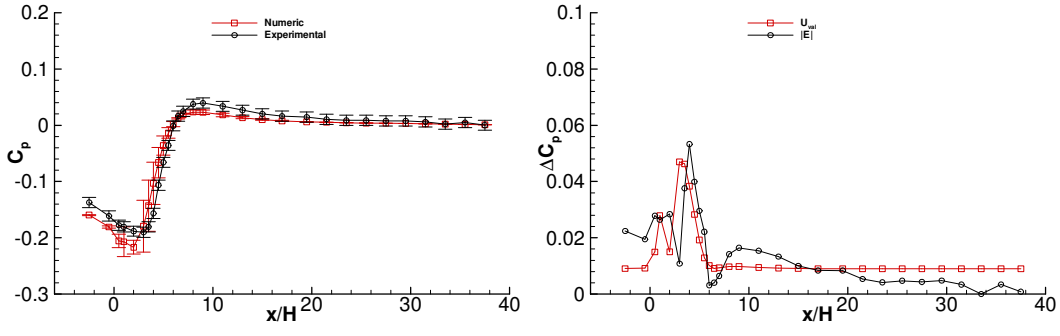
G


Numeric
Experimental
C_p
x/H
U_{val}
|E|
ΔC_p

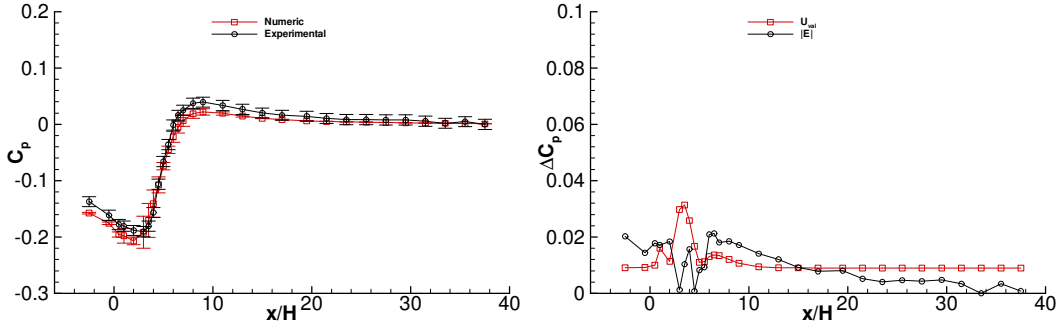
H


Numeric
Experimental
C_p
x/H
U_{val}
|E|
ΔC_p

I

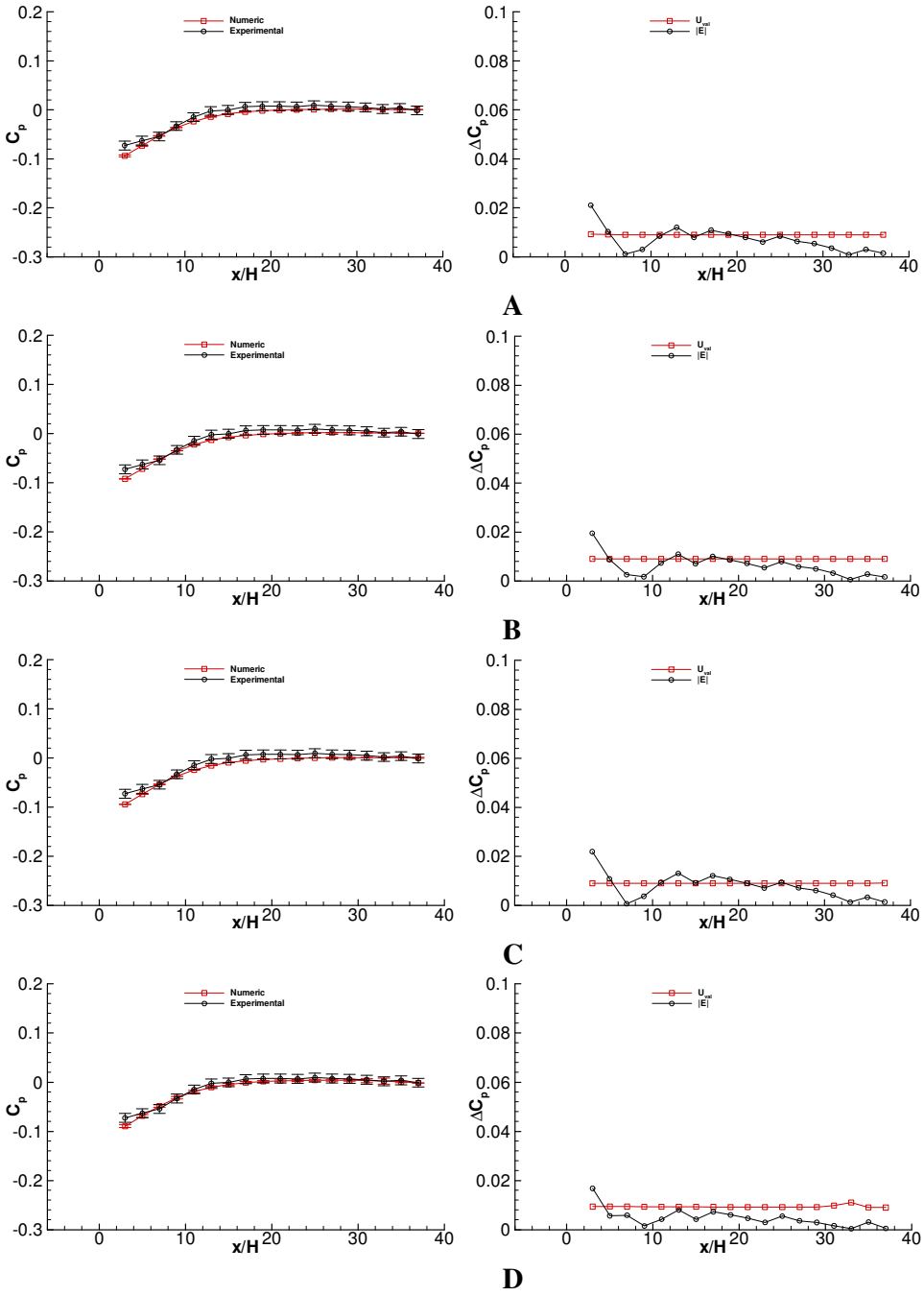

Numeric
Experimental
C_p
x/H
U_{val}
|E|
ΔC_p

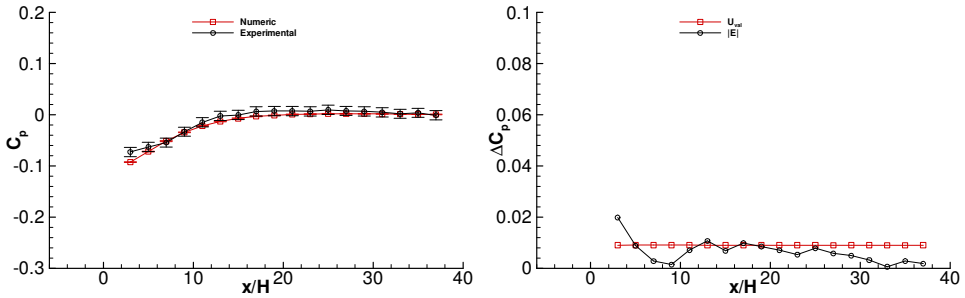
J


Numeric
Experimental
C_p
x/H
U_{val}
|E|
ΔC_p

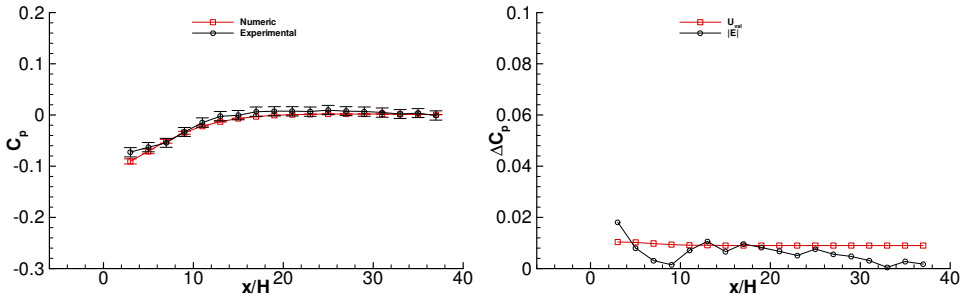
K

c) Pressure coefficient along top wall, $C_p = (p - p_{outlet})/(1/2\,\rho U_{ref}^2)$

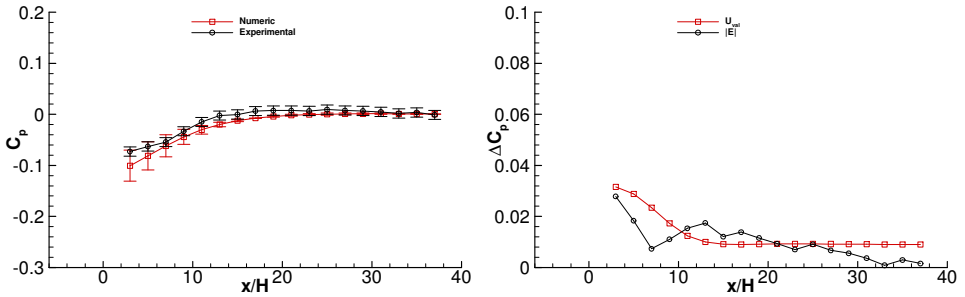



Numeric
Experimental
C_p
x/H
U_{val}
|E|
ΔC_p

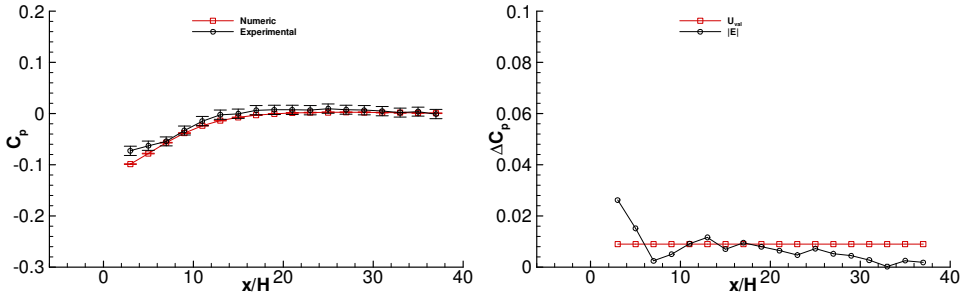
E


Numeric
Experimental
C_p
x/H
U_{val}
|E|
ΔC_p

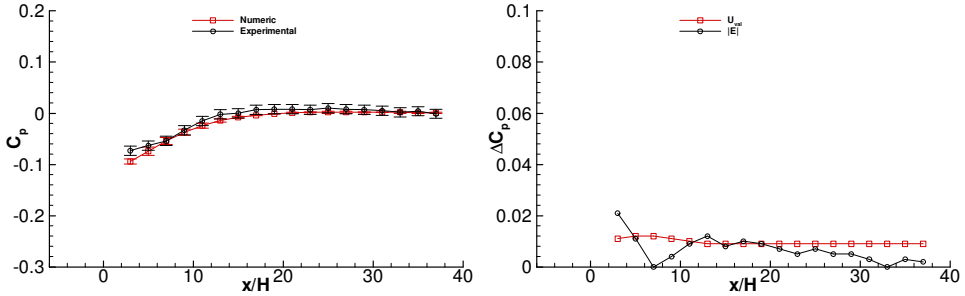
F


Numeric
Experimental
C_p
x/H
U_{val}
|E|
ΔC_p

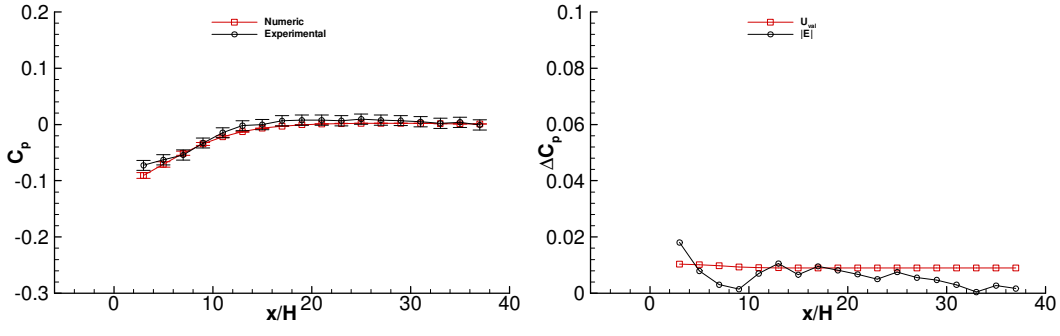
G


Numeric
Experimental
C_p
x/H
U_{val}
|E|
ΔC_p

H


Numeric
Experimental
C_p
x/H
U_{val}
|E|
ΔC_p

I



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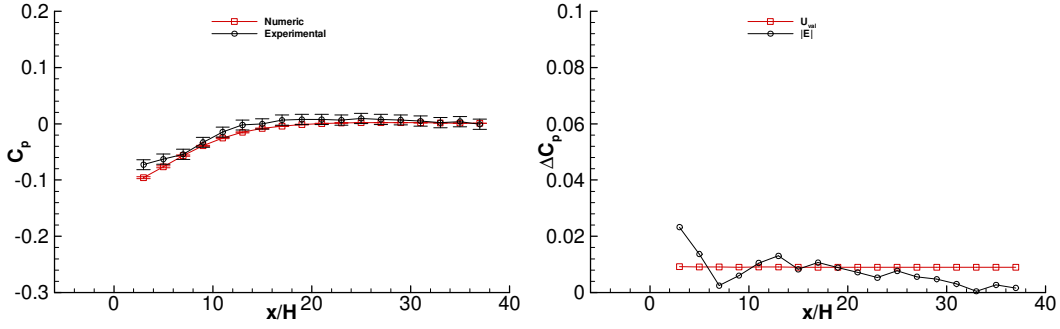
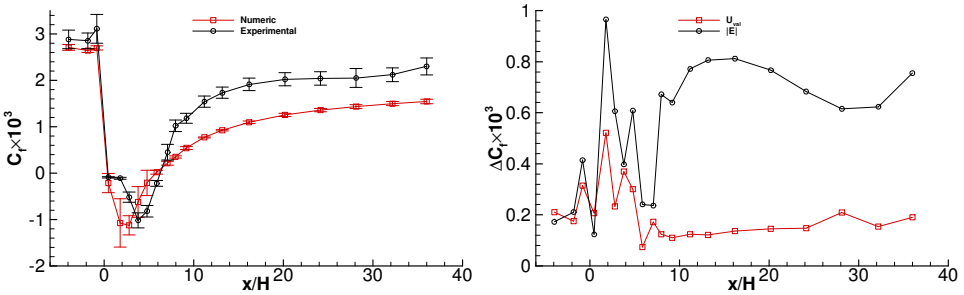


K

d) Skin friction coefficient along bottom wall, $C_f = \left(\mu(\partial u/\partial y)_{y=0}\right)/\left(1/2\,\rho U_{ref}^2\right)$



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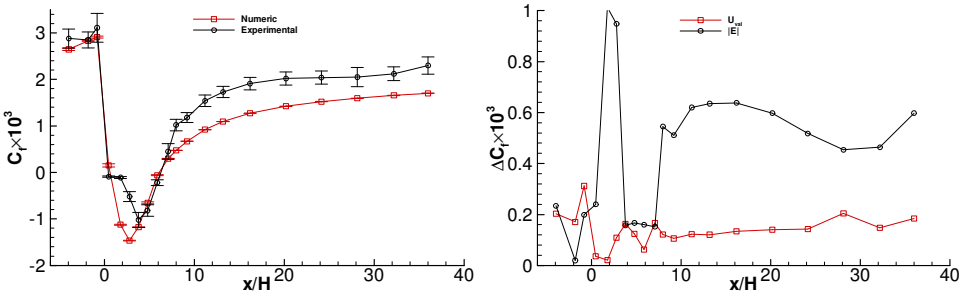

