Summary of the CFDVAL2004 Workshop and Follow-on Results

Christopher L. Rumsey
NASA Langley Research Center
Hampton, VA

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Summary

- This talk is in 2 parts:
  - 1st part is summary of the CFDVAL workshop, March 2004, which examined 3 flow-control validation cases (See AIAA Paper 2004-2217 and http://cfdval2004.larc.nasa.gov)
  - 2nd part is summary of the 11th ERCOFTAC/ IAHR turbulence modeling workshop continuation of Case 3, April 2005 (hump model) and comparison with CFDVAL

Introduction

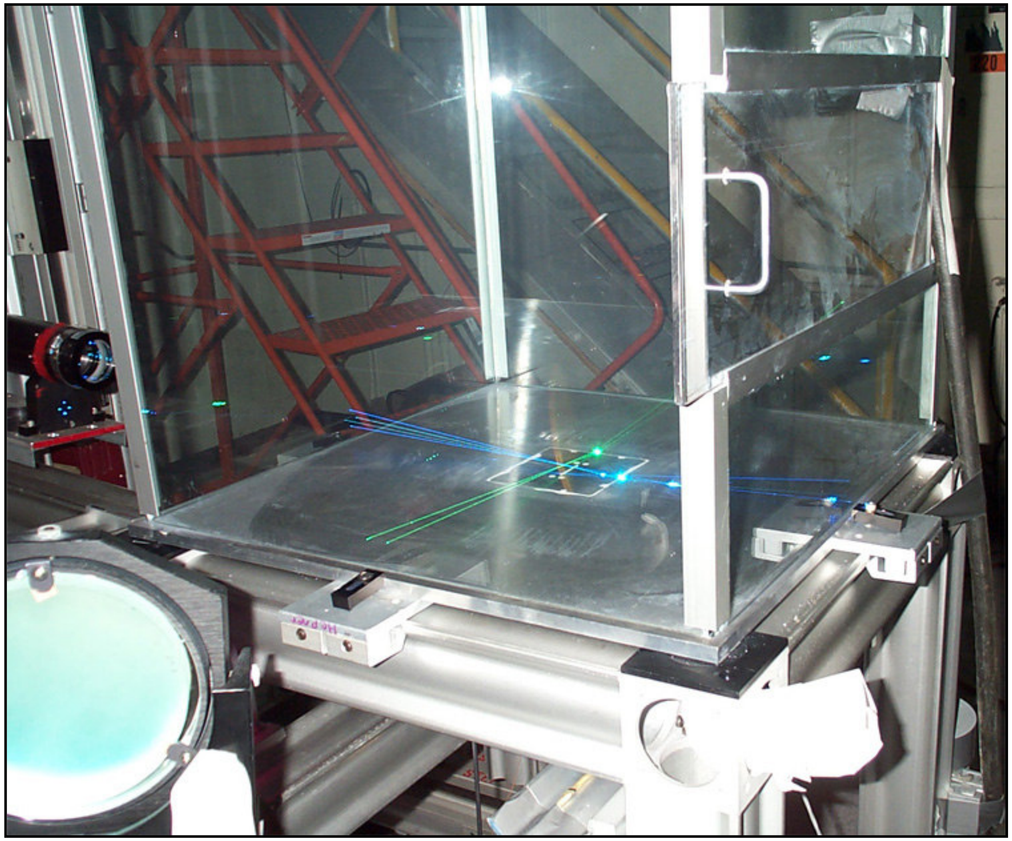
- CFDVAL2004 3-day workshop held March 2004 in Williamsburg, VA
- 3 cases (experiments performed at NASA LaRC)
  - Increasing geometric/physical complexity
  - Measured using multiple instrumentation systems
  - Designed for CFD validation, not highest performance
- 75 participants at the workshop
- 7 countries (62 U.S., 4 France, 3 Italy, 2 Germany, 2 Japan, 1 U.K., 1 Switzerland)
- Representation from universities, companies, and public sector research laboratories

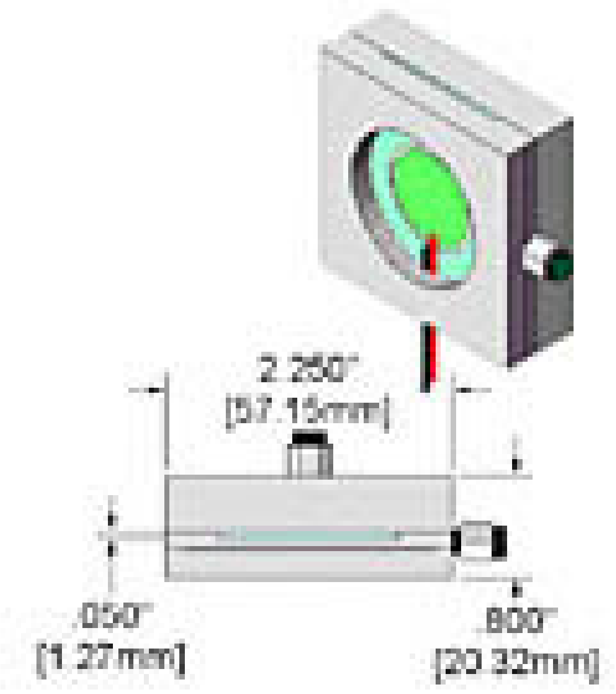
Case 1

Synthetic jet in quiescent air

8 contributors

25 separate cases

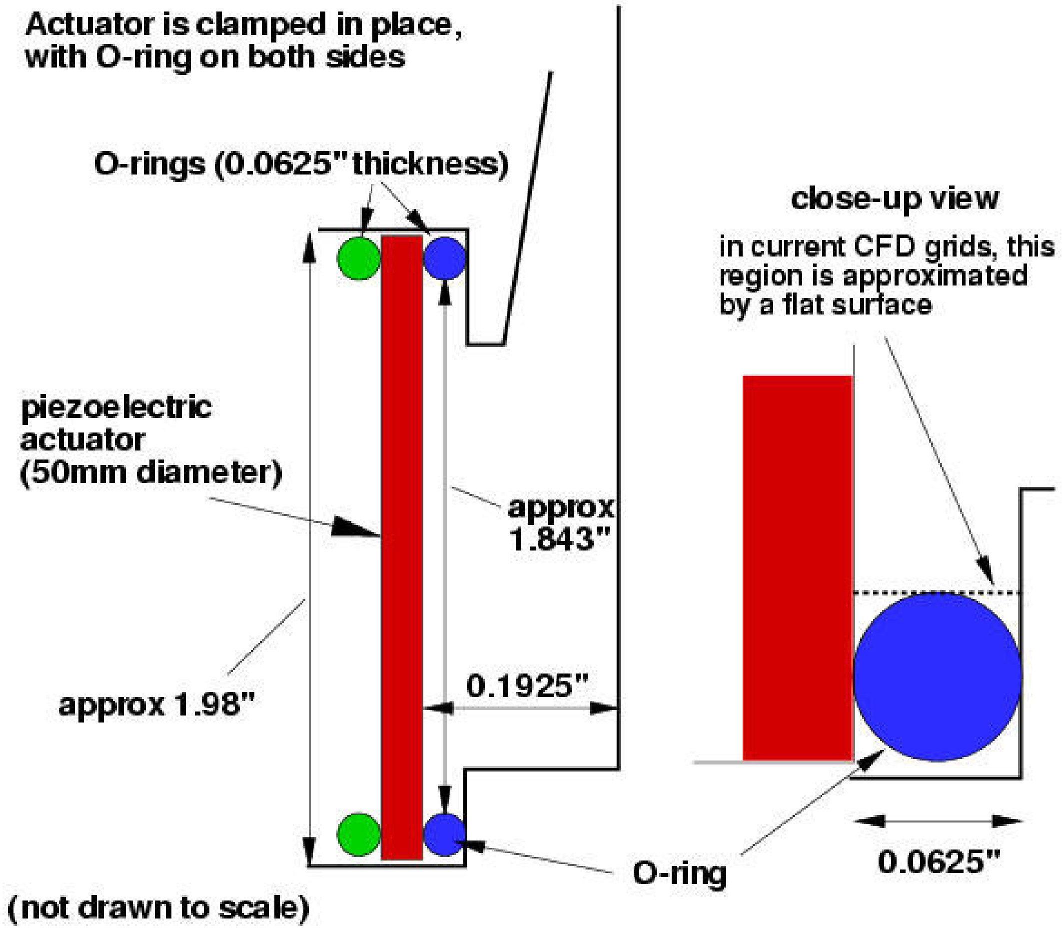




Case 1 Details

- Synthetic jet flow in and out of slot (1.27mm wide by 35.56mm long)
- Driven by side-mounted circular piezo-electric diaphragm inside cavity
  - 444.7 Hz
  - Max velocity out of slot approx 25-30 m/s
- Flow issues into enclosed box 0.61m per side

Cavity

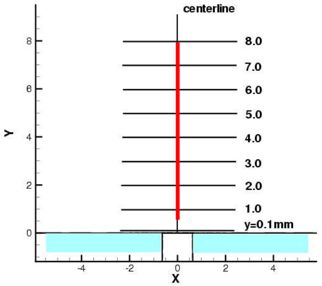


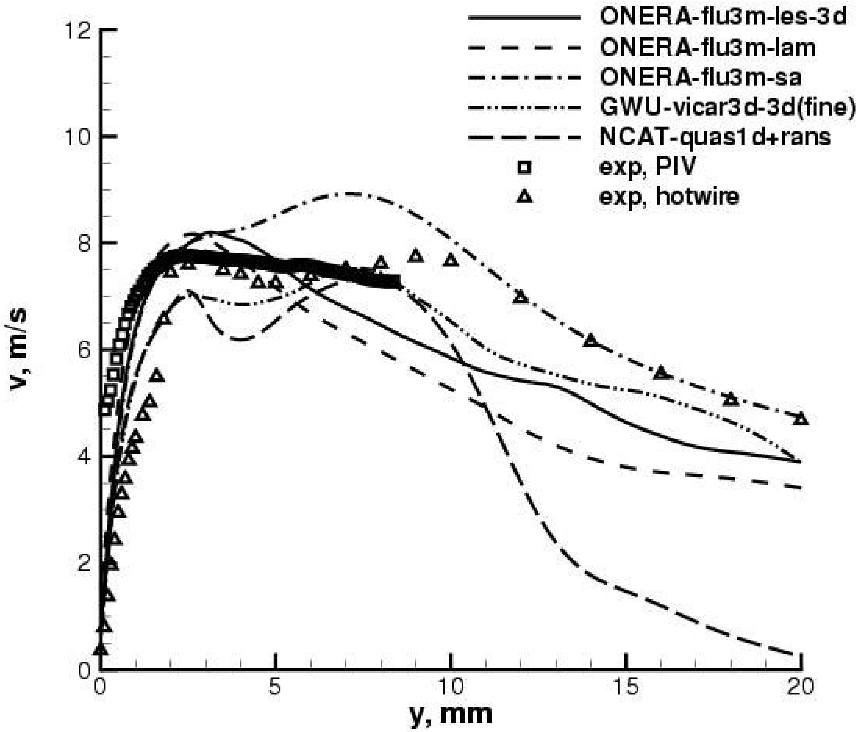
Actuator is clamped in place,
with O-ring on both sides
O-rings (0.0625" thickness)
piezoelectric
actuator
(50mm diameter)
approx
1.843"
approx 1.98"
0.1925"
(not drawn to scale)
O-ring
close-up view
in current CFD grids, this
region is approximated
by a flat surface
0.0625"

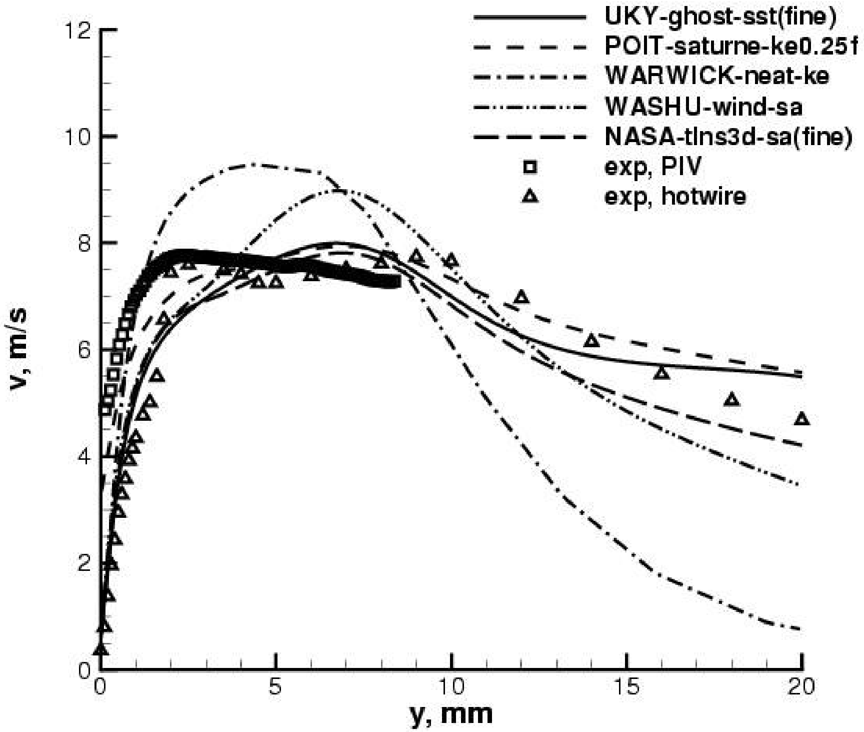
Methodologies

- Structured & unstructured URANS (various turbulence models: SA, SST, k-e, nonlinear k-e, EASM, RSM)
- Mostly 2nd order in space and time
- Several Laminar, 1 RANS/LES, & 1 LES
- 1 reduced-order model (quasi-1-D inside slot) – 4th order in space and time
- Mostly 2-D; a few 3-D (periodic)
- Most modeled (an approximation of) the cavity, 2 applied BCs at slot exit
- Wide variety of grid sizes and time steps

Average v-velocity at centerline (x=0)

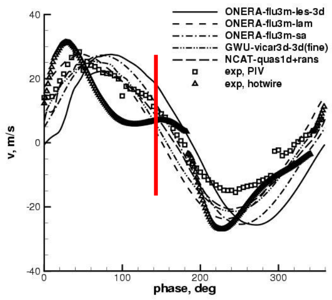


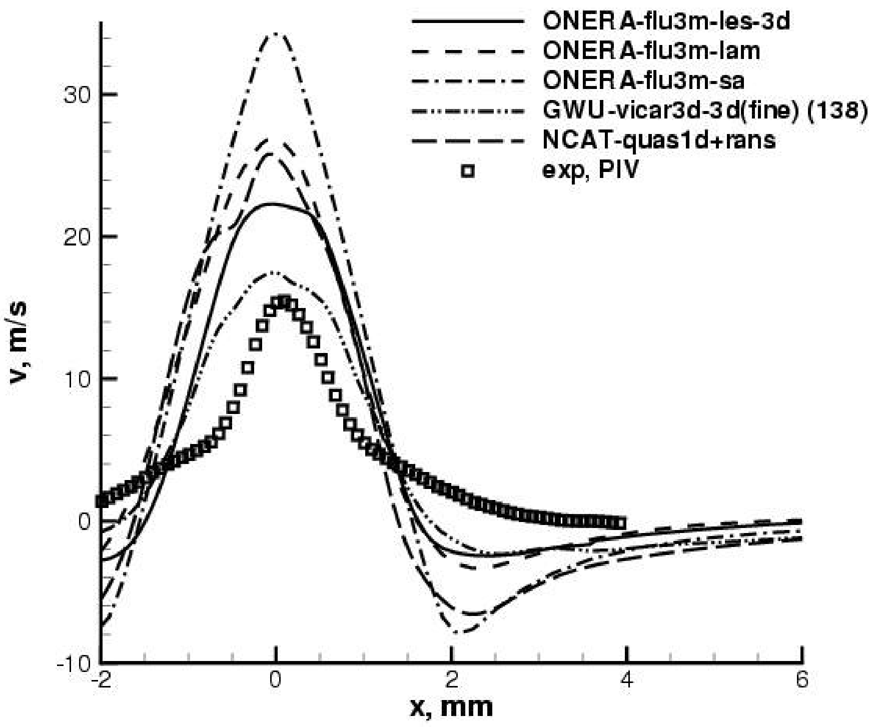


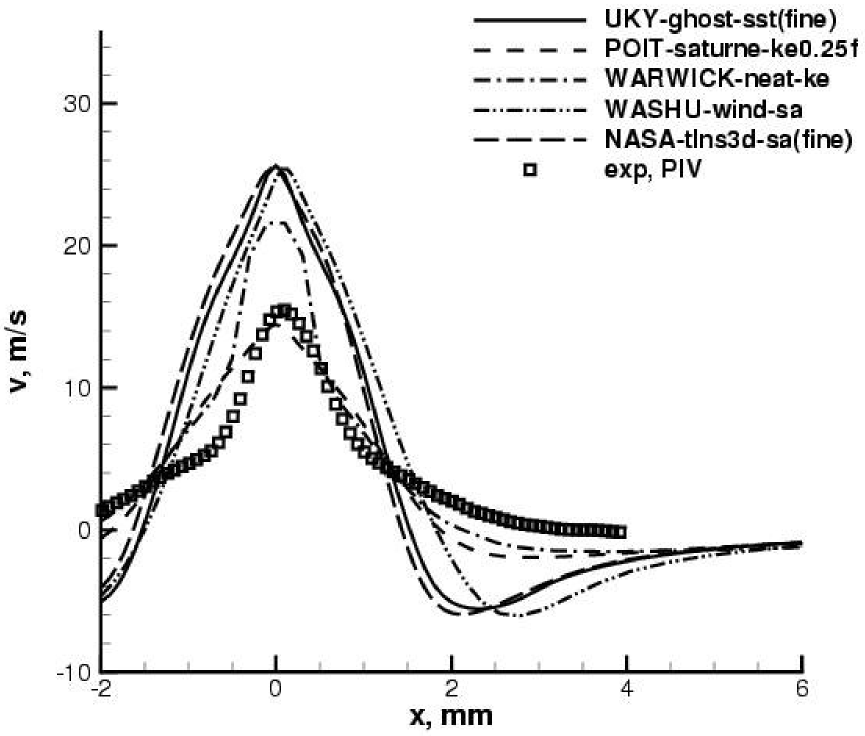


(both plots of same thing, with different participants' results)

Phase-averaged v-velocity profiles at y=4 mm, phase=135 deg

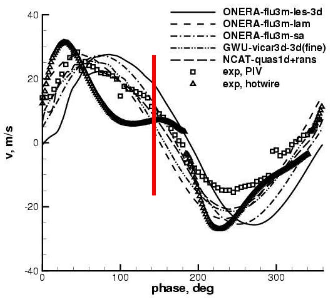




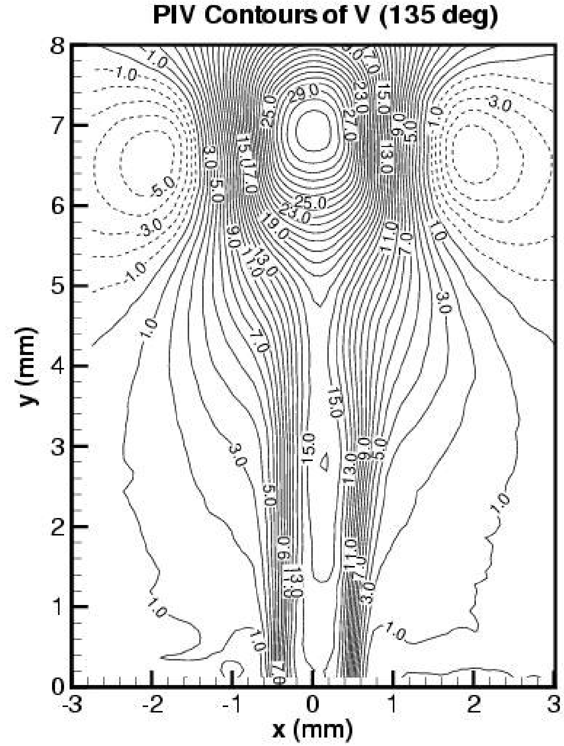


(both plots of same thing, with different participants' results)