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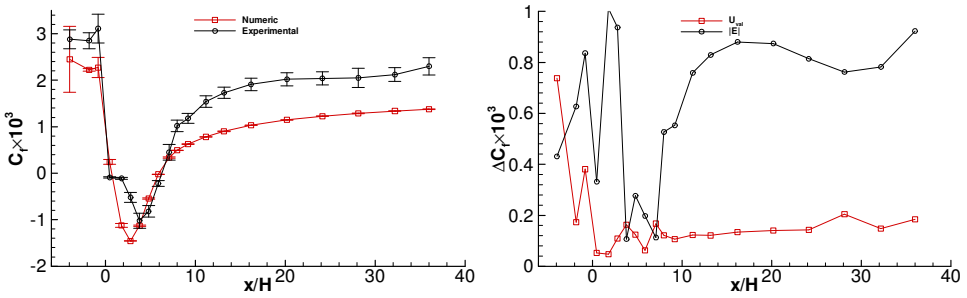
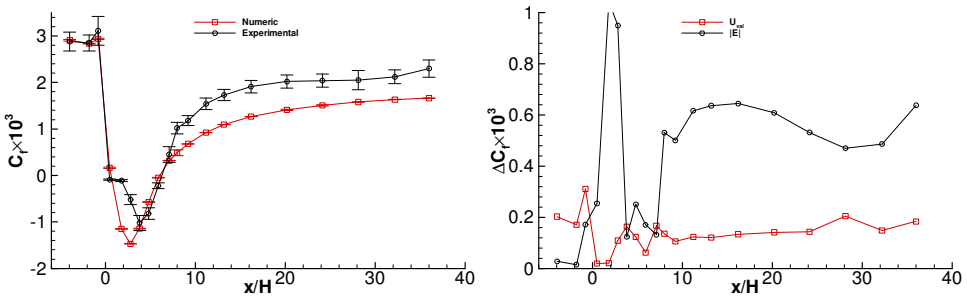
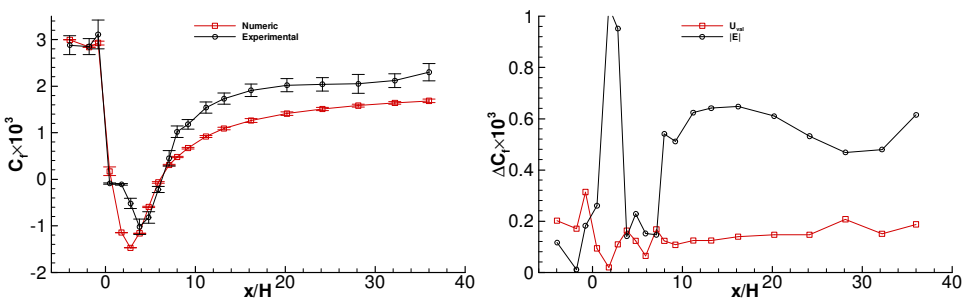

Numeric
Experimental
$C_f \times 10^3$
x/H
U_{val}
$|E|$
$\Delta C_f \times 10^3$

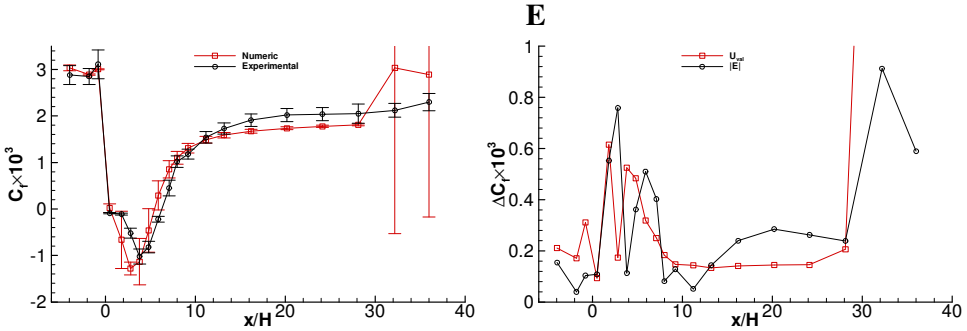
C


Numeric
Experimental
$C_f \times 10^3$
x/H
U_{val}
$|E|$
$\Delta C_f \times 10^3$

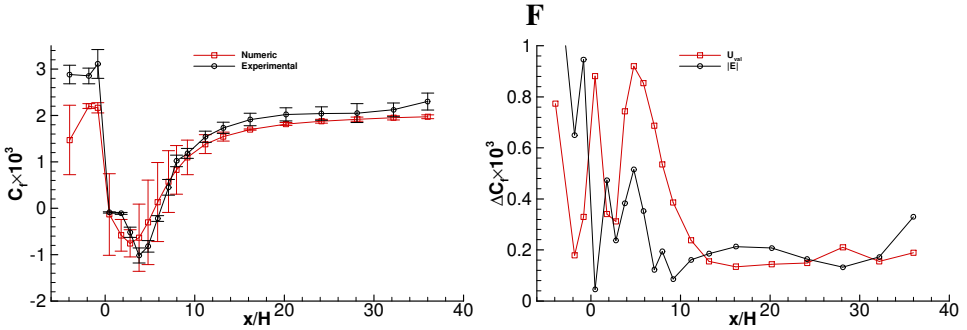
D


Numeric
Experimental
$C_f \times 10^3$
x/H
U_{val}
$|E|$
$\Delta C_f \times 10^3$

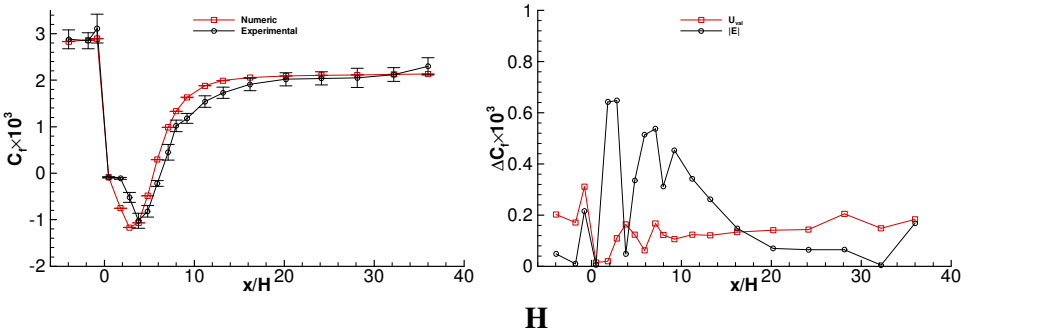
E


Numeric
Experimental
$C_f \times 10^3$
x/H
U_{val}
$|E|$
$\Delta C_f \times 10^3$

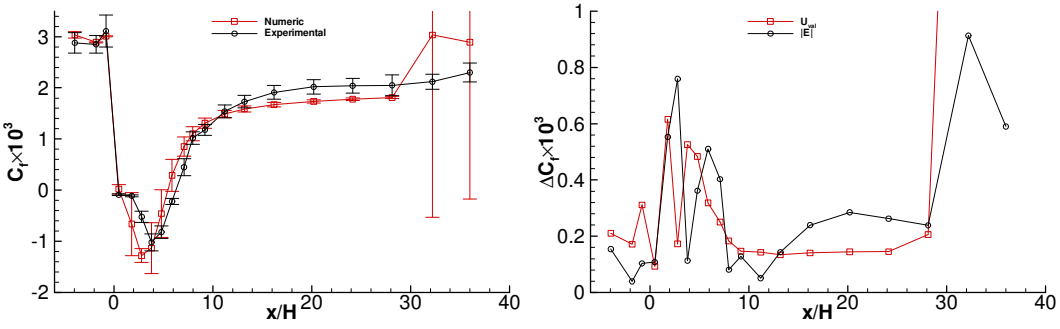
F


Numeric
Experimental
$C_f \times 10^3$
x/H
U_{val}
$|E|$
$\Delta C_f \times 10^3$

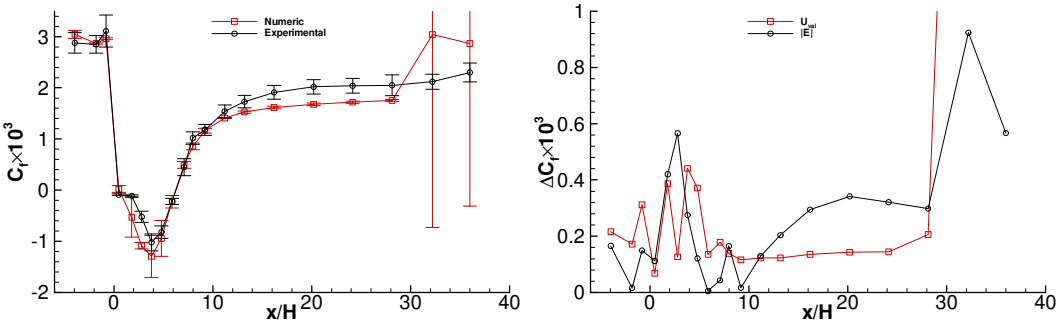
G



H



J



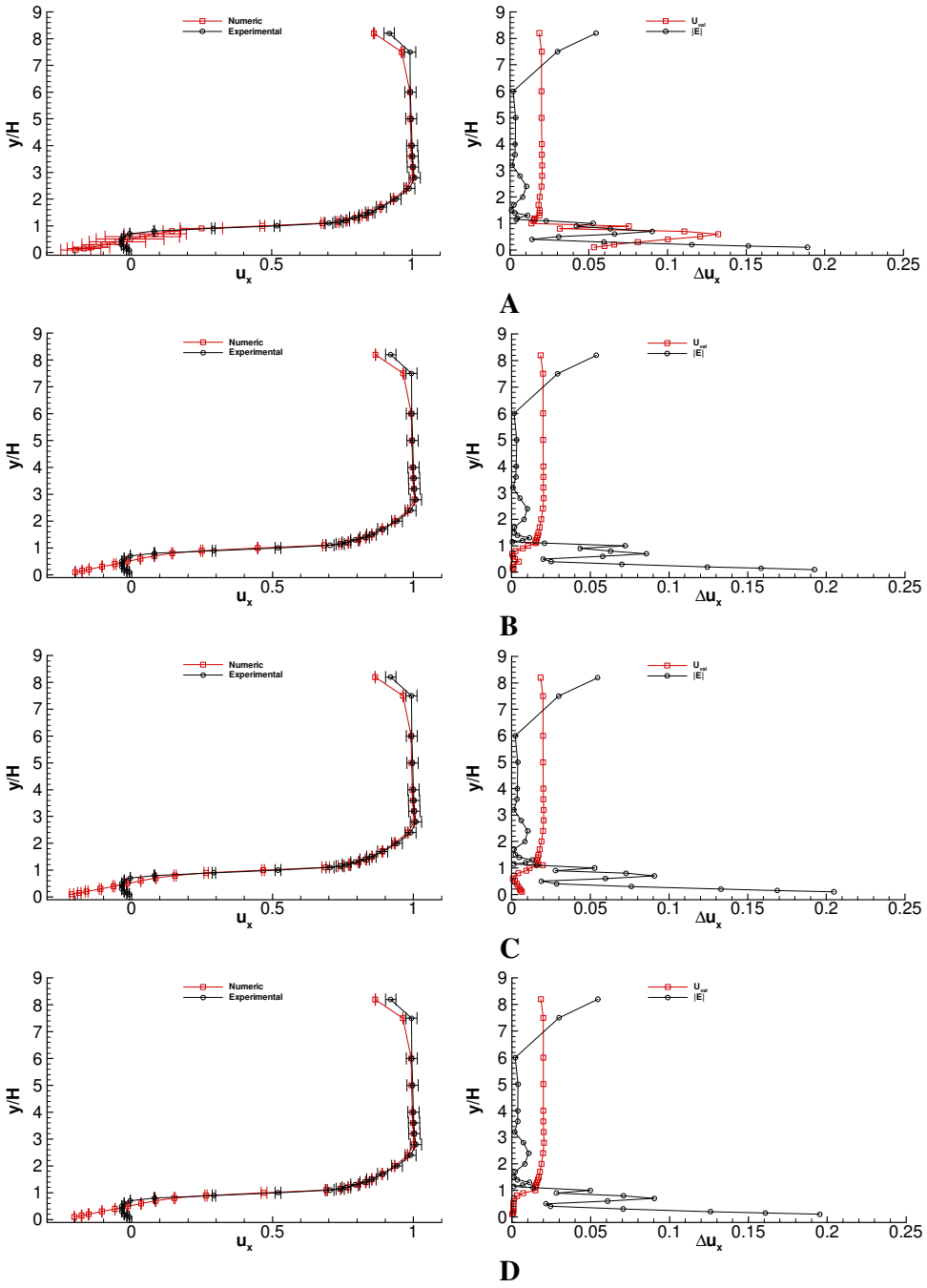
K

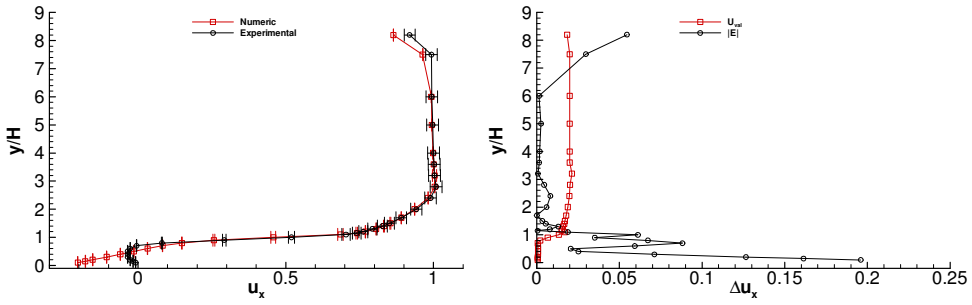
e) Re-attachement point , x_{ret}/H

S	Code	S	D	|E|	U_{val}
A	FLUENT	5.77	6.26	0.49	0.19
B	ISIS	6.02	6.26	0.24	0.10
C	OpenFOAM	5.94	6.26	0.32	0.10
D	CFL3D	6.01	6.26	0.25	0.10
E	FUN3D	6.06	6.26	0.20	0.11
F	PARNASSOS	6.08	6.26	0.18	0.12
G	FLUENT	5.55	6.26	0.71	1.36
H	CADYF	5.47	6.26	0.79	0.10
I	CHAPMAN	5.52	6.26	0.74	0.60
J	PARNASSOS	5.44	6.26	0.82	0.63
K	PARNASSOS	6.21	6.26	0.05	0.61