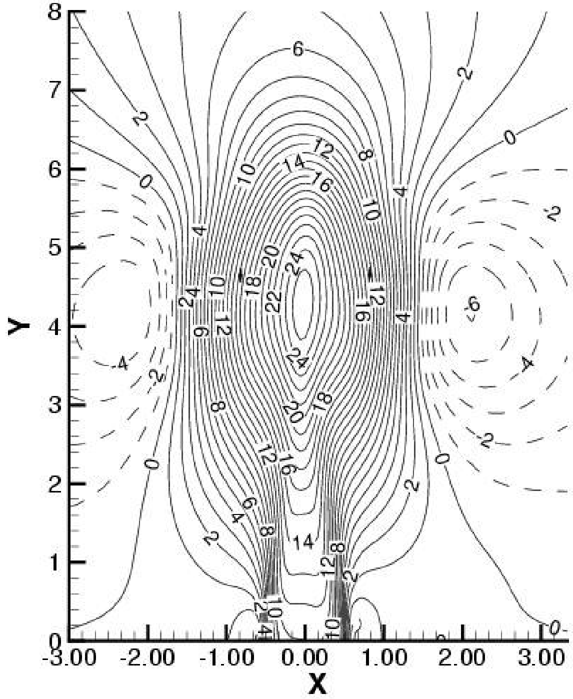
Example contours of phase-averaged v-velocity, phase=135 deg



experiment



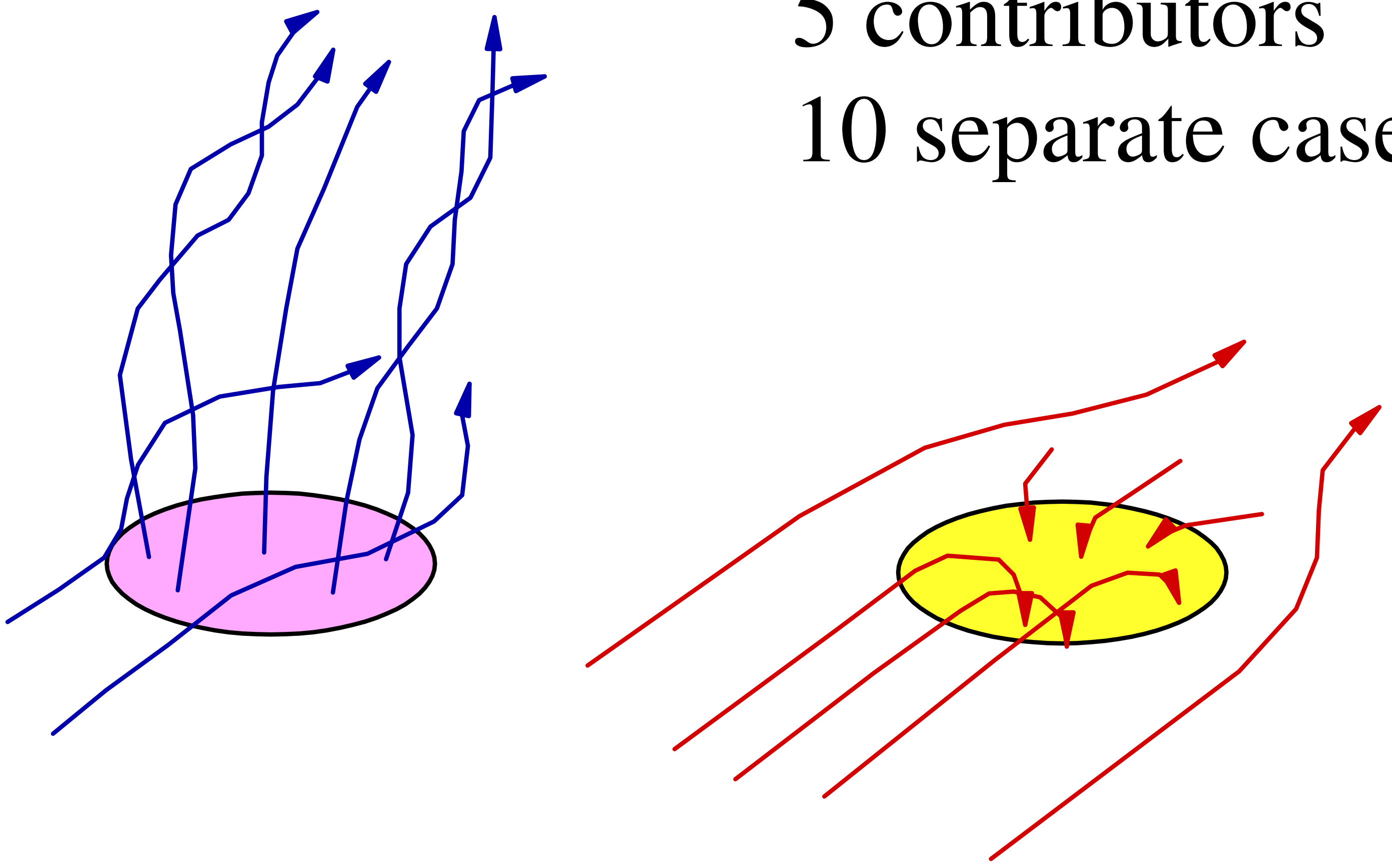
NASA-tlns3d-sa(fine)



Case 2

Synthetic jet in crossflow

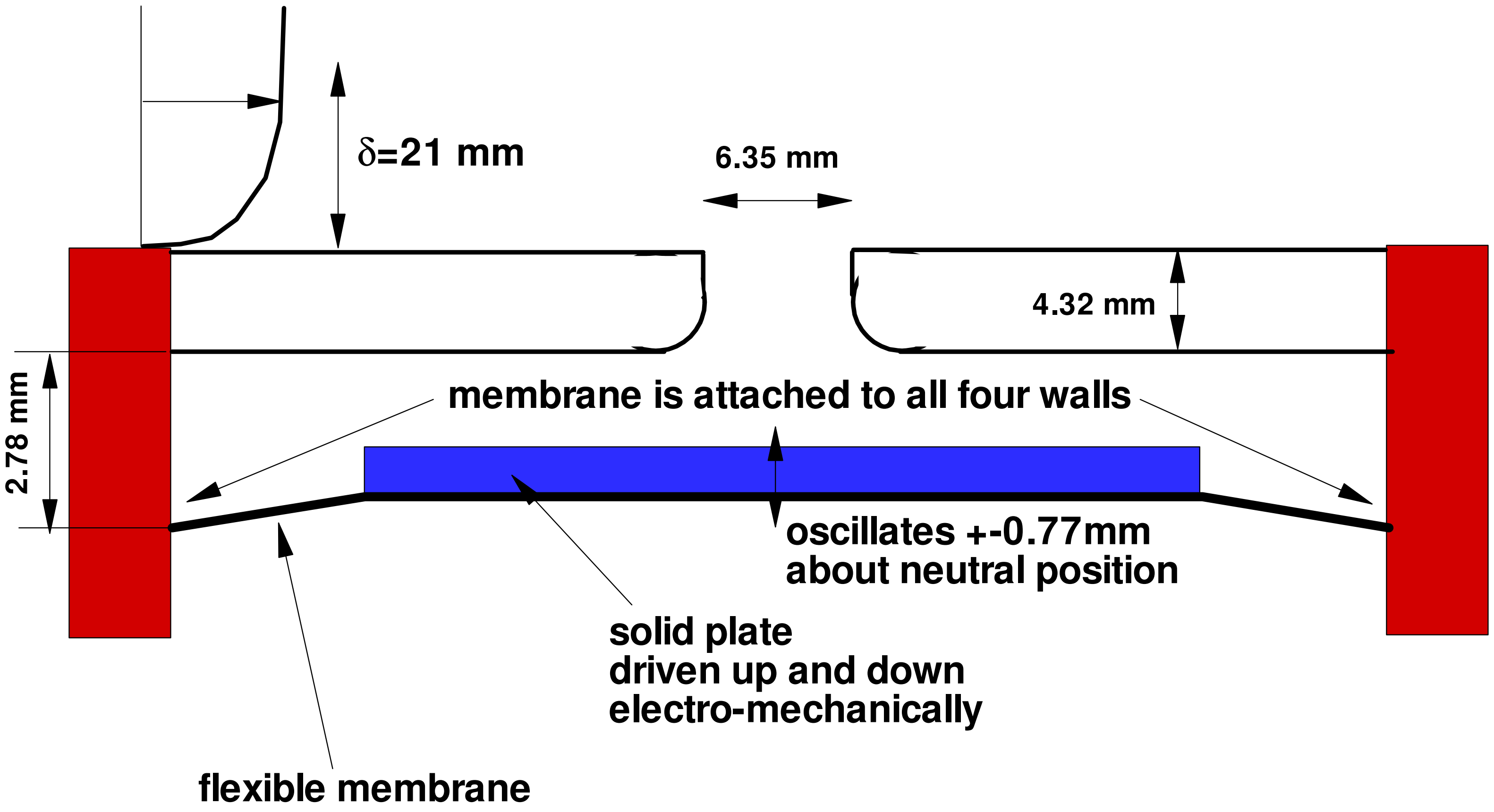
5 contributors
10 separate cases



Case 2 Details

- Synthetic jet flow in and out of circular orifice (6.35mm diameter)
- Driven by bottom-mounted square-shaped piston (on elastic membrane) inside cavity
  - Cavity is approx 1.7mm deep (tunnel on)
  - 150 Hz
  - Max velocity out of slot approx 43 m/s (=1.3Uinf)
- Flow issues into turbulent boundary layer (M=0.1, BL thickness approx 21mm)

Cavity



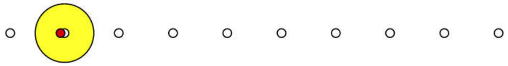
(not drawn to scale)

Methodologies

- Structured & unstructured URANS (various turbulence models: SA, SST, k-e, EASM)
- 1 LES
- All methods 2nd order in space and time
- Both full-plane and half-plane modeled
- 4 modeled a cavity, 1 did not
- Wide variety of grid sizes and time steps