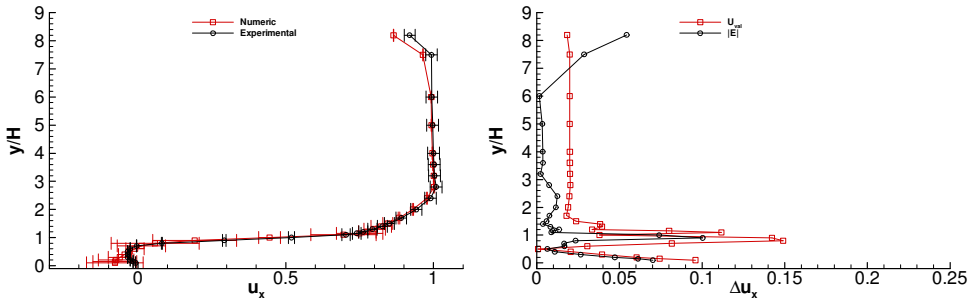
f) Profiles at x=H

i) Horizontal velocity, u/U_{ref}

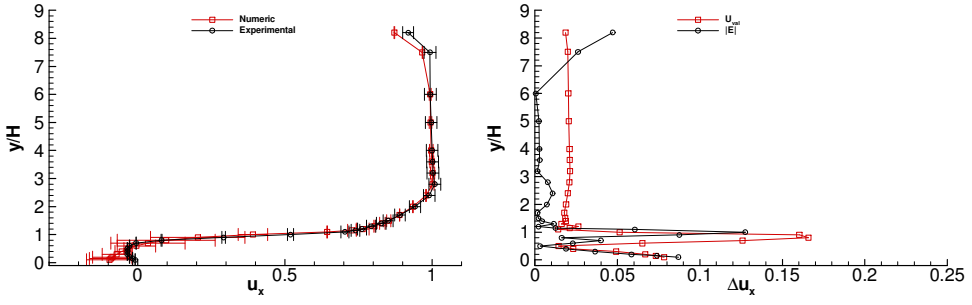



Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

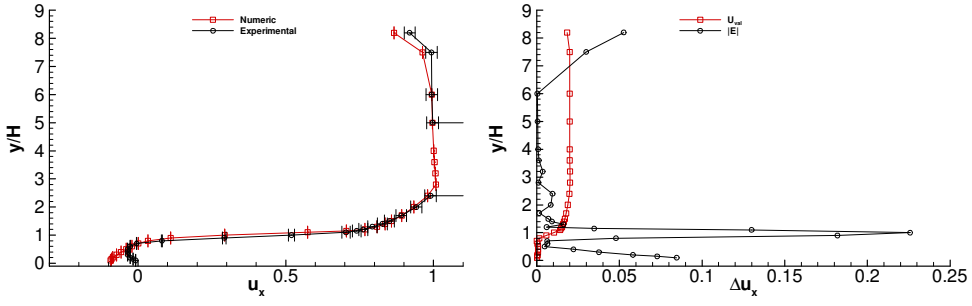
E


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

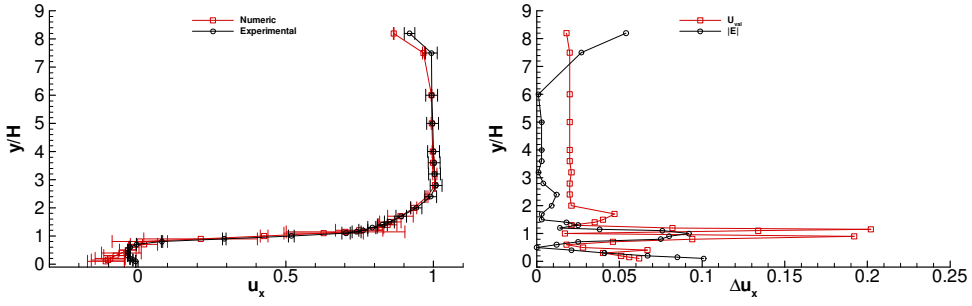
F


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

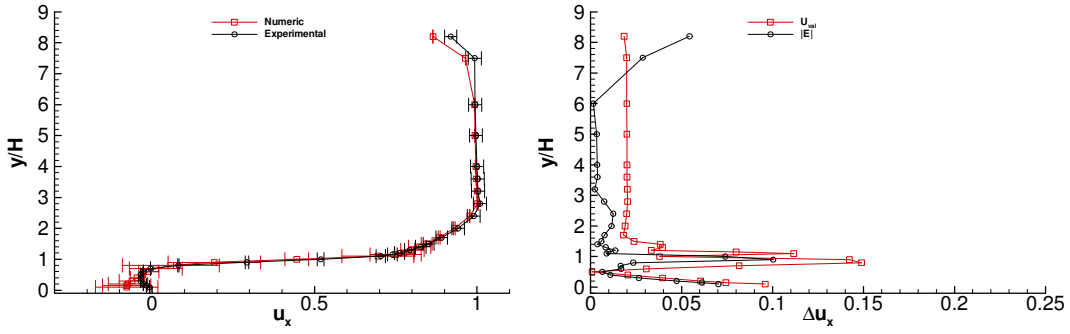
G


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

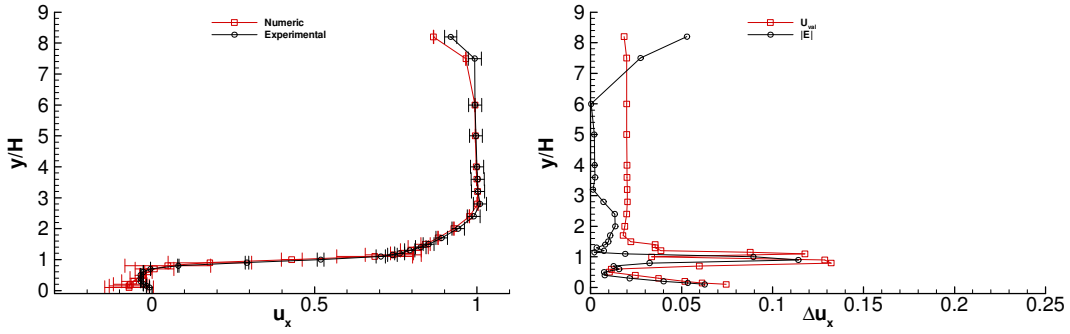
H


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

I

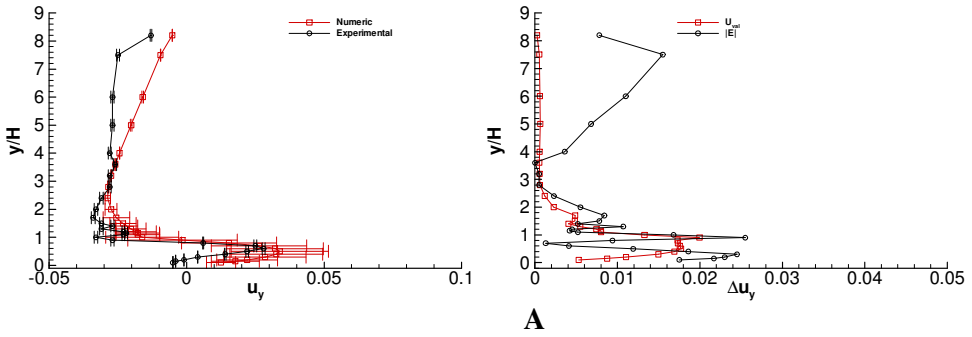


J

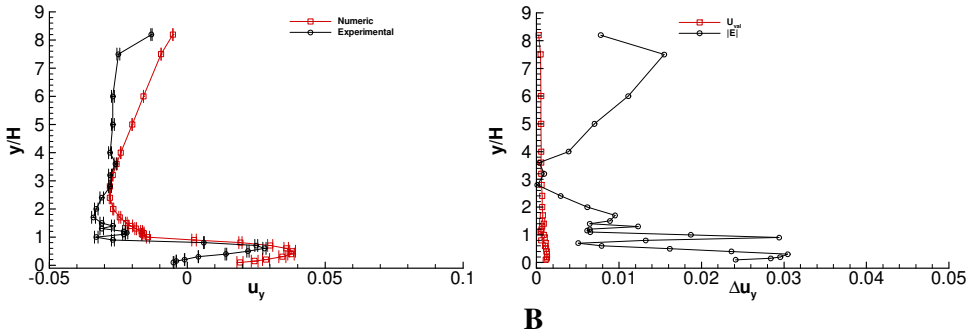


K

ii) Vertical velocity, v/U_{ref}



A



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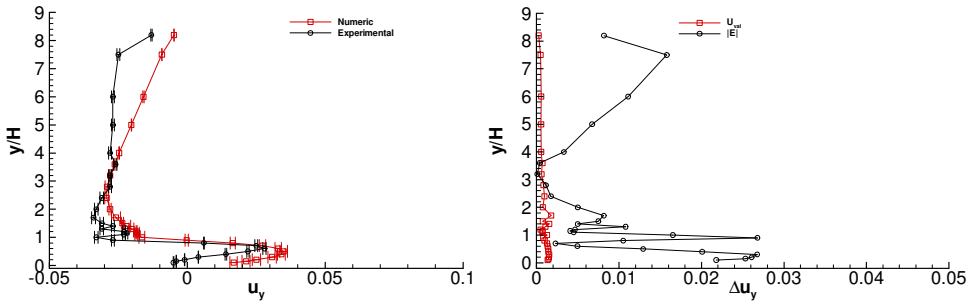
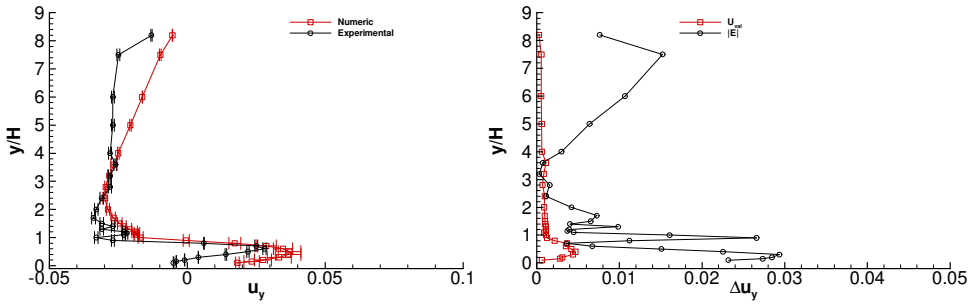
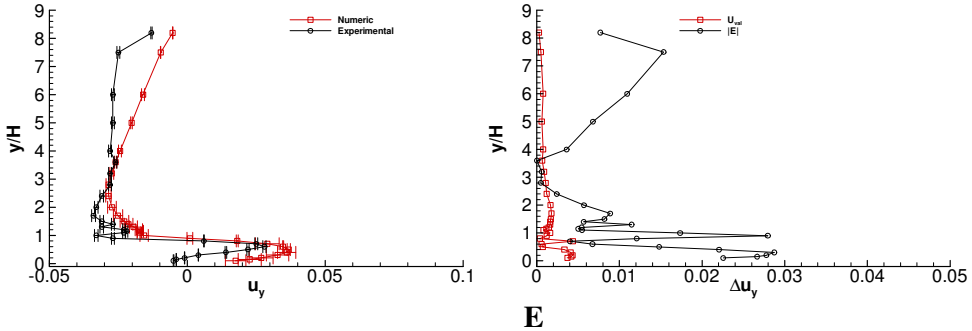

Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

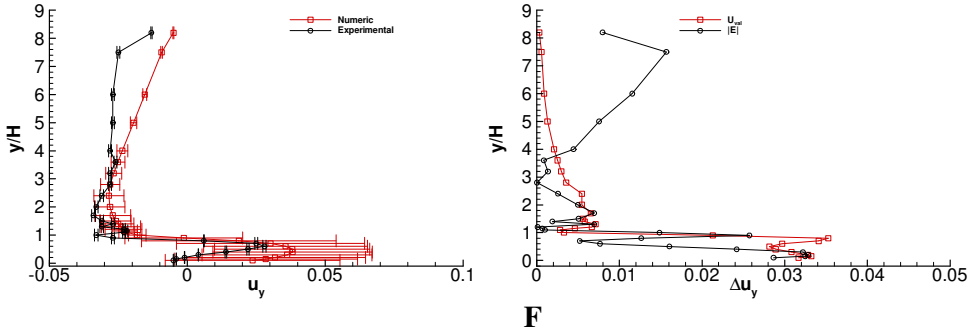
C


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

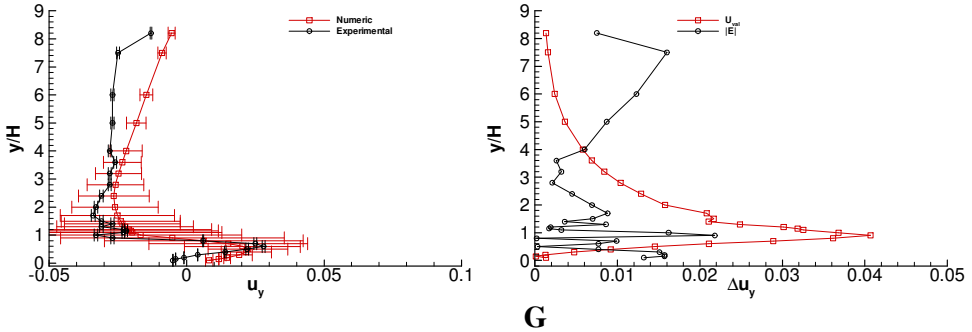
D


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

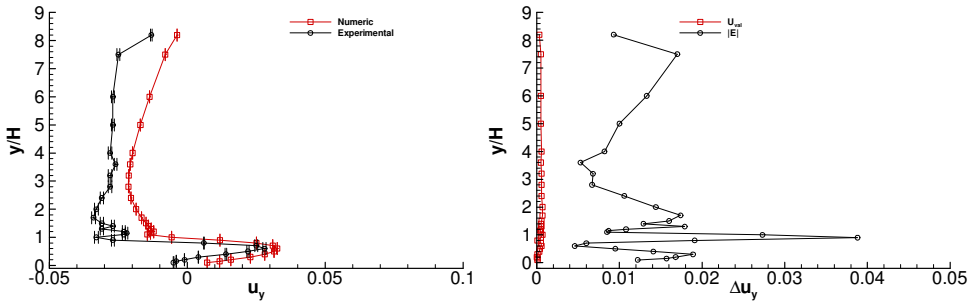
E


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

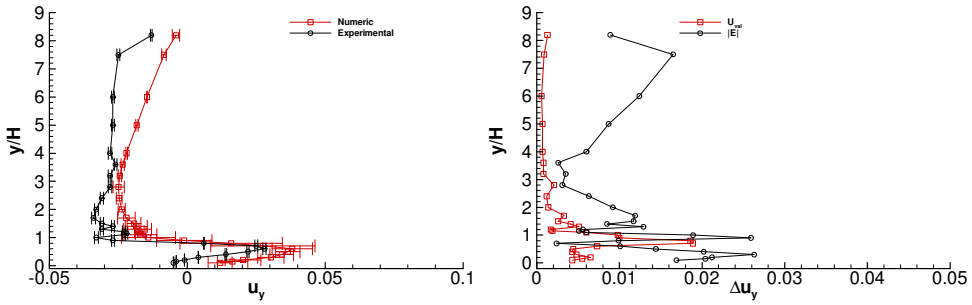
F


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

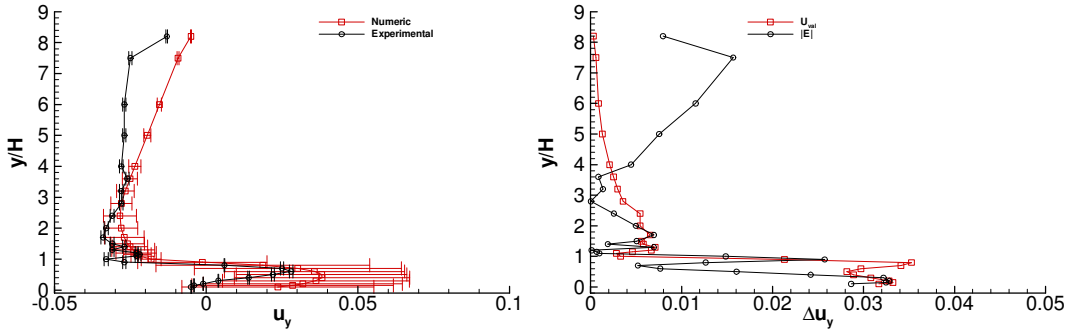
G


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

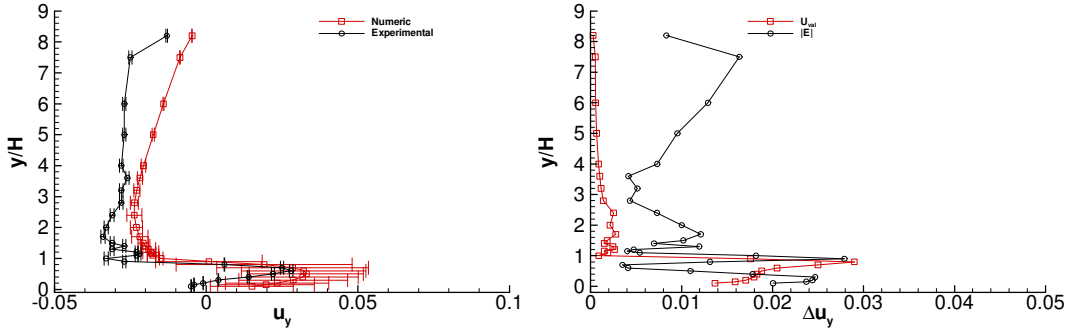
H


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

I

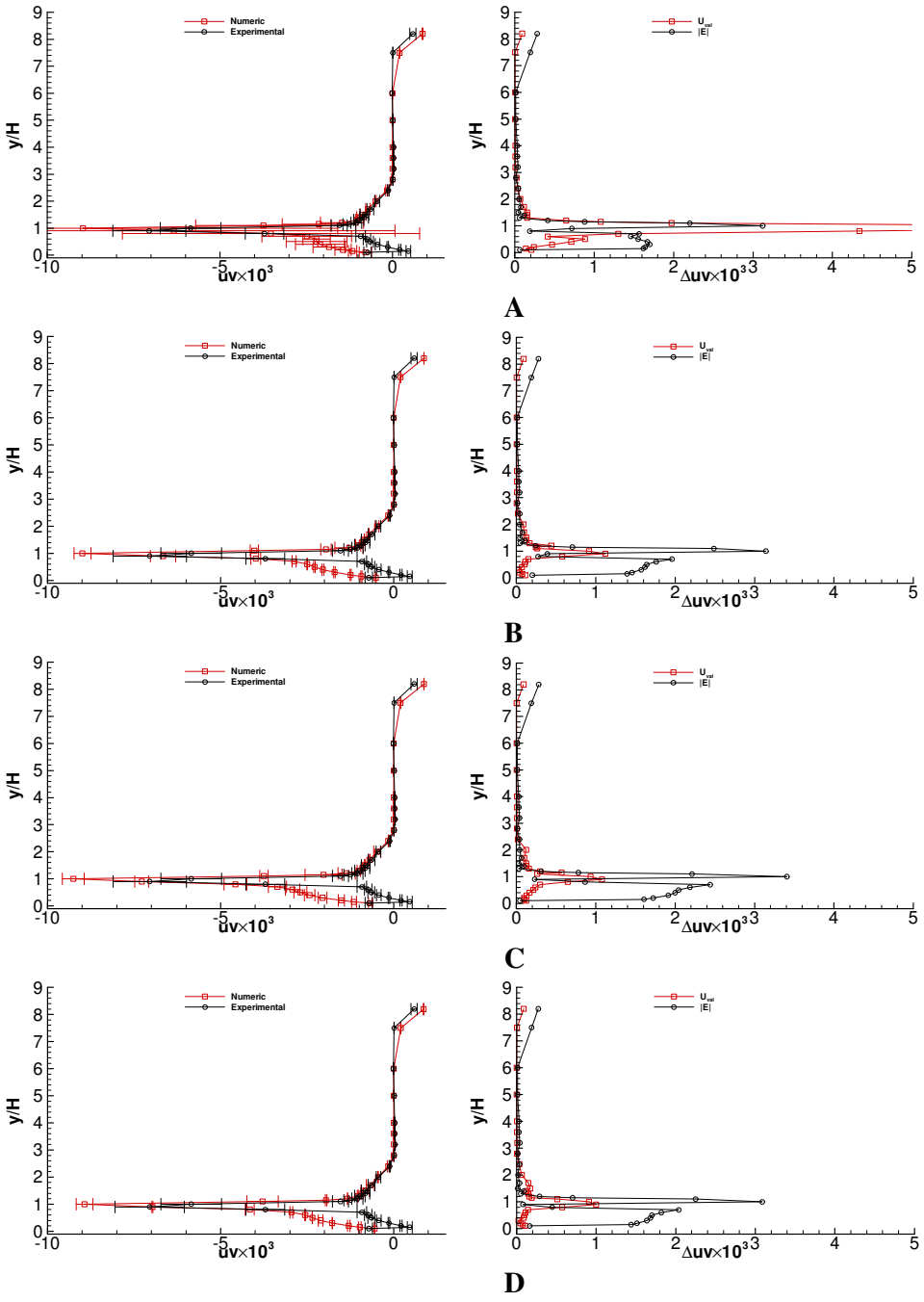

Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

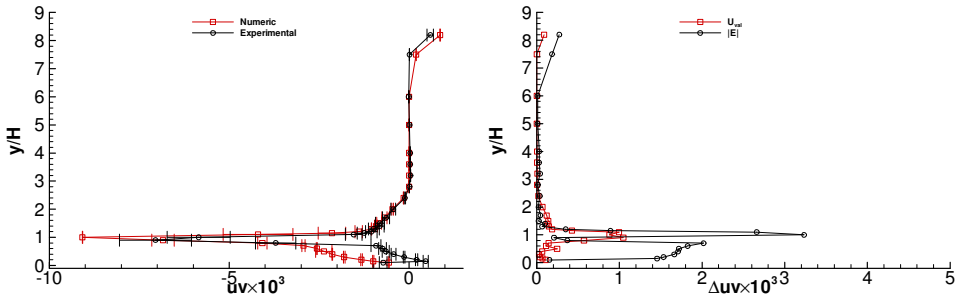
J


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

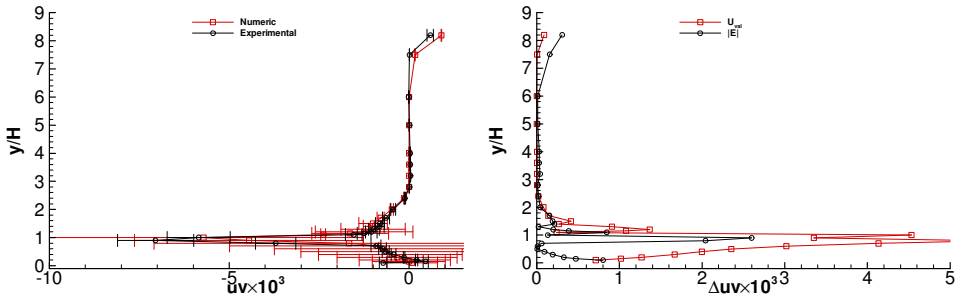
K

iii) Reynolds stress, $\overline{uv}/U_{ref}^2$

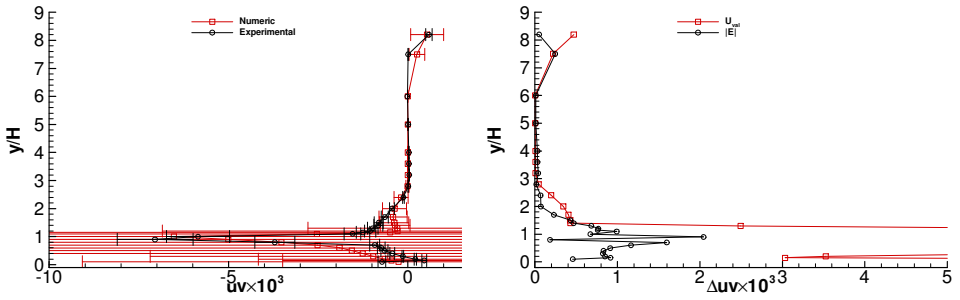



Numeric
Experimental
y/H
uv×10³
U_rel
|E|
Δuv×10³

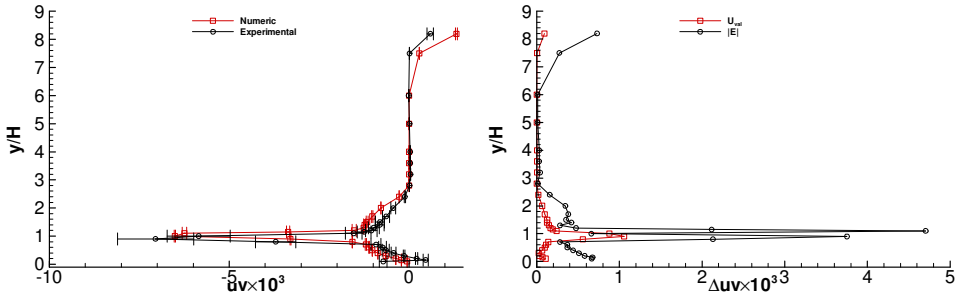
E


Numeric
Experimental
y/H
uv×10³
U_rel
|E|
Δuv×10³

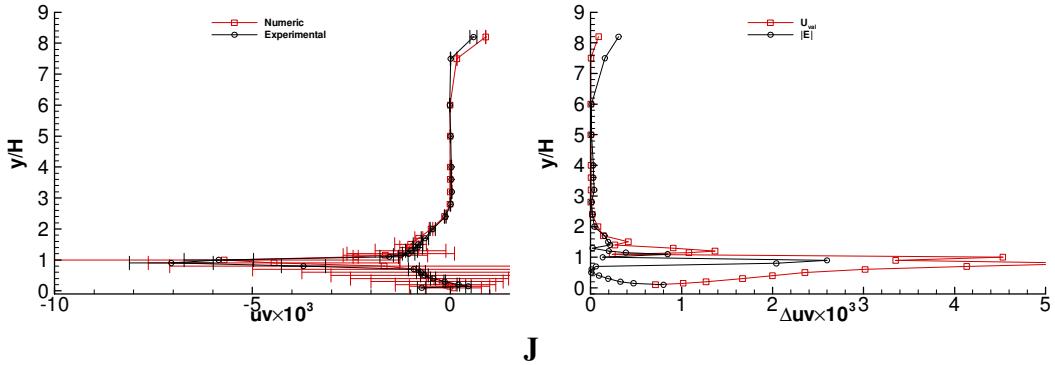
F


Numeric
Experimental
y/H
uv×10³
U_rel
|E|
Δuv×10³

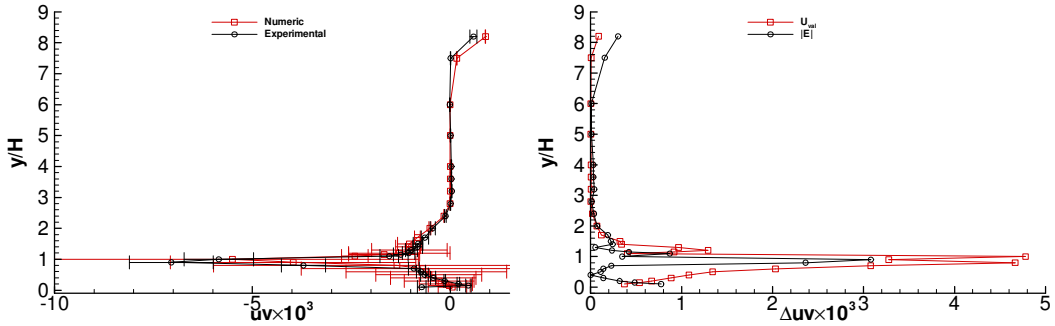
G


Numeric
Experimental
y/H
uv×10³
U_rel
|E|
Δuv×10³

H


Numeric
Experimental
y/H
uv×10³
U_rel
|E|
Δuv×10³

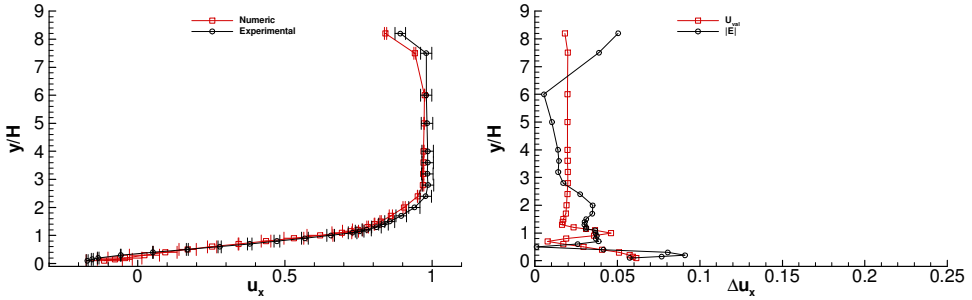
J



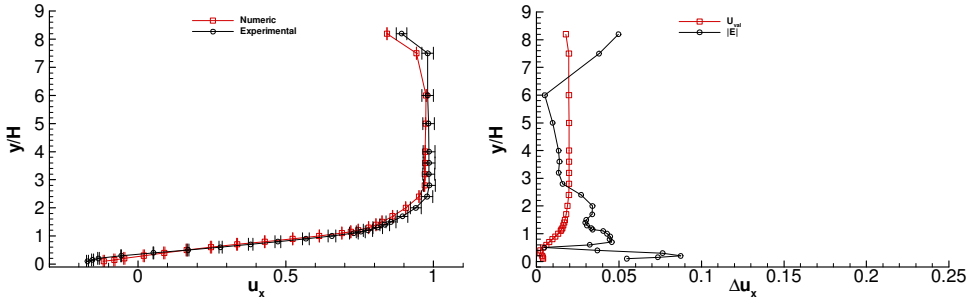
K

g) Profiles at x=4H

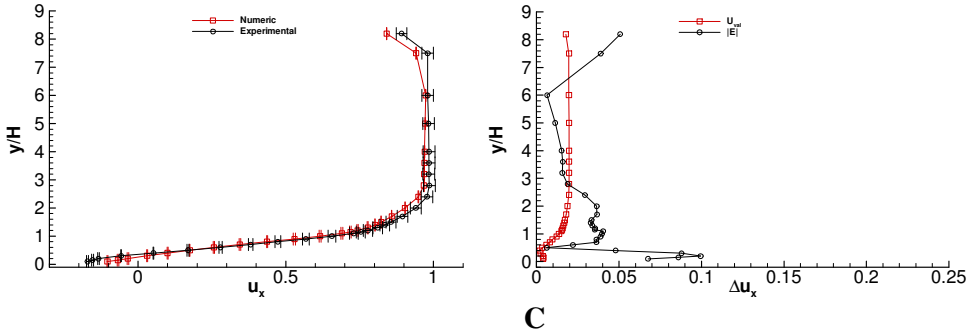
i) Horizontal velocity, u/U_{ref}



A



B



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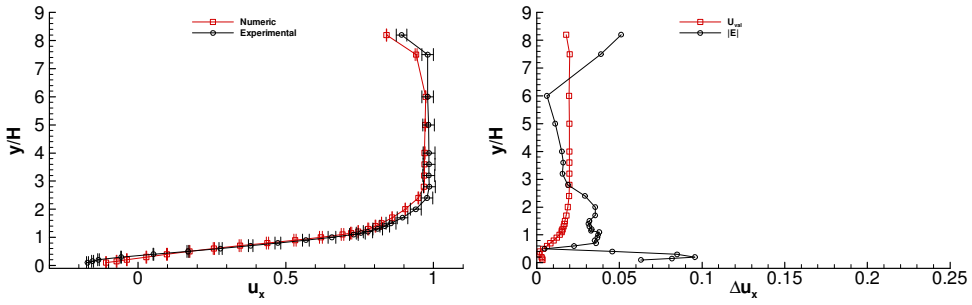
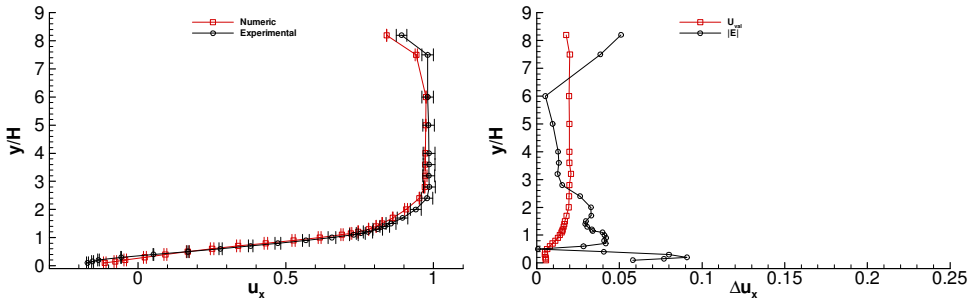
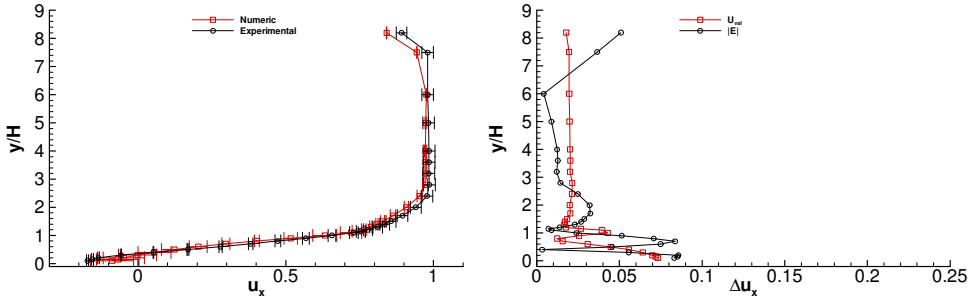

Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

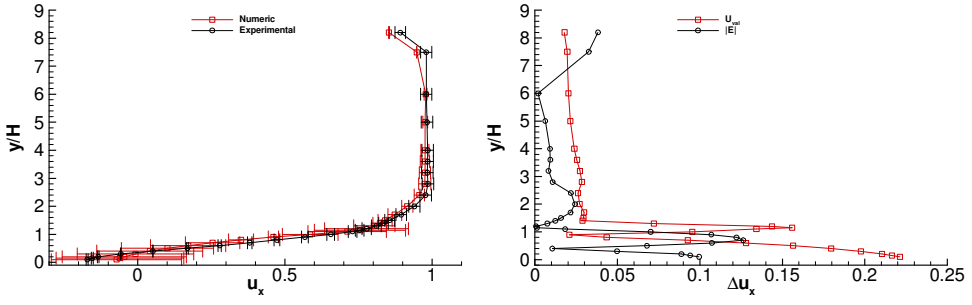
D


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

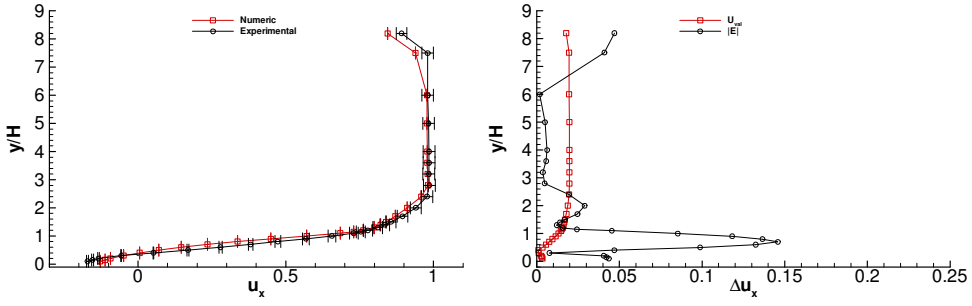
E


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

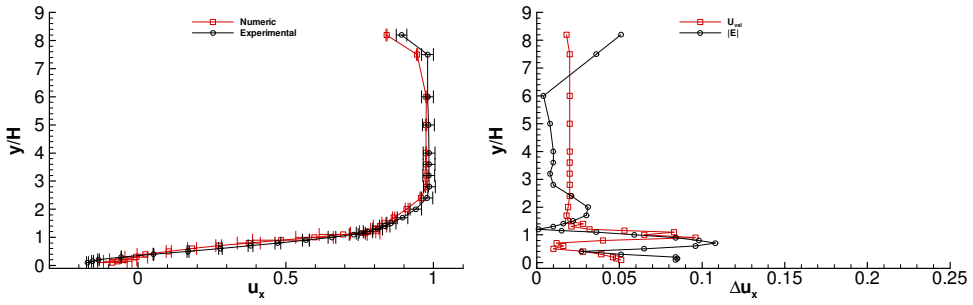
F


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

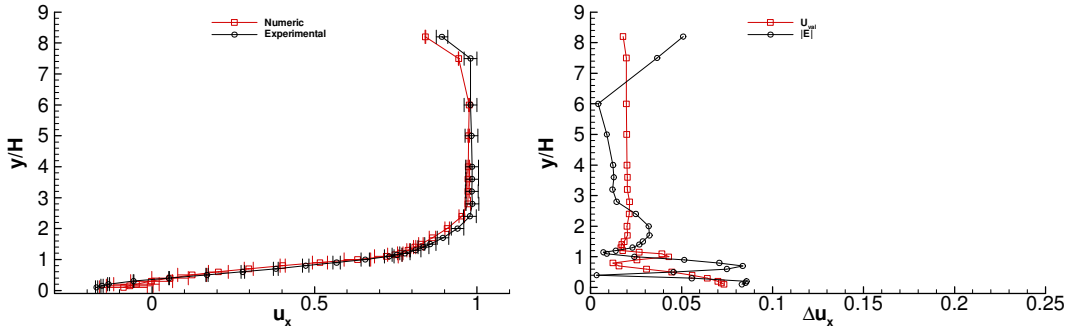
G


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

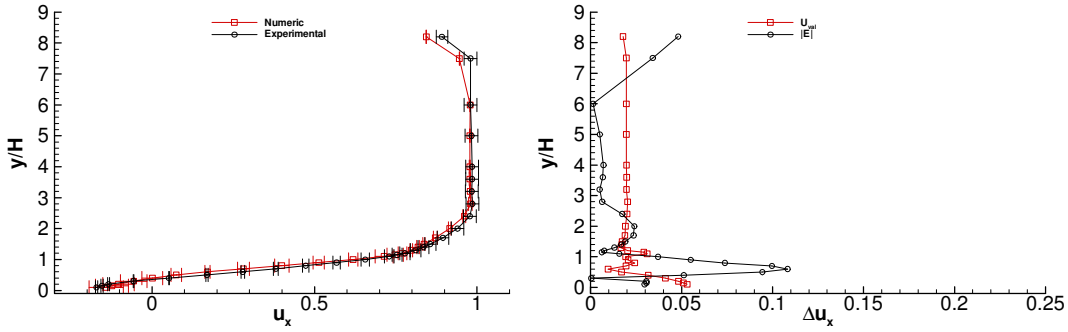
H



I

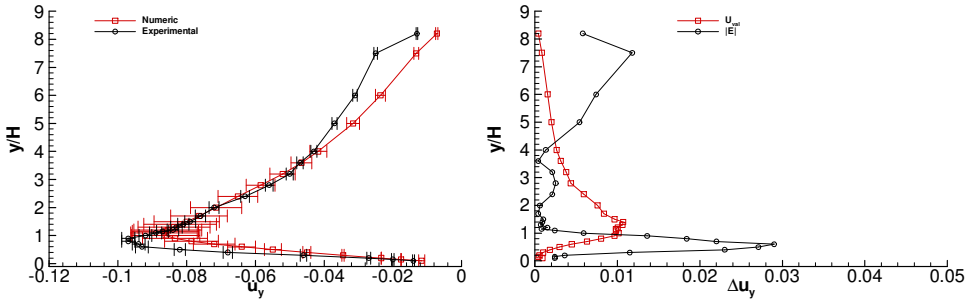


J

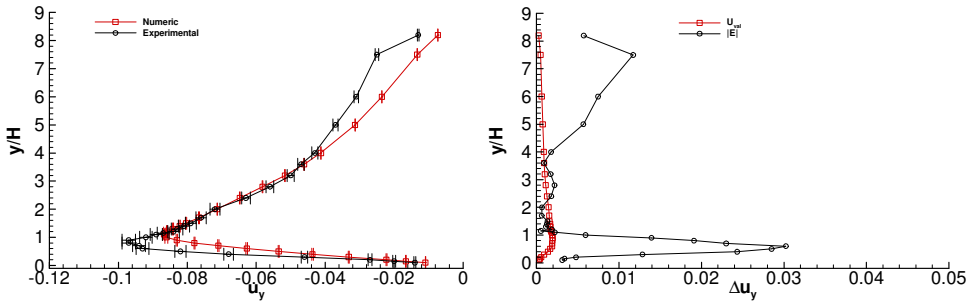


K

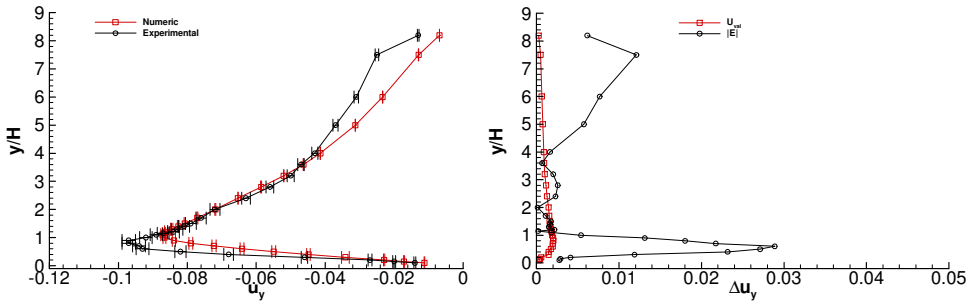
ii) Vertical velocity, v/U_{ref}



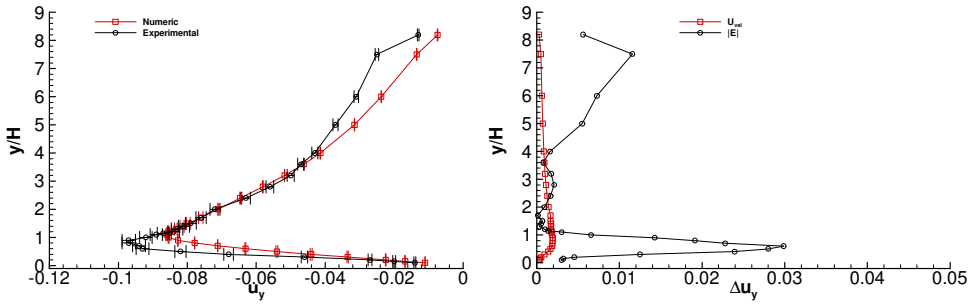
A


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

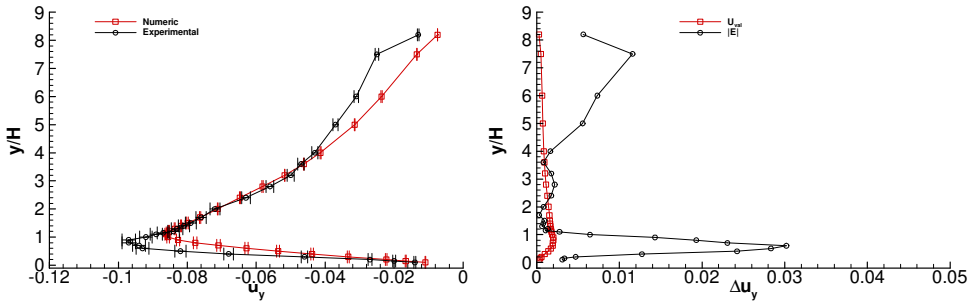
B


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

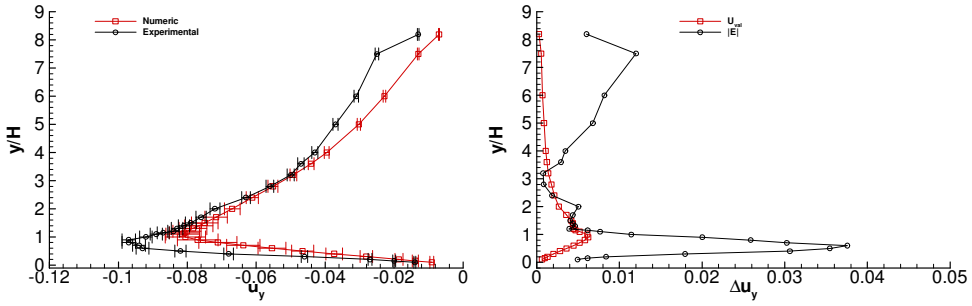
C


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

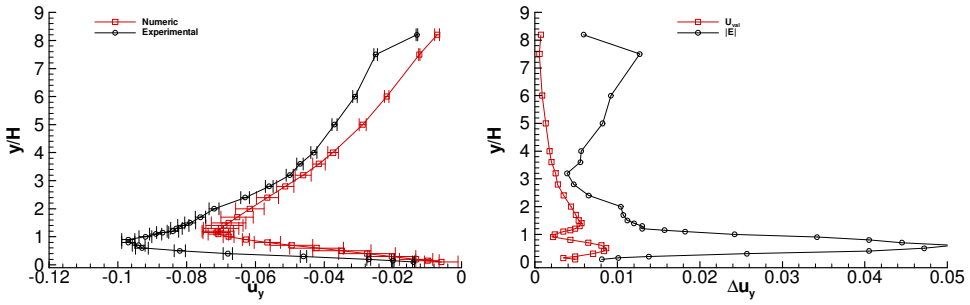
D


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

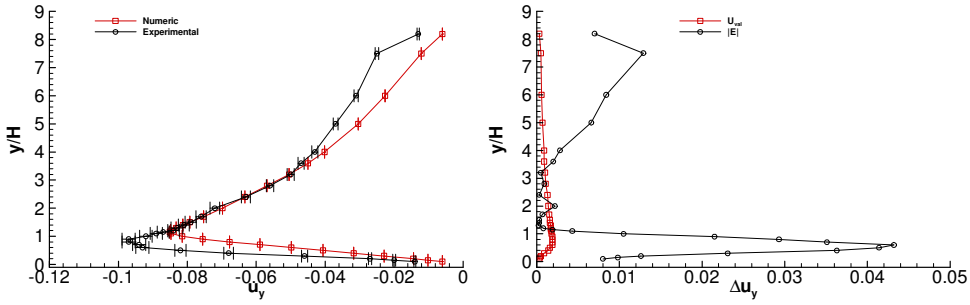
E


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

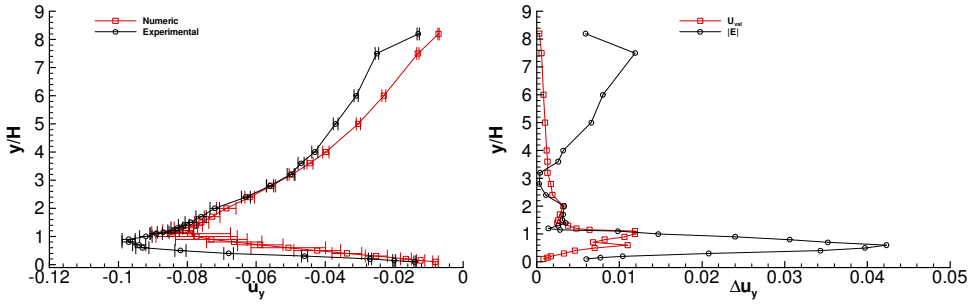
F


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

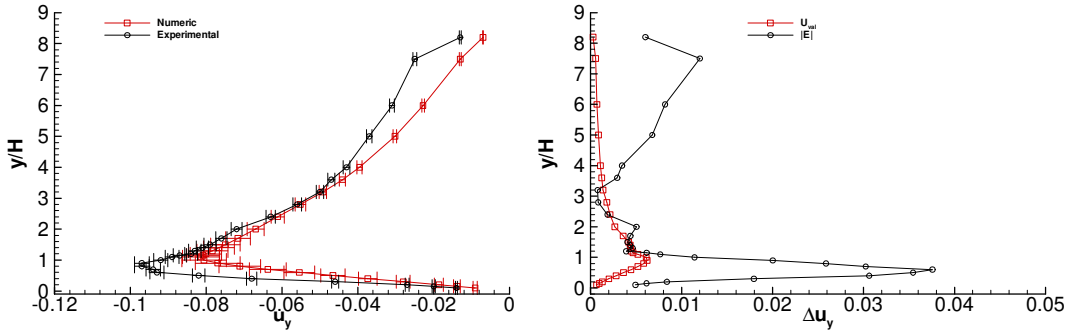
G


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

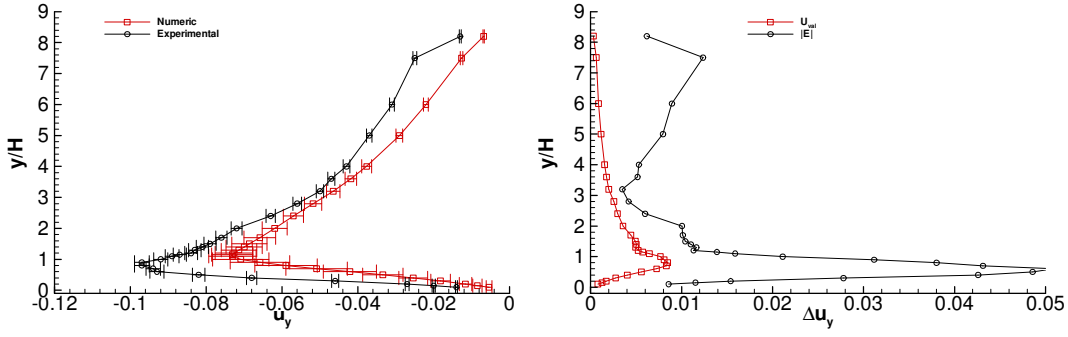
H


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

I

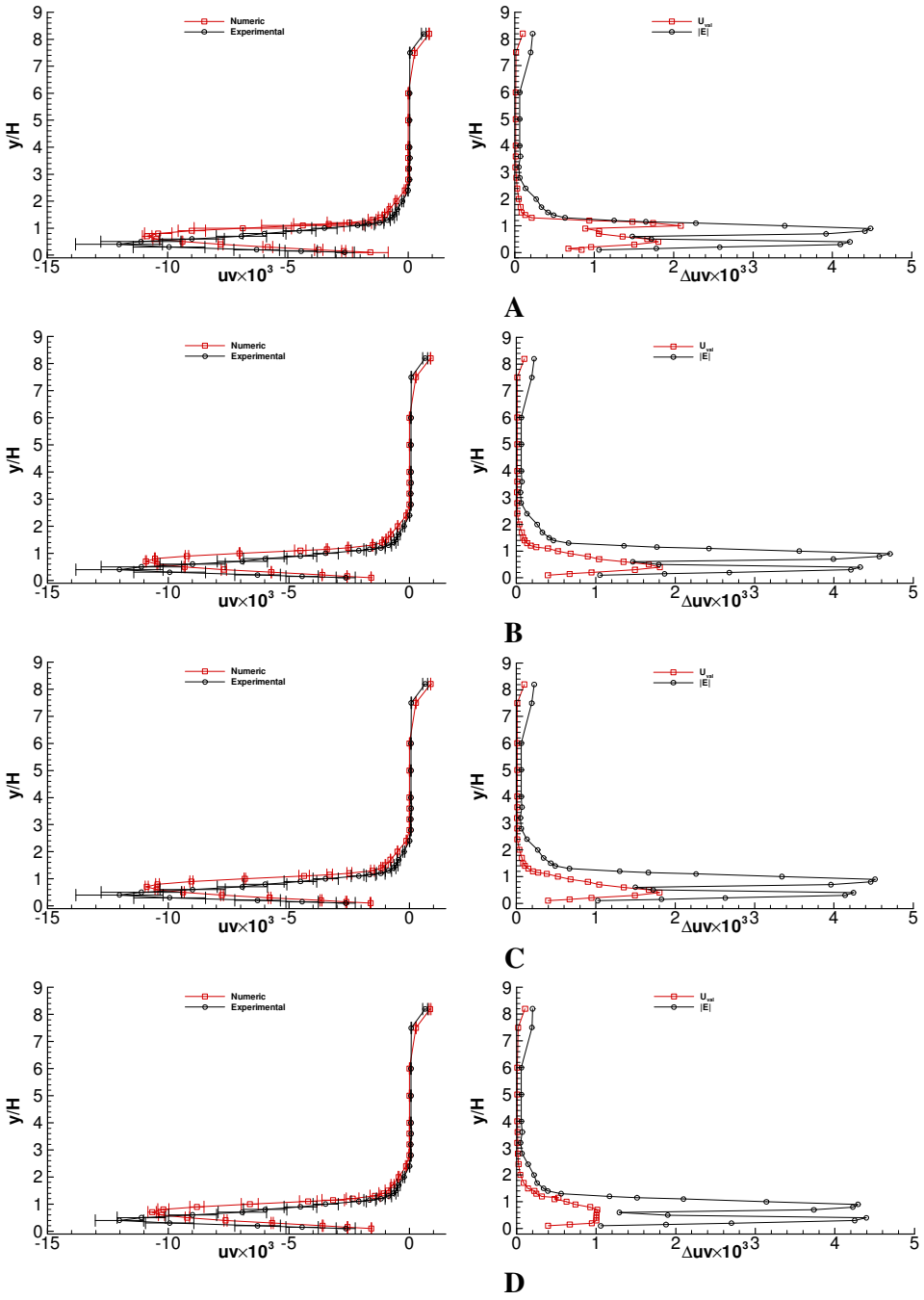

Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

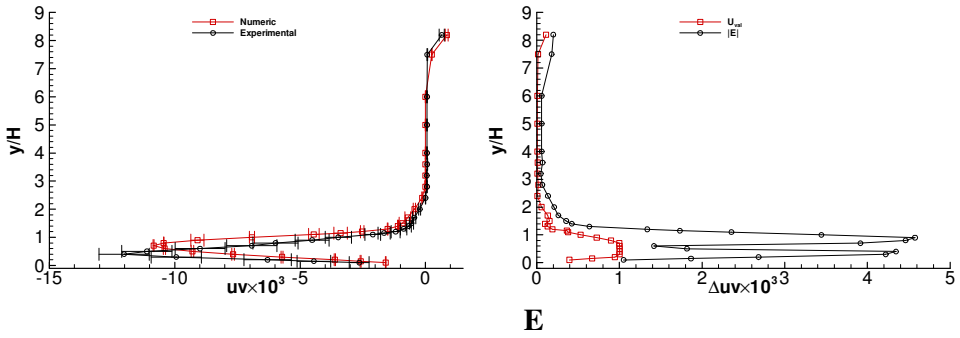
J


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

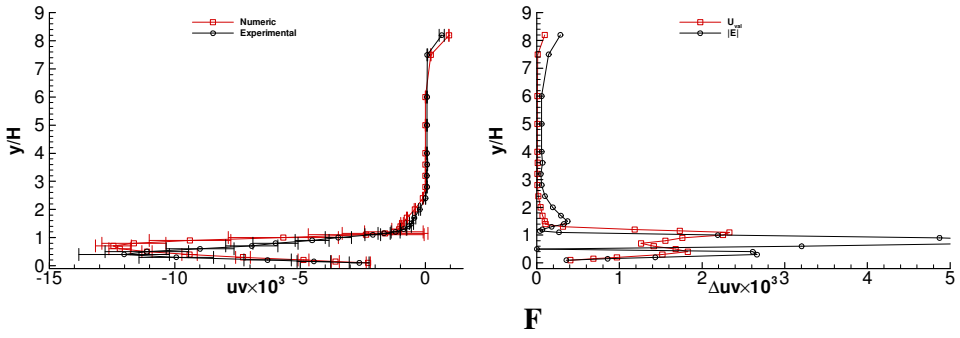
K

iii) Reynolds stress, $\overline{uv}/U_{ref}^2$

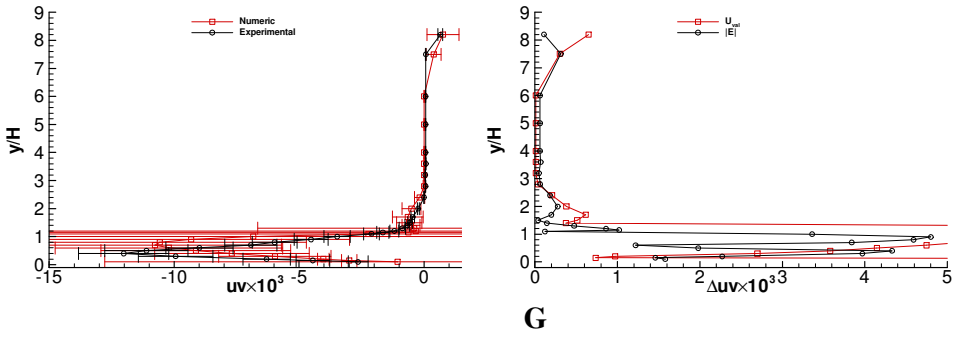



Numeric
Experimental
y/H
uv×10³
U_vel
|E|
Δuv×10³

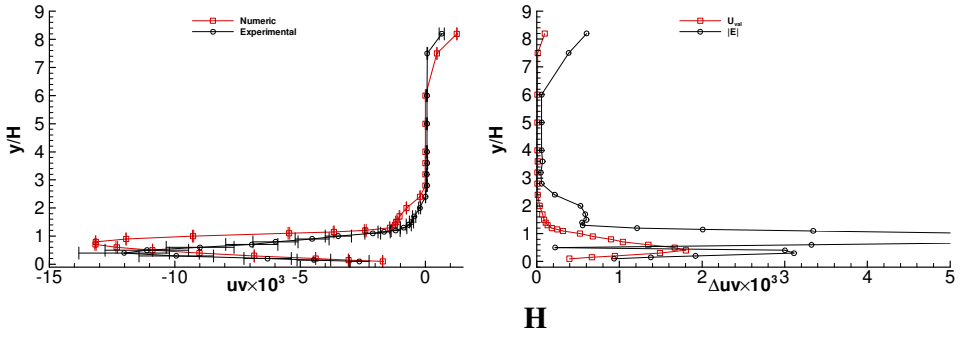
E


Numeric
Experimental
y/H
uv×10³
U_vel
|E|
Δuv×10³

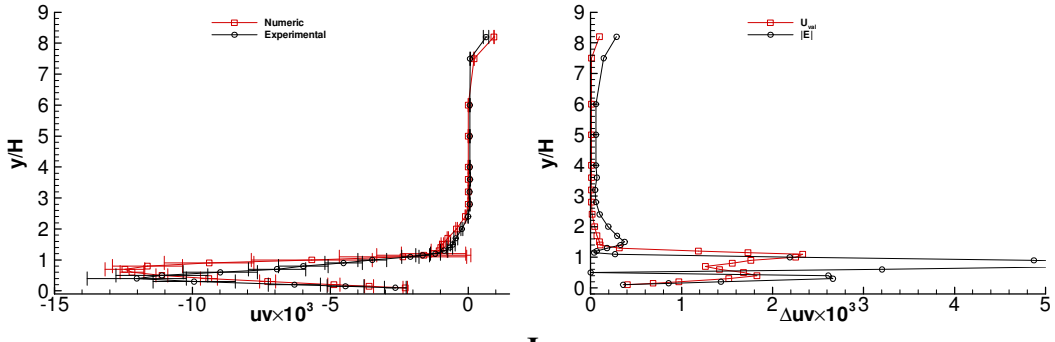
F


Numeric
Experimental
y/H
uv×10³
U_vel
|E|
Δuv×10³

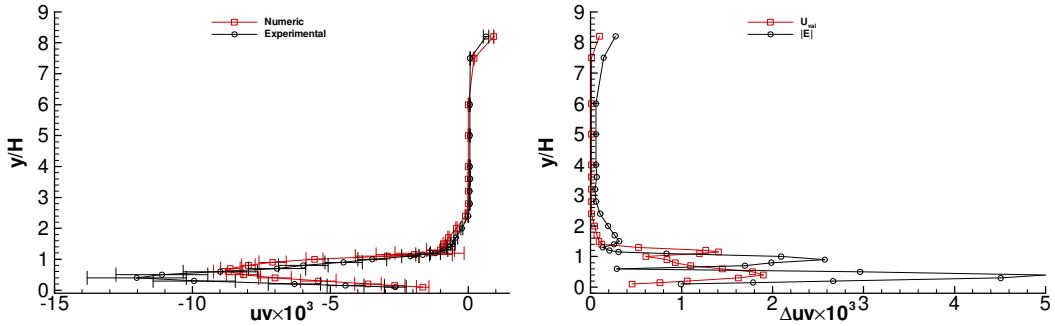
G


Numeric
Experimental
y/H
uv×10³
U_vel
|E|
Δuv×10³

H


Numeric
Experimental
y/H
uv×10³
U_vel
|E|
Δuv×10³

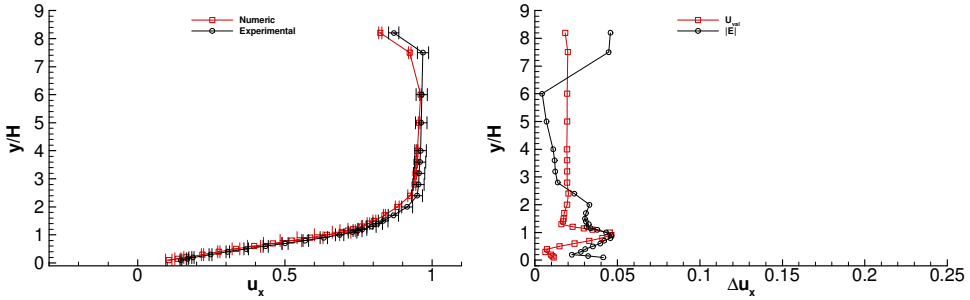
J



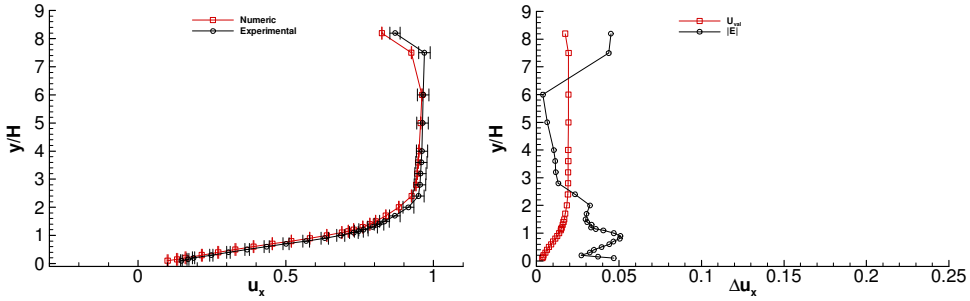
K

h) Profiles at x=6H

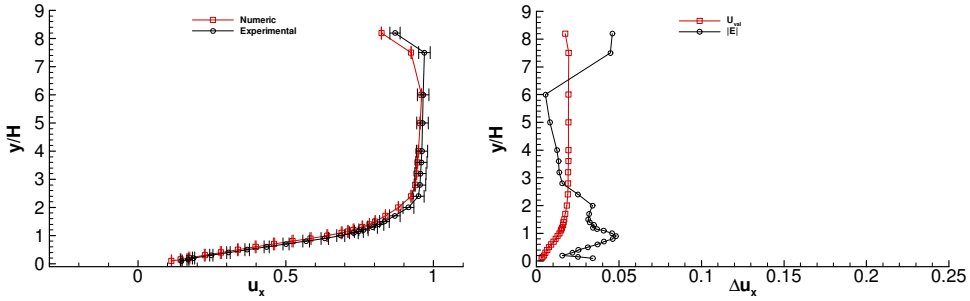
i) Horizontal velocity, u/U_{ref}



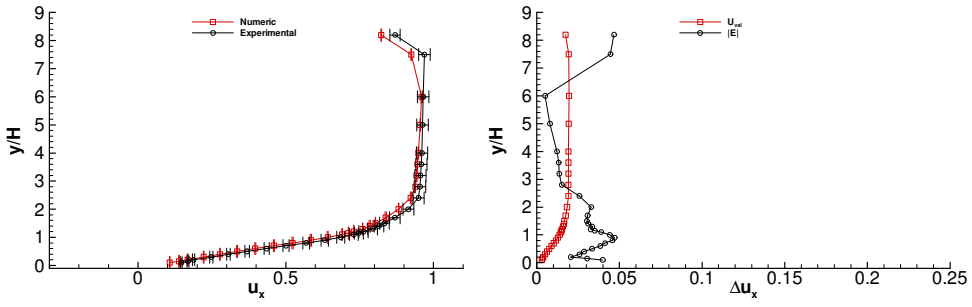