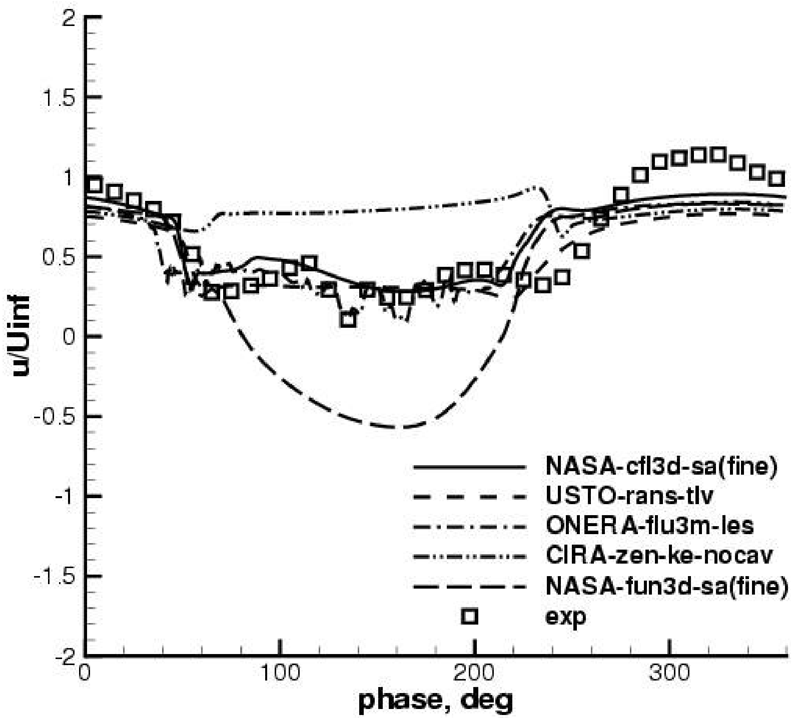
Time histories above orifice

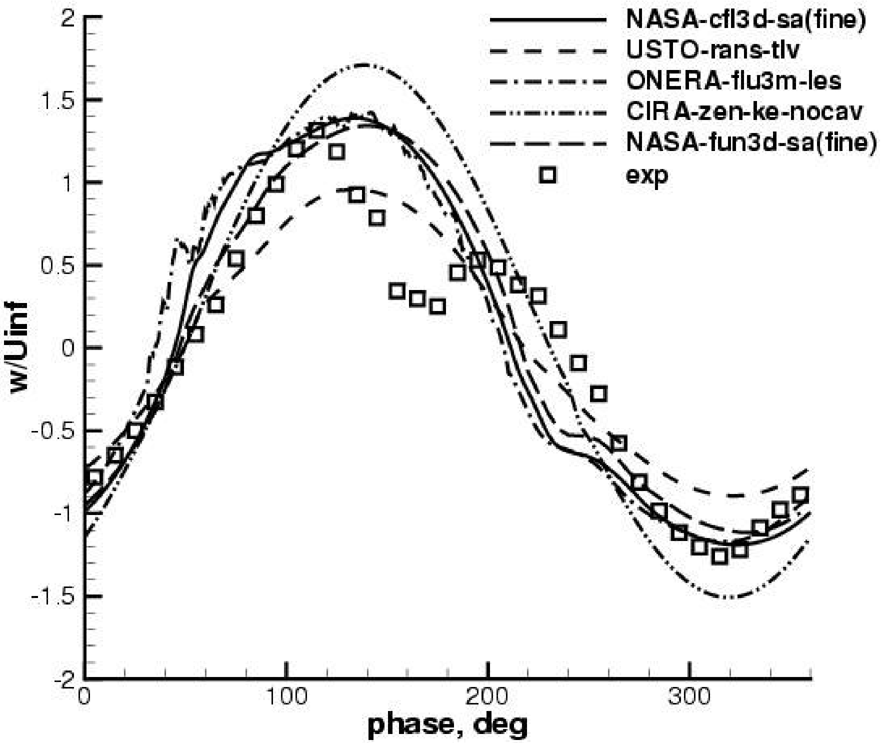
x=50.63mm, y=0, z=0.4mm



u-velocity

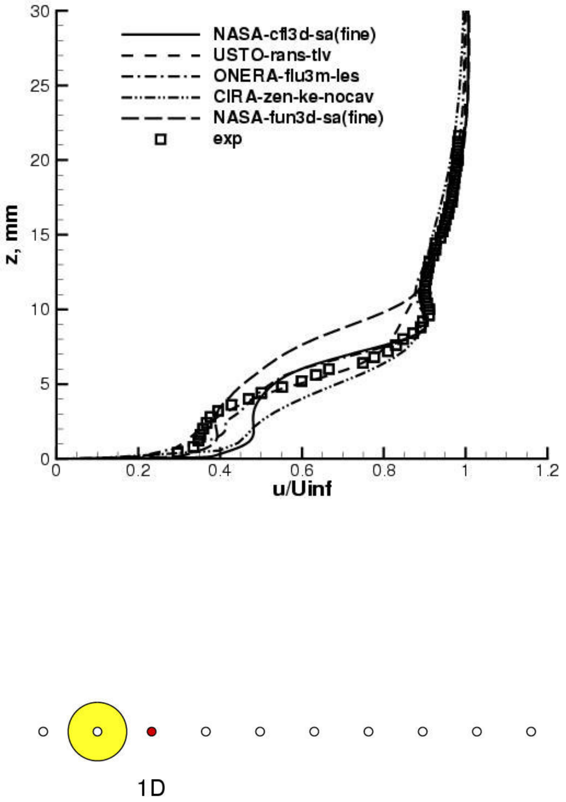
w-velocity



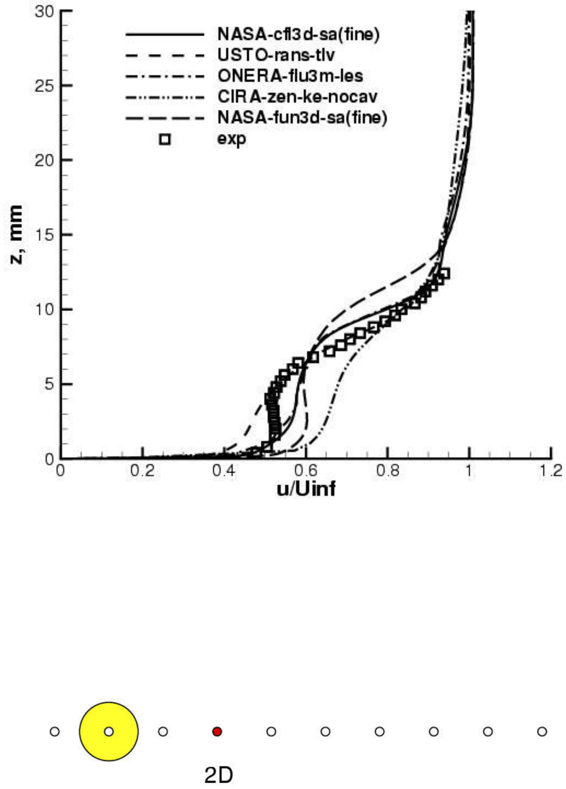


Average u-velocity on centerplane

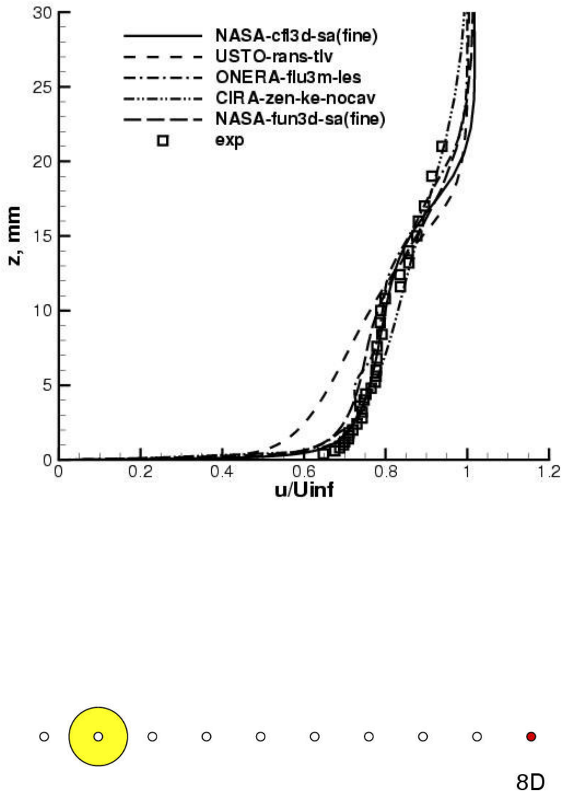
1D downstream



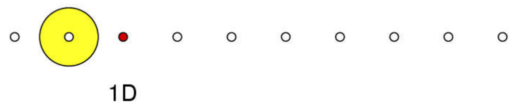
2D downstream



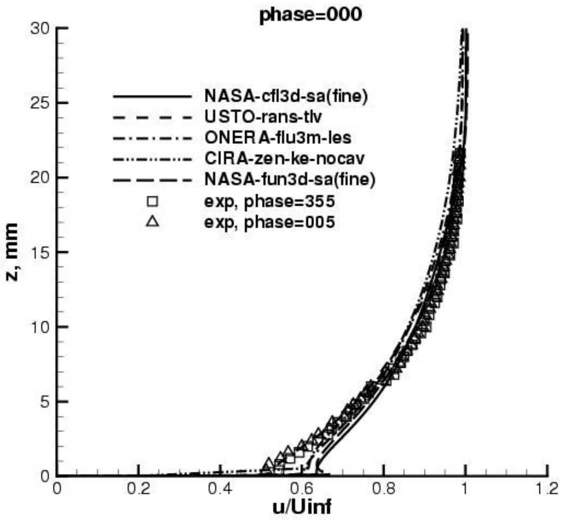
8D downstream



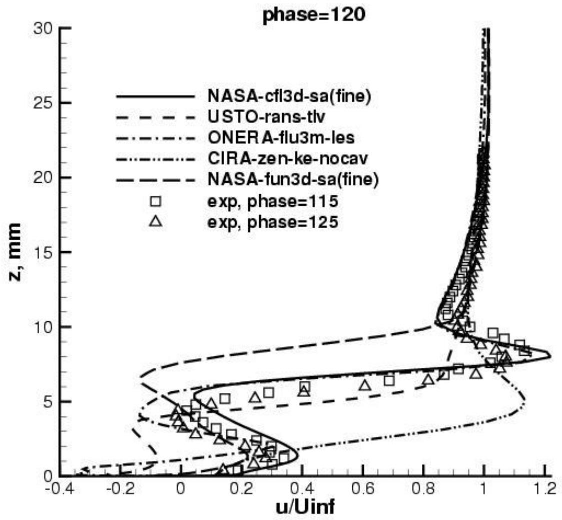
Phase-averaged u-velocity on centerplane 1D downstream



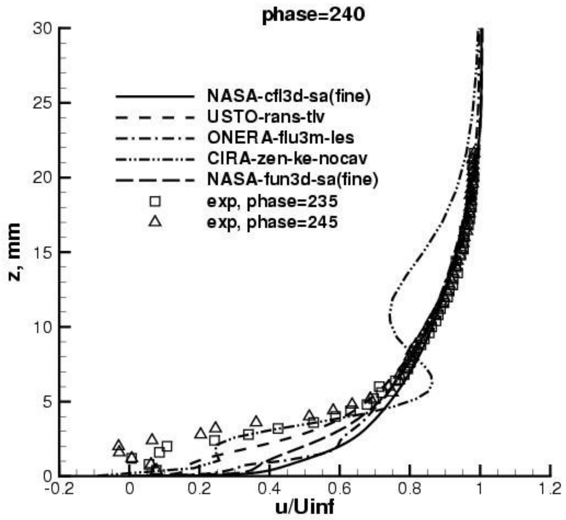
phase=0 deg

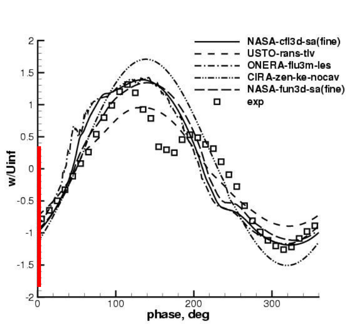


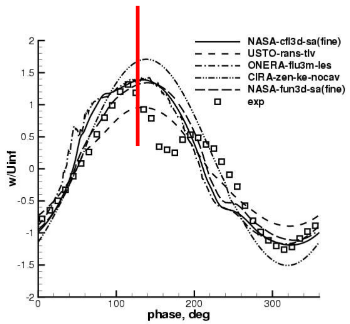
phase=120 deg

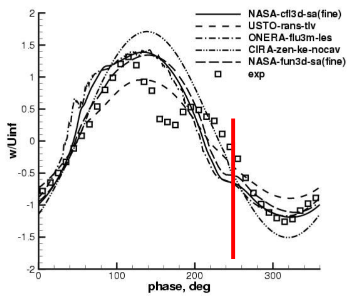


phase=240 deg

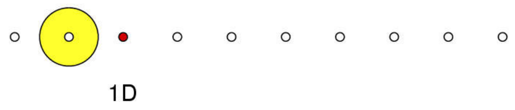




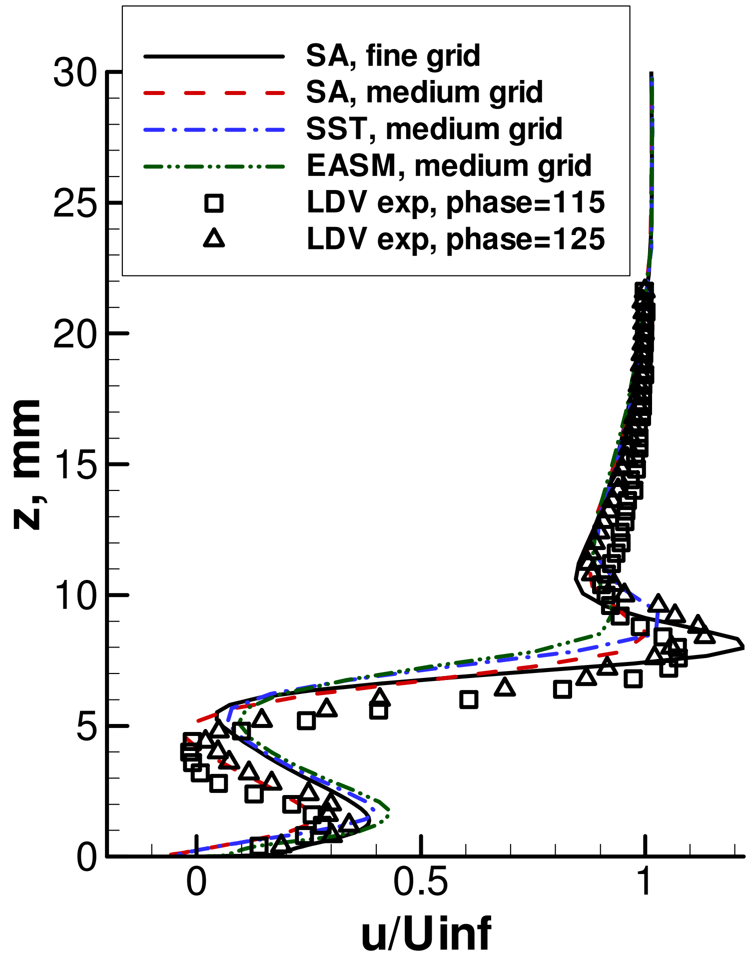


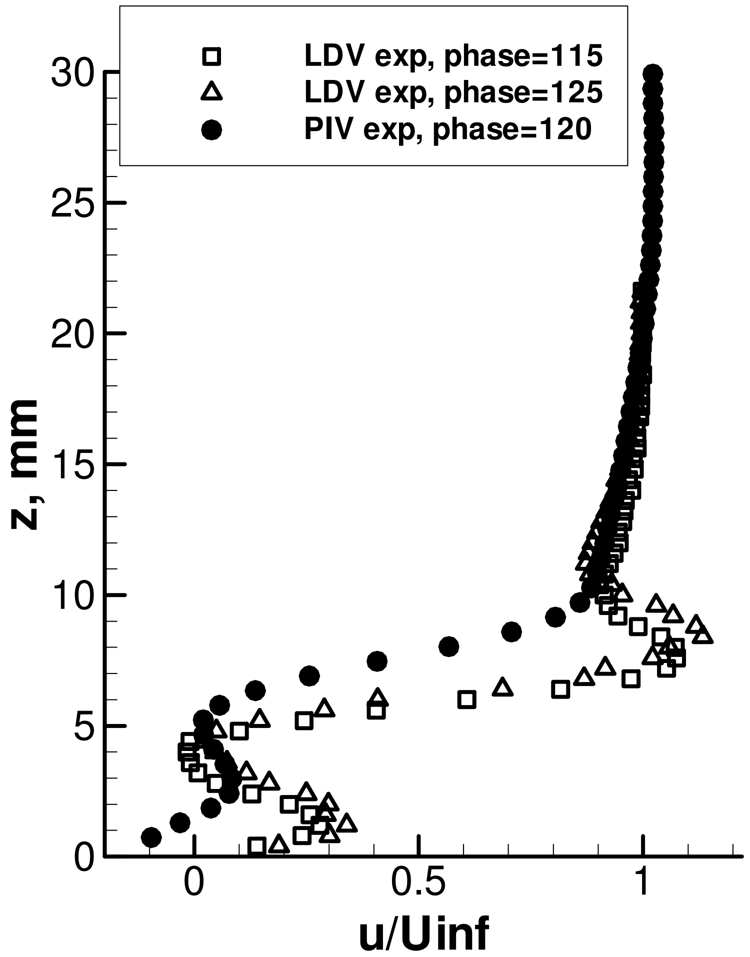


Phase-averaged u-velocity on centerplane 1D downstream

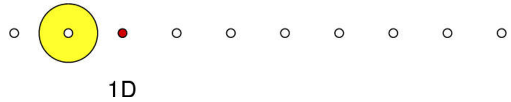


phase=120 deg



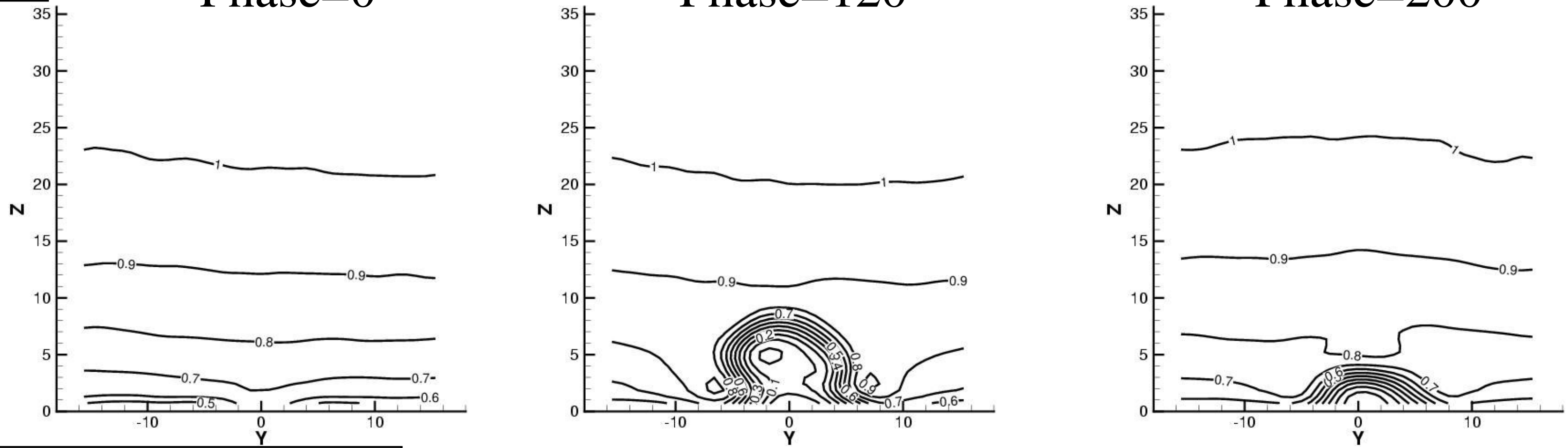


Example contours of phase-averaged u-velocity (1D downstream)

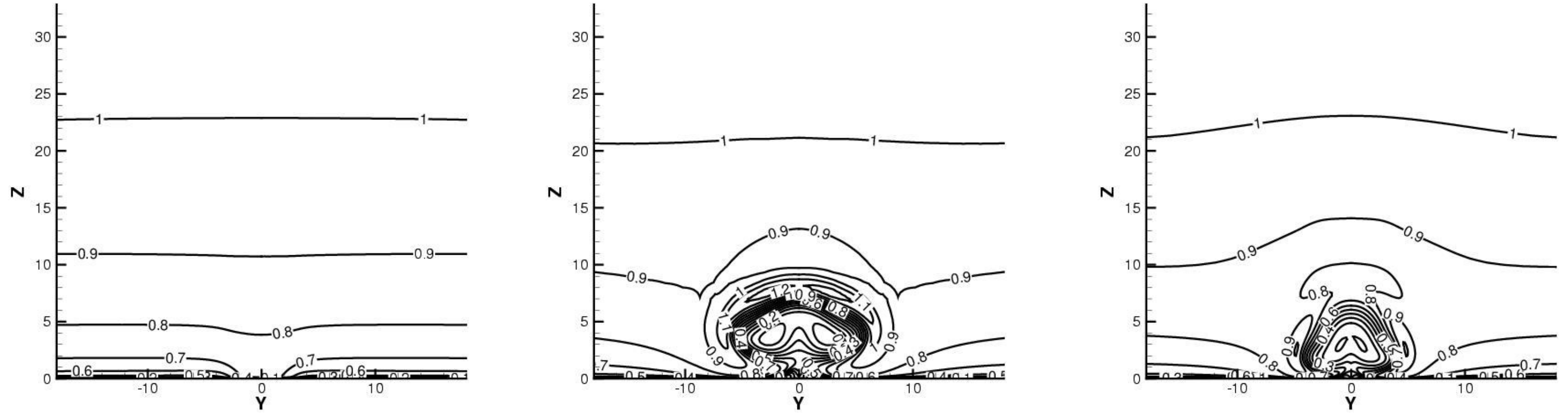


Exp:

Phase=0 | Phase=120 | Phase=200



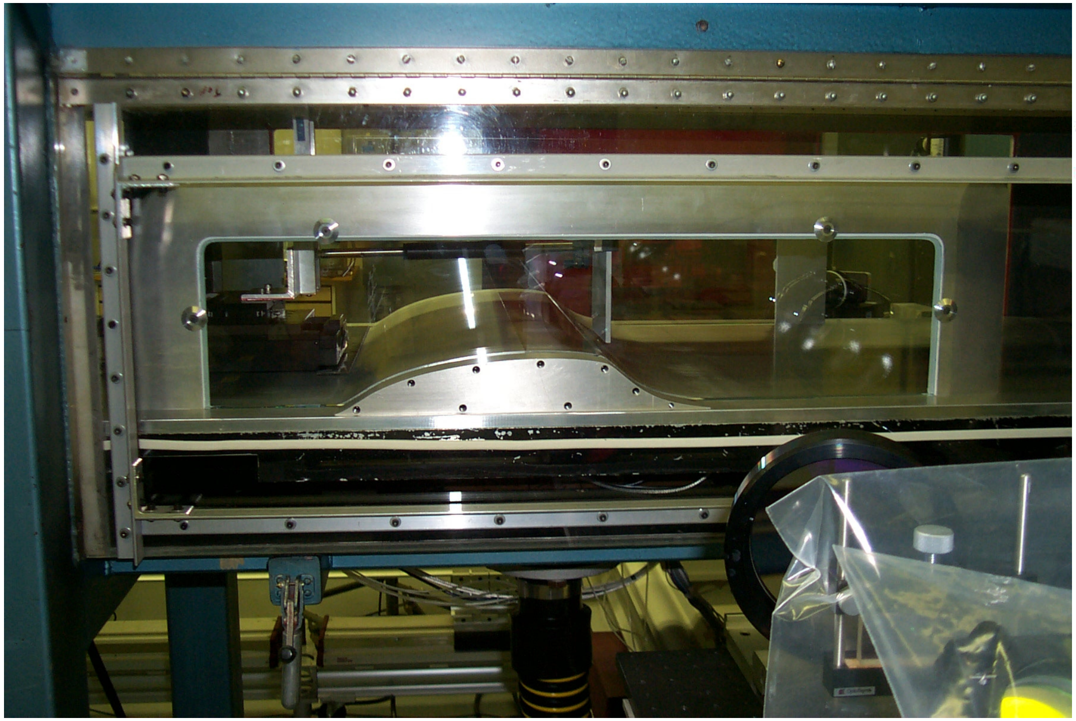
NASA-cfl3d-sa(fine):

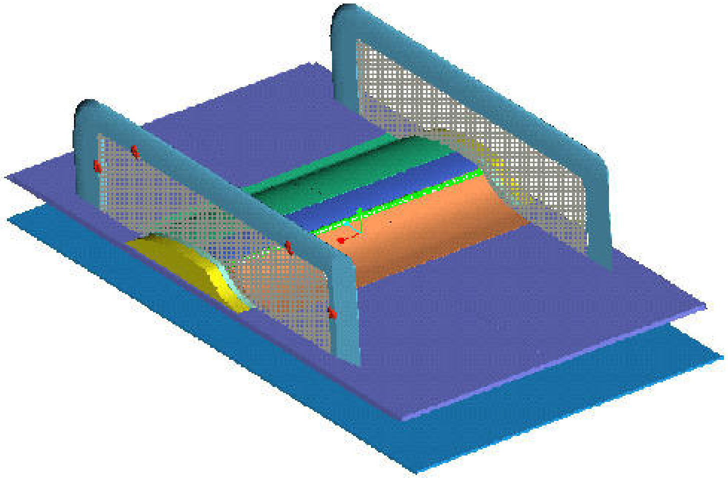


Case 3

Flow over a hump model

13 contributors
56 separate cases

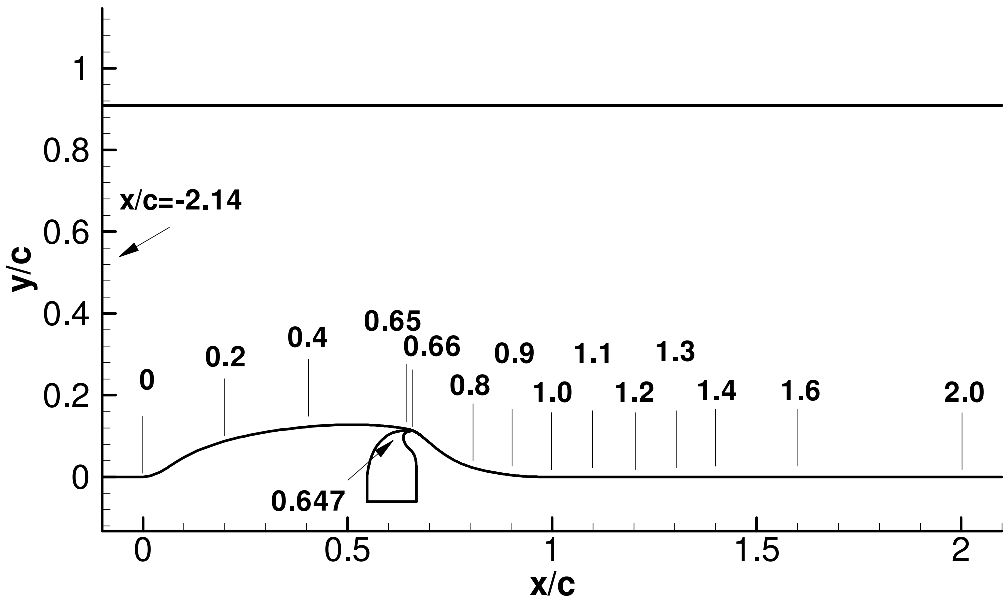


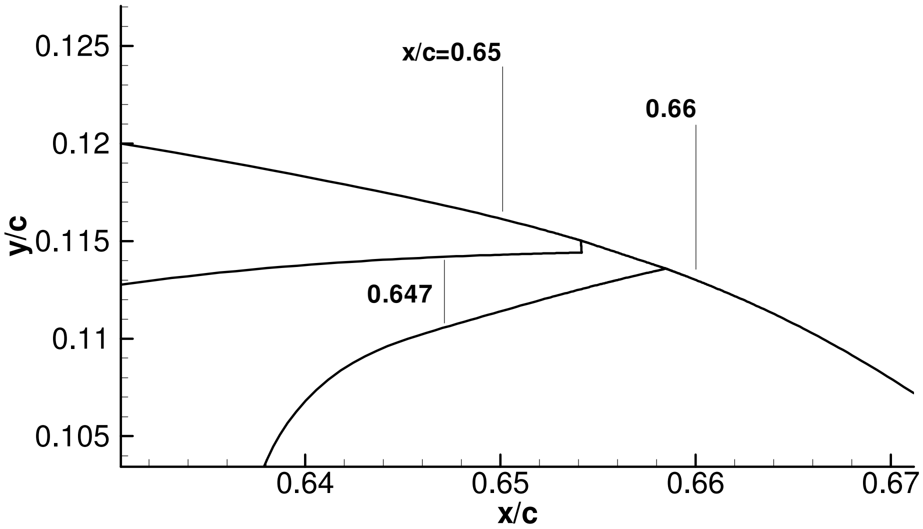


Case 3 Details

- Flow over wall-mounted hump (chord = 420mm)
  - Slot near 65%c (close to where separation occurs)
  - Nominally 2-D flow – endplates at both sides
  - M=0.1
- Two mandatory test cases
  - No flow control (no flow through slot)
  - Steady suction (mdot = 0.01518 kg/s)
- One optional test case
  - Synthetic jet (138.5 Hz, peak velocity out of slot = 27m/s)
  - Driven by bottom-mounted piston deep inside cavity