A



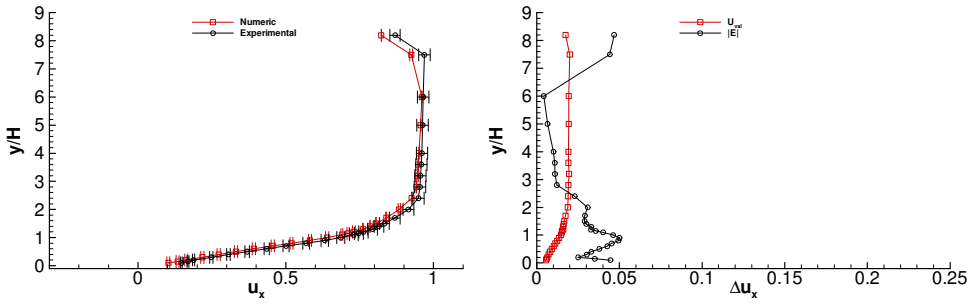
B



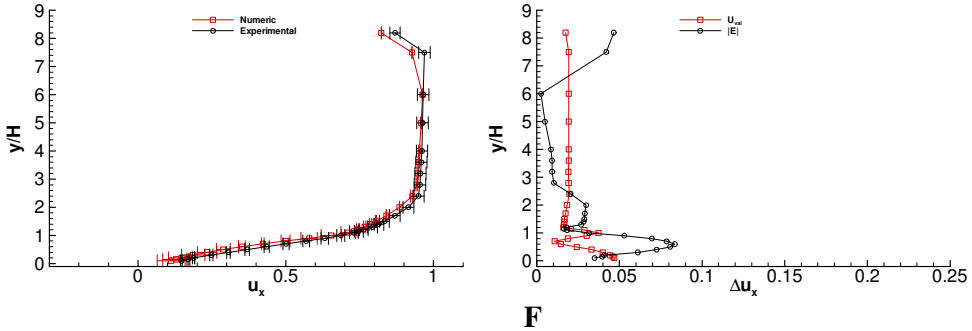
C


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

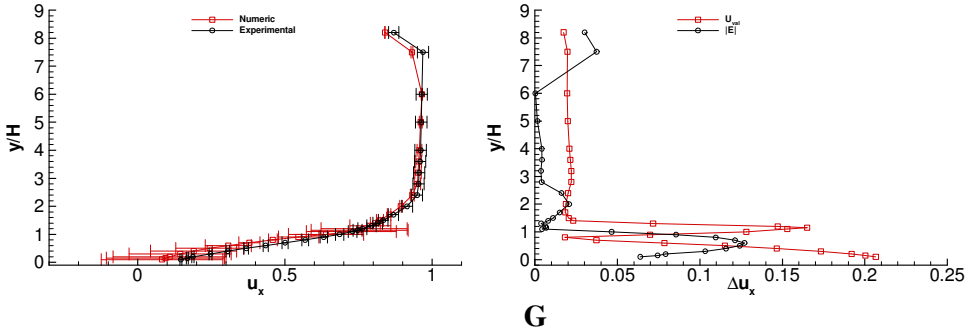
D


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

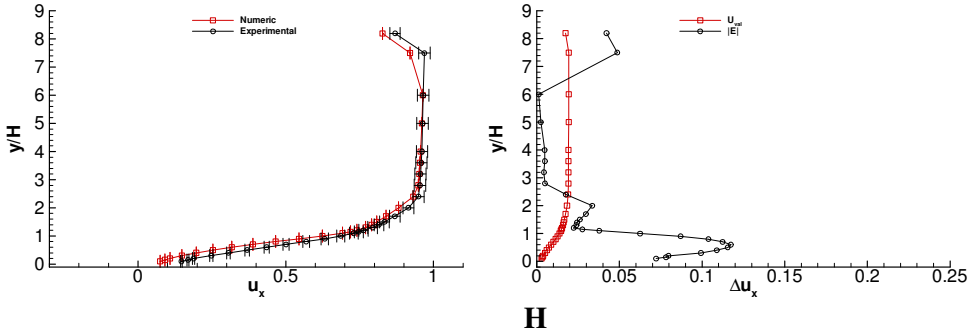
E


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

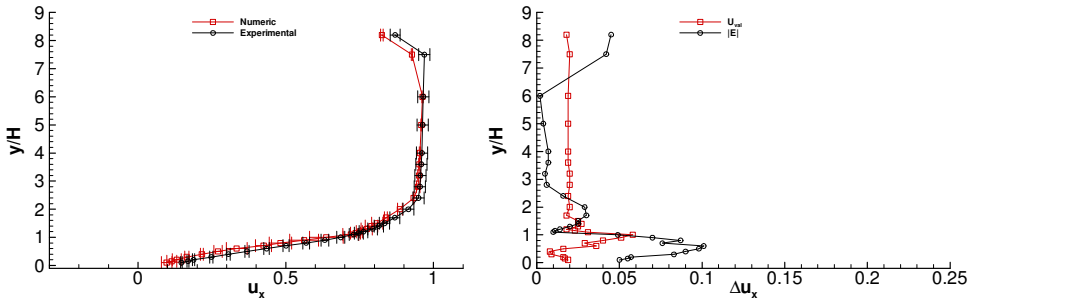
F


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

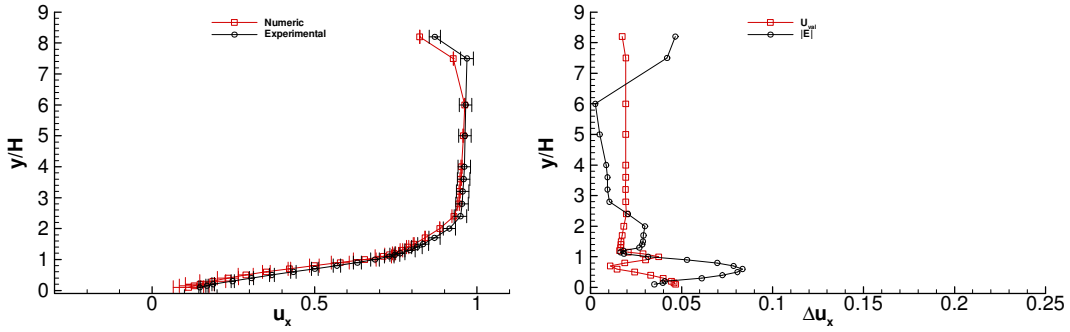
G


Numeric
Experimental
y/H
u_x
U_{val}
|E|
Δu_x

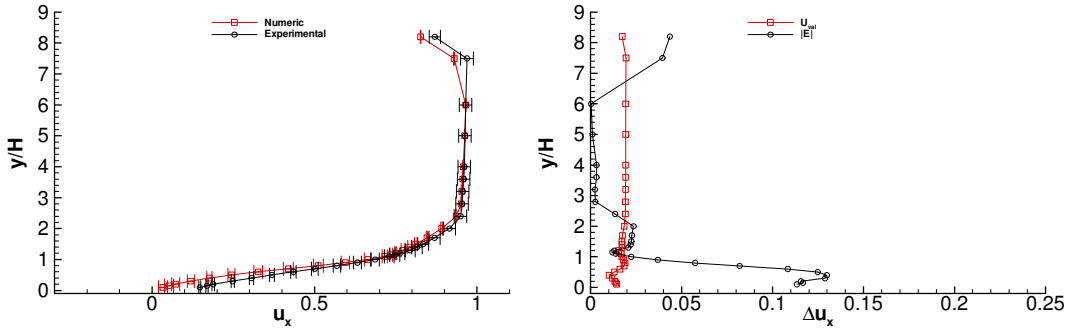
H



I

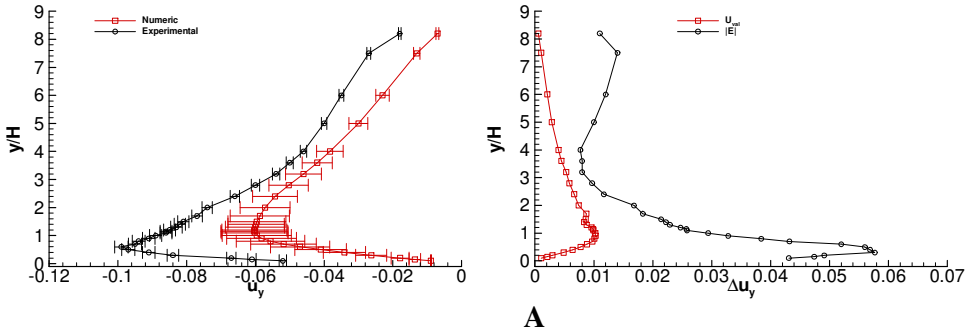


J

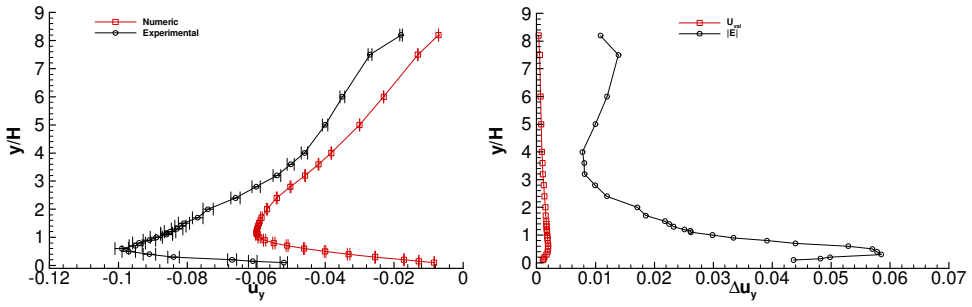


K

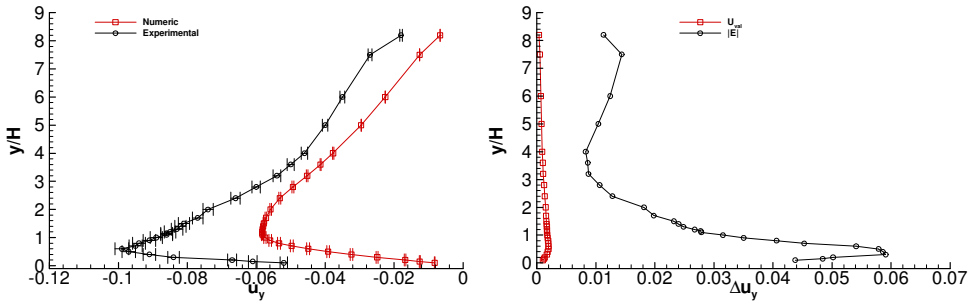
ii) Vertical velocity, v/U_{ref}



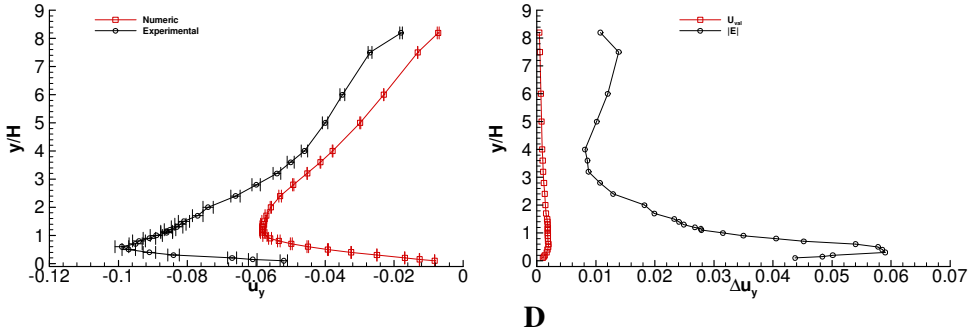
A


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

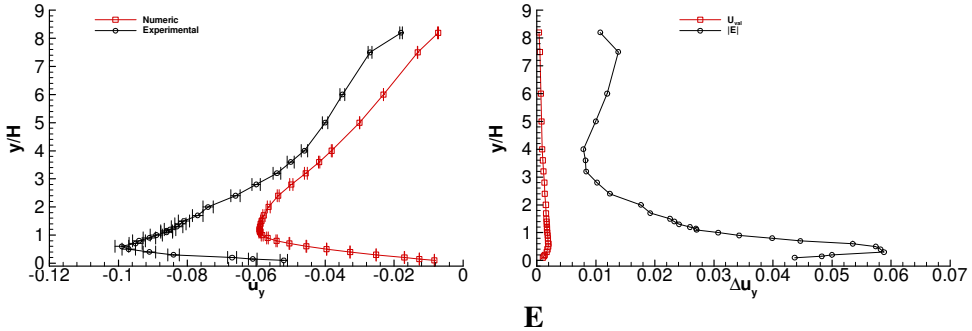
B


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

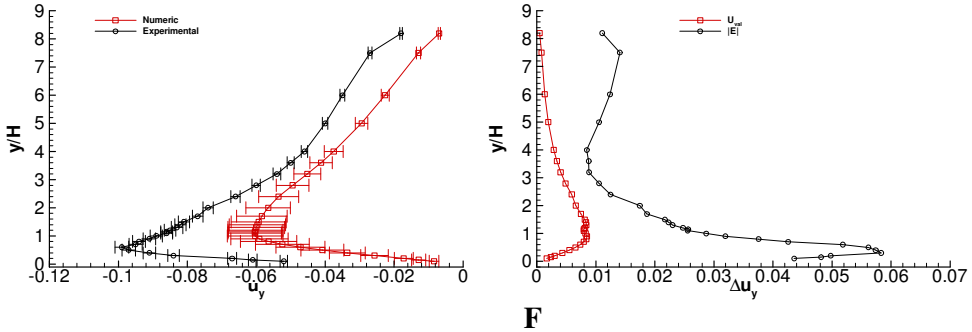
C


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

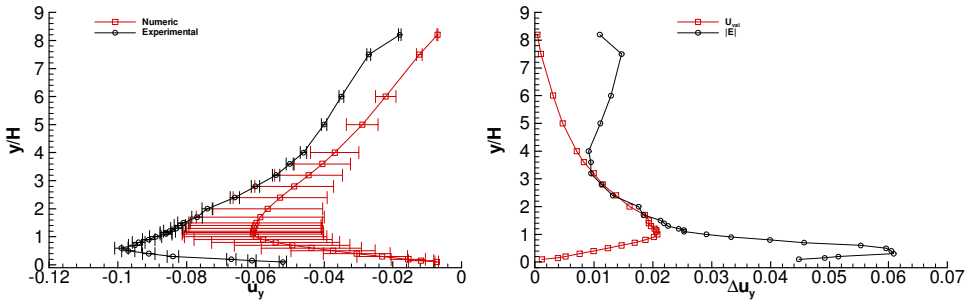
D


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

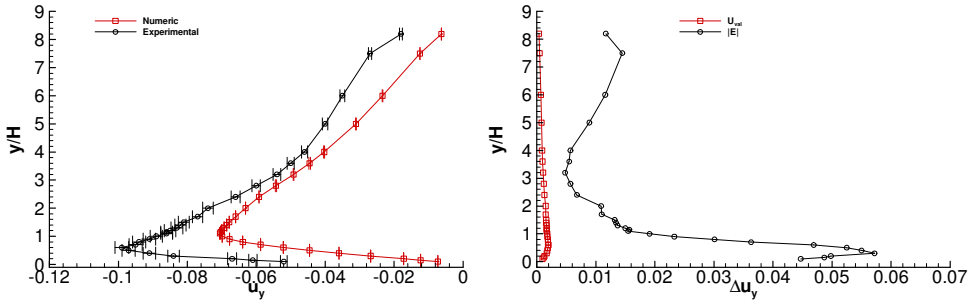