Sketch of case 3 comparison locations

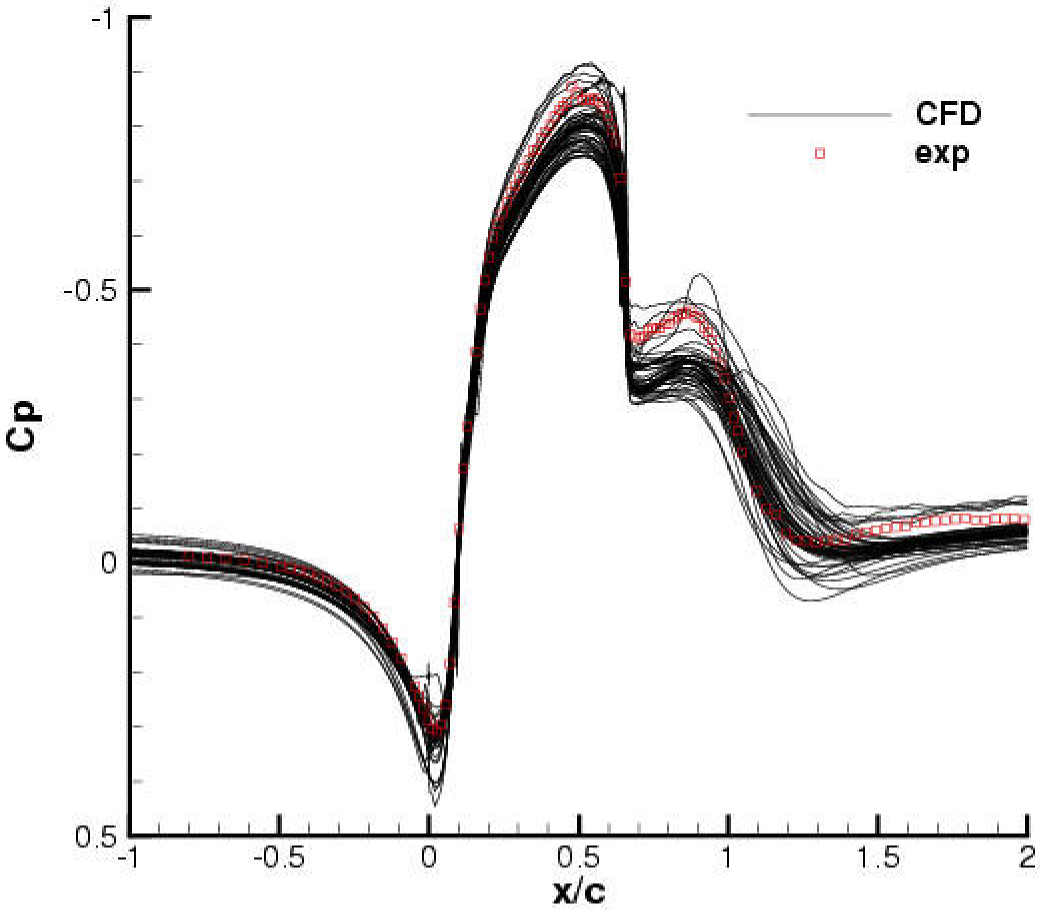




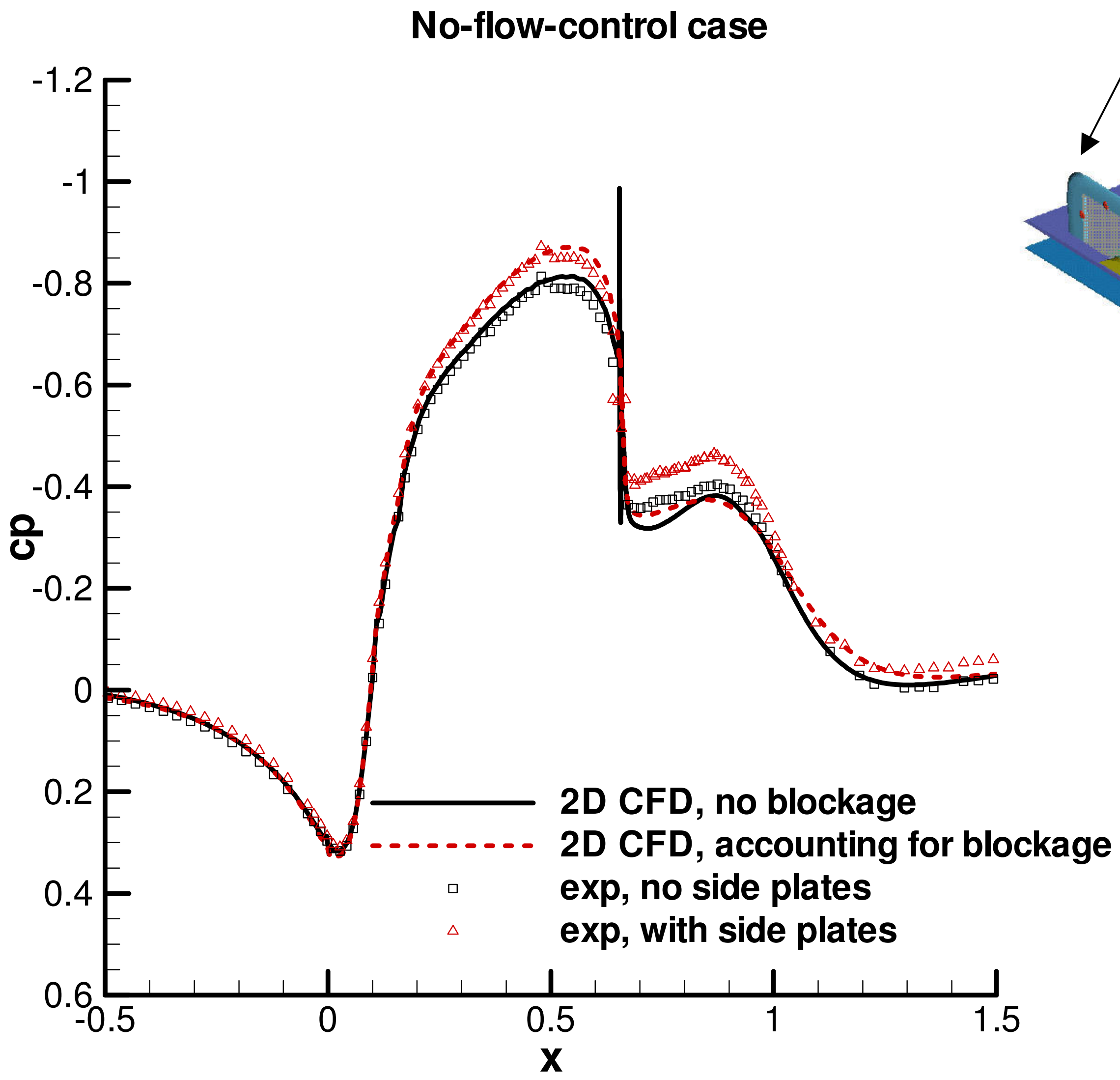
Methodologies

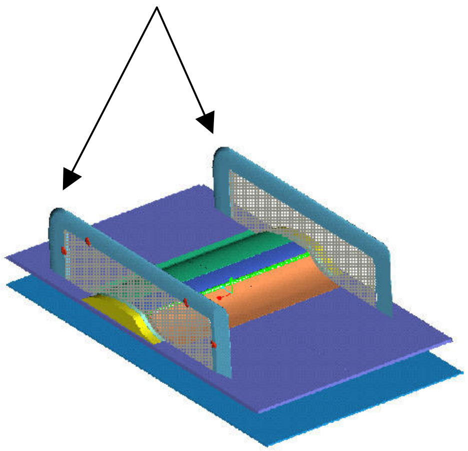
- Structured & unstructured RANS (various turbulence models: SA, SST, k-e, k-o, cubic k-e, EASM, v2f)
- Mostly 2nd order in space (some 4th order)
- A few blended RANS/LES (DES, LNS, FSM)
- 1 DNS (under-resolved near wall)
- Mostly 2-D; some 3-D
- Most modeled cavity, several did not
- Many parametric variations performed; 2-D grids were generally very well-resolved