E


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

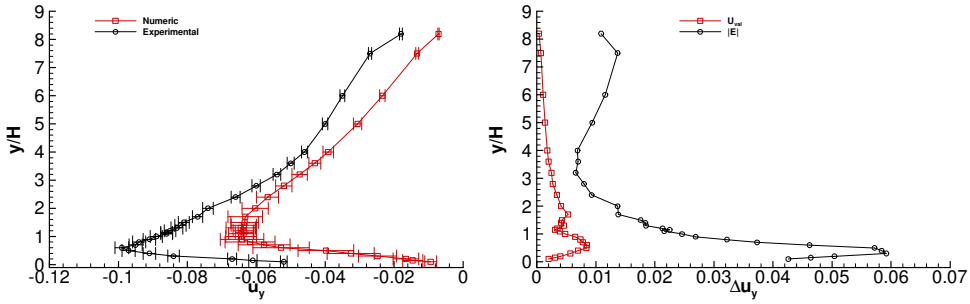
F


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

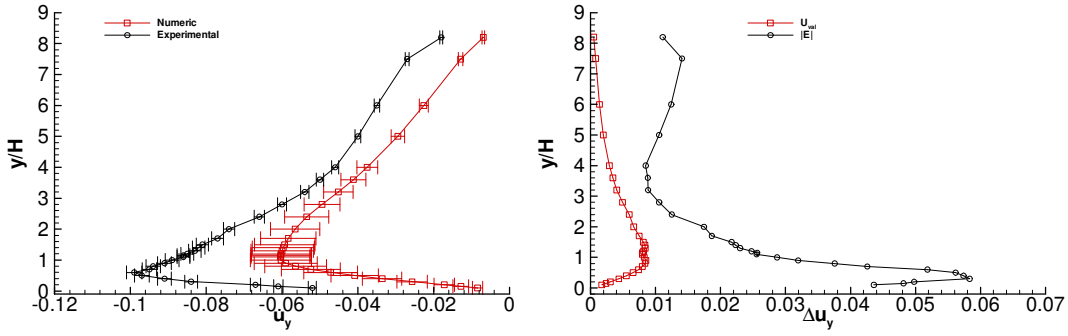
G


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

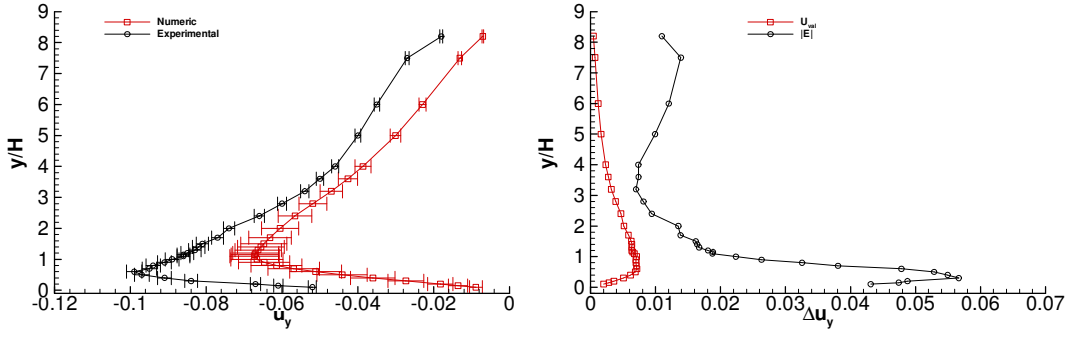
H


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

I

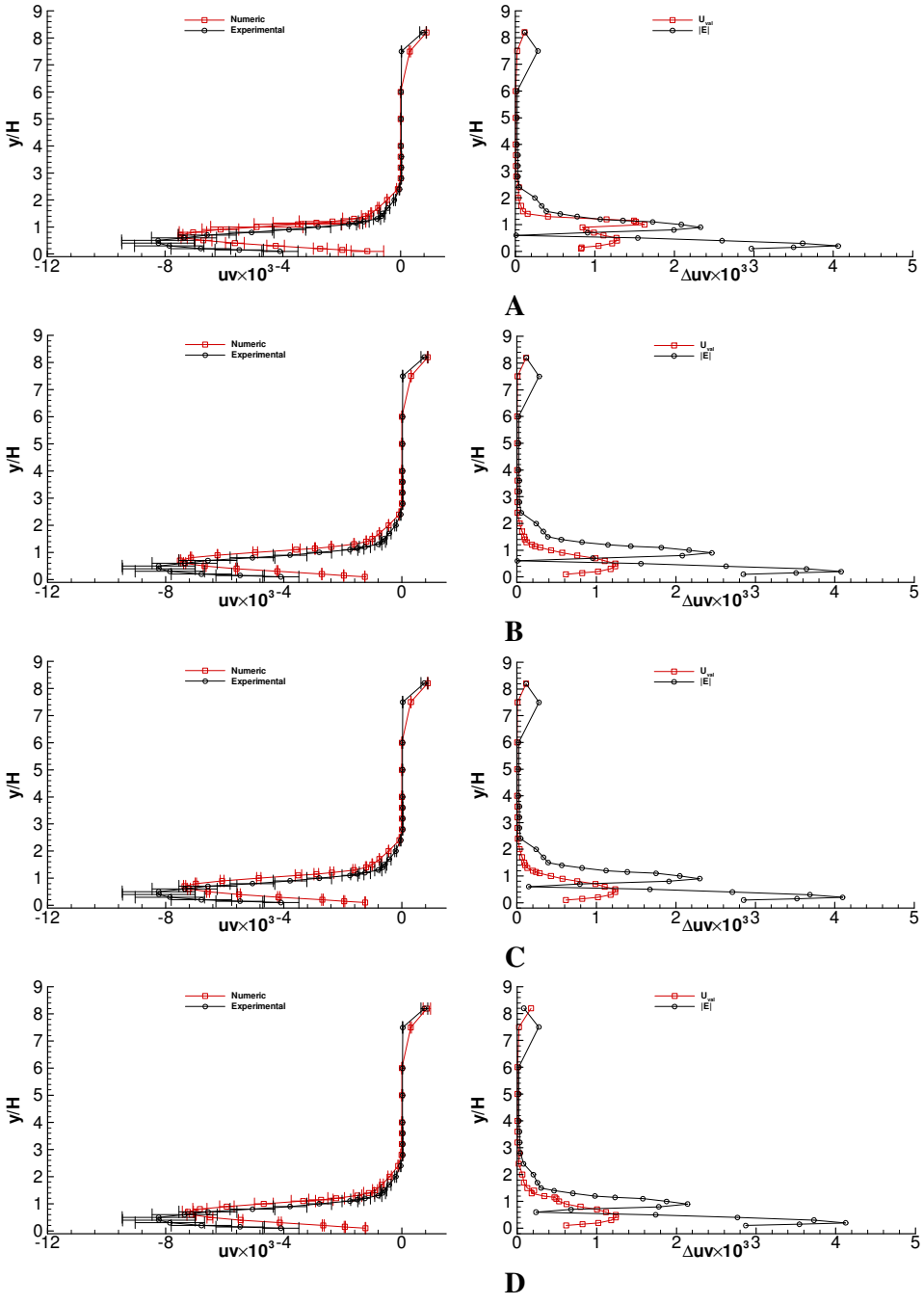

Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

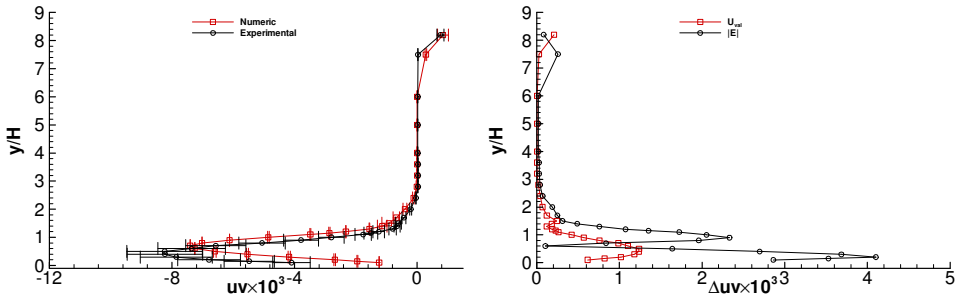
J


Numeric
Experimental
y/H
u_y
U_{val}
|E|
Δu_y

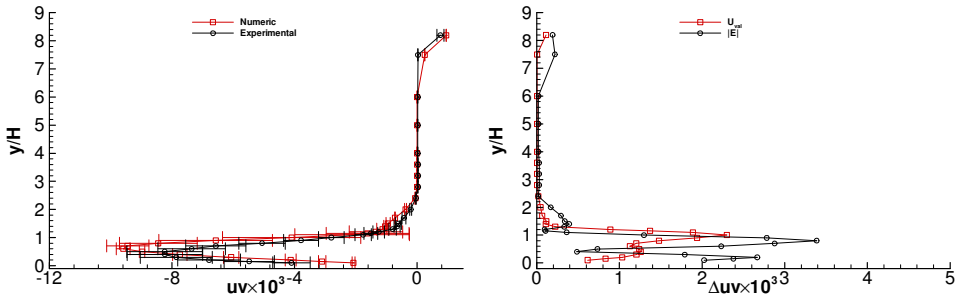
K

iii) Reynolds stress, $\overline{uv}/U_{ref}^2$

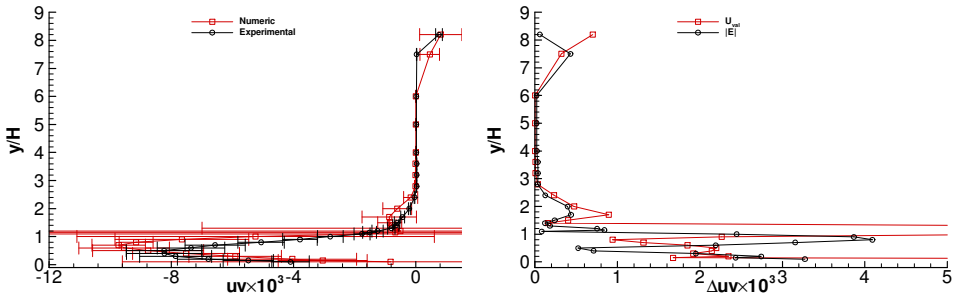



Numeric
Experimental
y/H
uv×10³
-12
-8
-4
0
U_rel
|E|
Δuv×10³
1
2
3
4
5

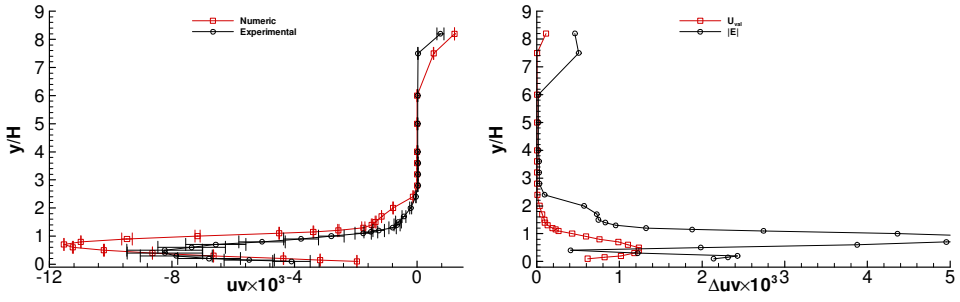
E


Numeric
Experimental
y/H
uv×10³
-12
-8
-4
0
U_rel
|E|
Δuv×10³
1
2
3
4
5

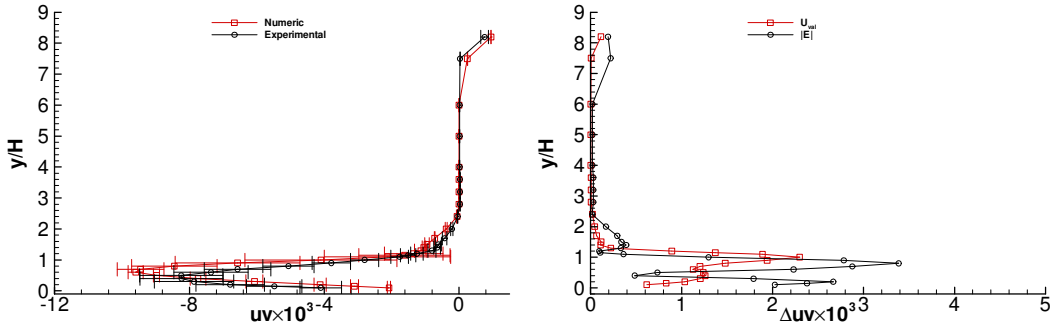
F


Numeric
Experimental
y/H
uv×10³
-12
-8
-4
0
U_rel
|E|
Δuv×10³
1
2
3
4
5

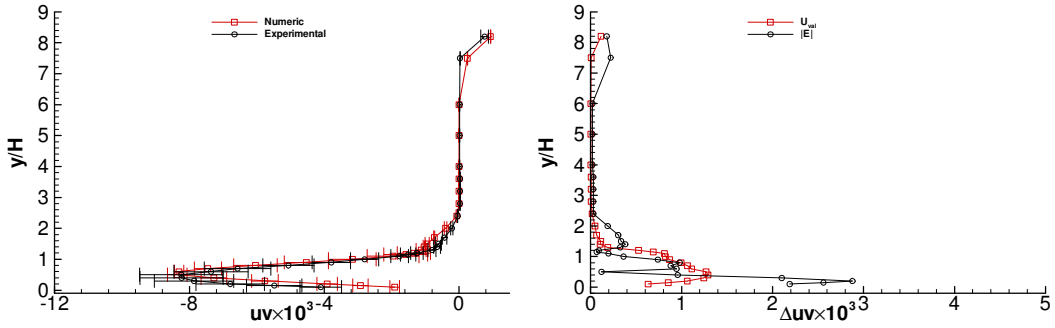
G


Numeric
Experimental
y/H
uv×10³
-12
-8
-4
0
U_rel
|E|
Δuv×10³
1
2
3
4
5

H


Numeric
Experimental
y/H
uv×10³
-12
-8
-4
0
U_rel
|E|
Δuv×10³
1
2
3
4
5

J



K