No-flow-control Cp's



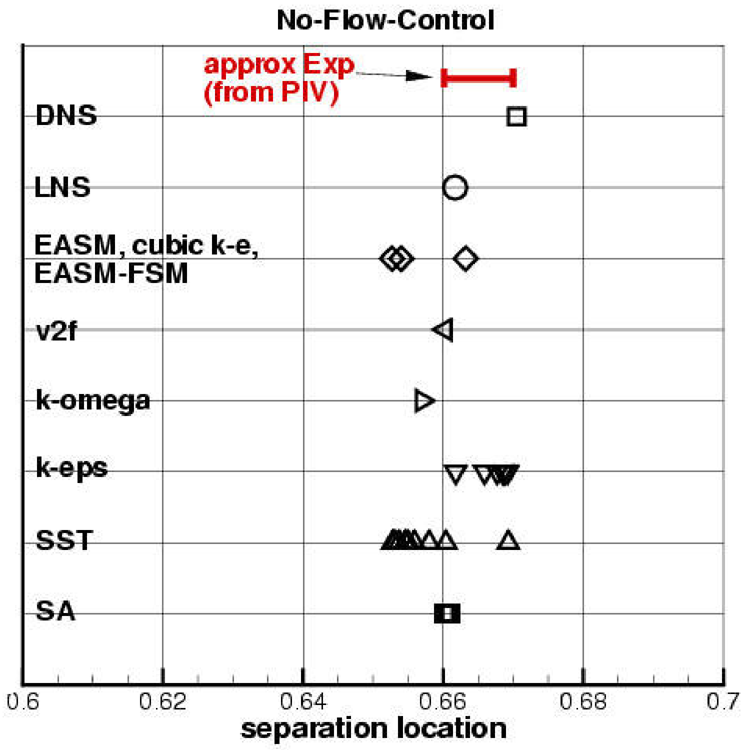
Blockage due to side plates

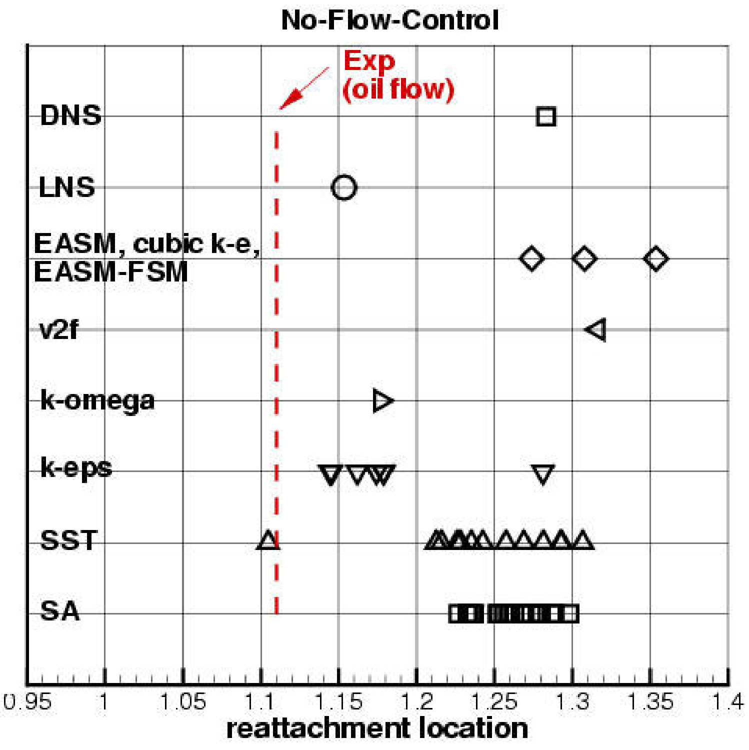




Separation and reattachment locations

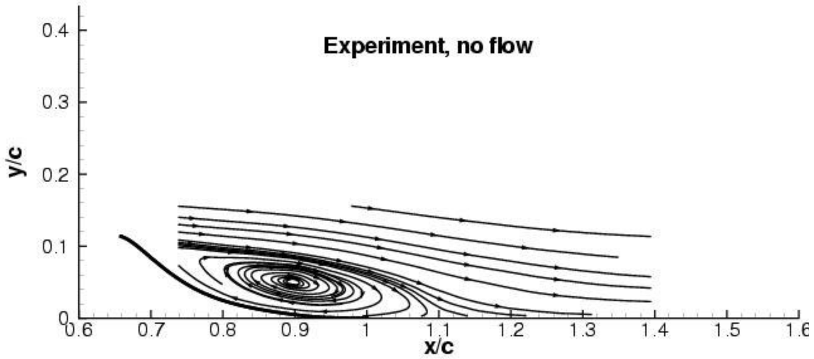
no-flow-control case



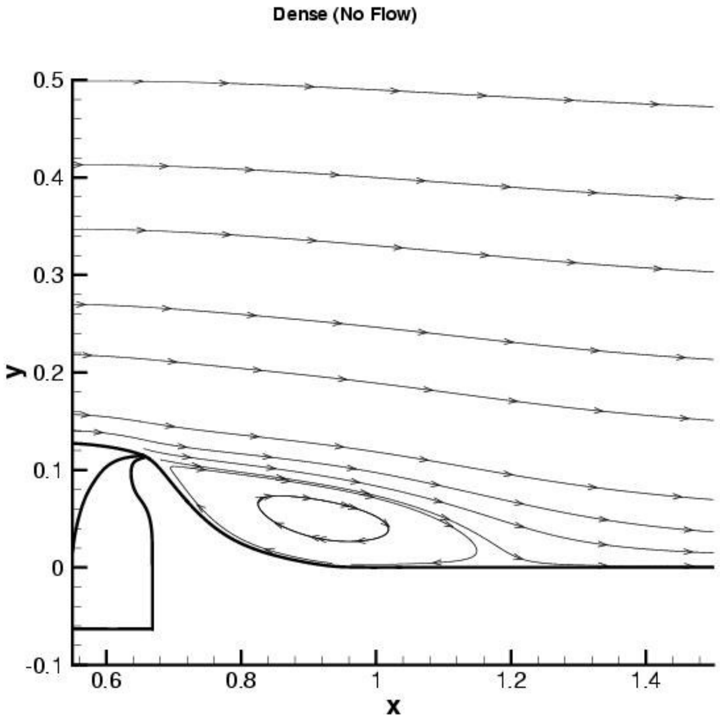


Example no-flow-control streamlines

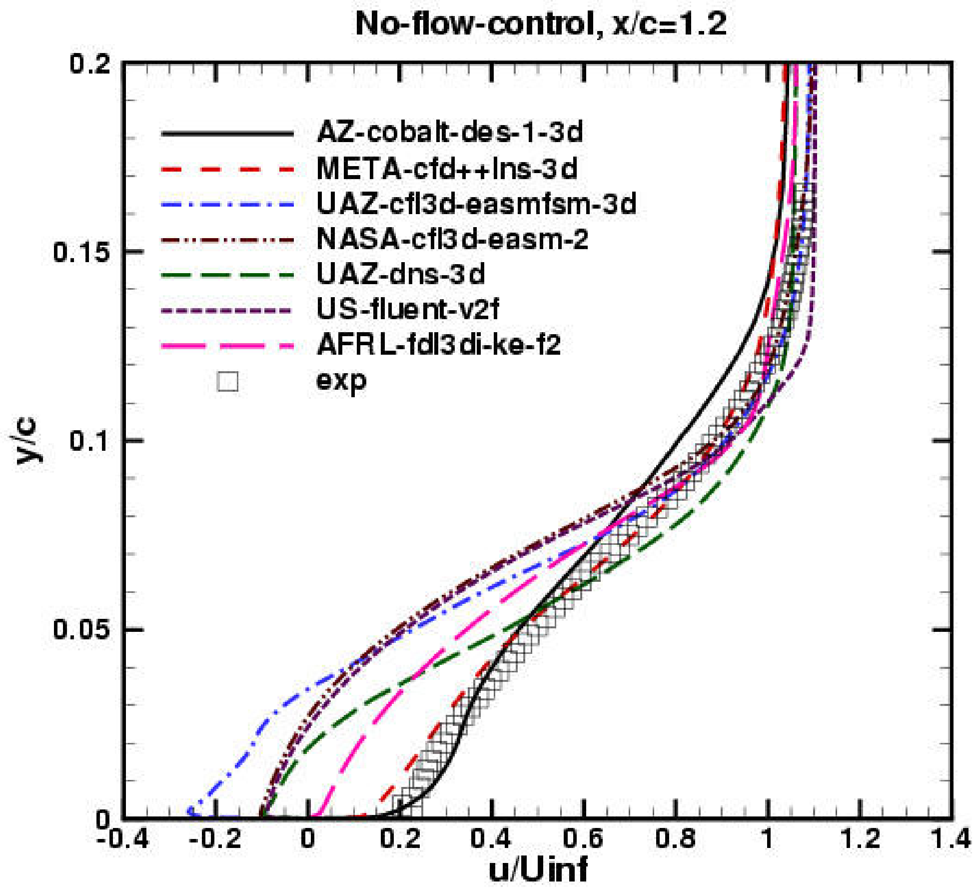
Experiment

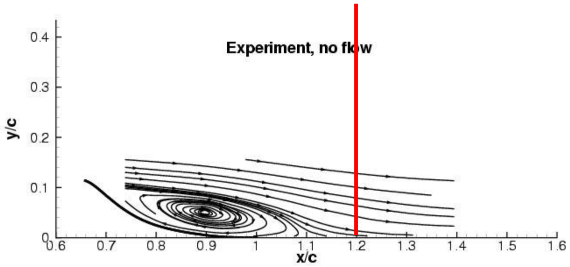


UK-ghost-sst-1

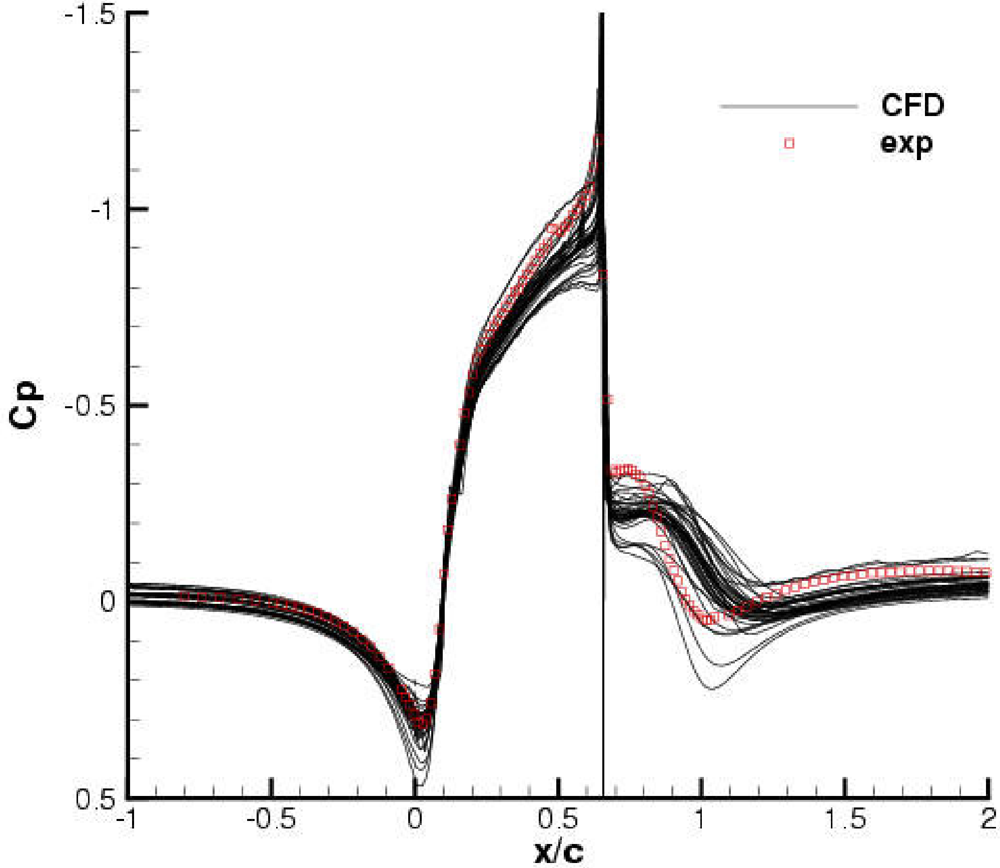


Sample u-velocity profiles at x/c=1.2
(downstream of experimental reattachment)



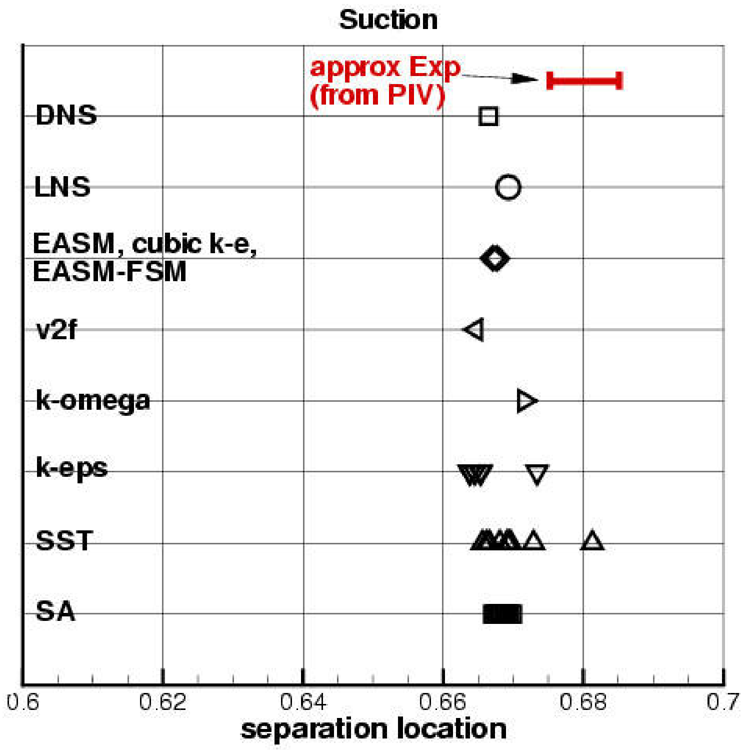


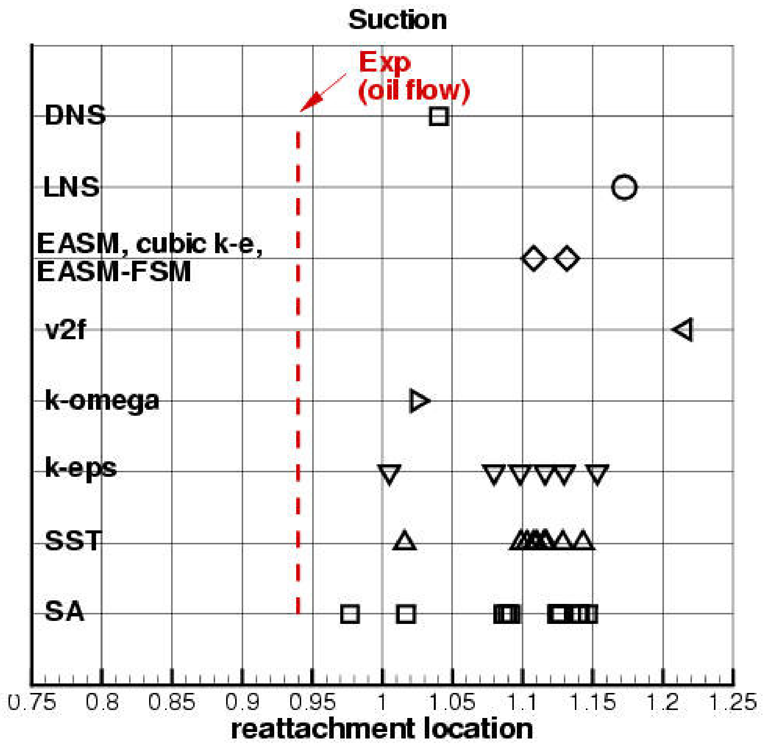
Suction Cp's



Separation and reattachment locations

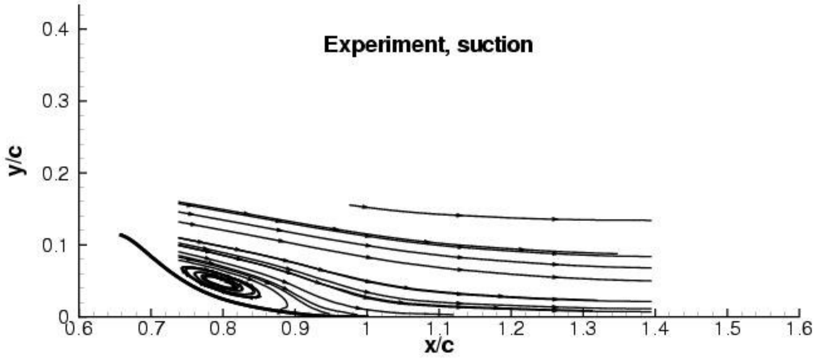
suction case



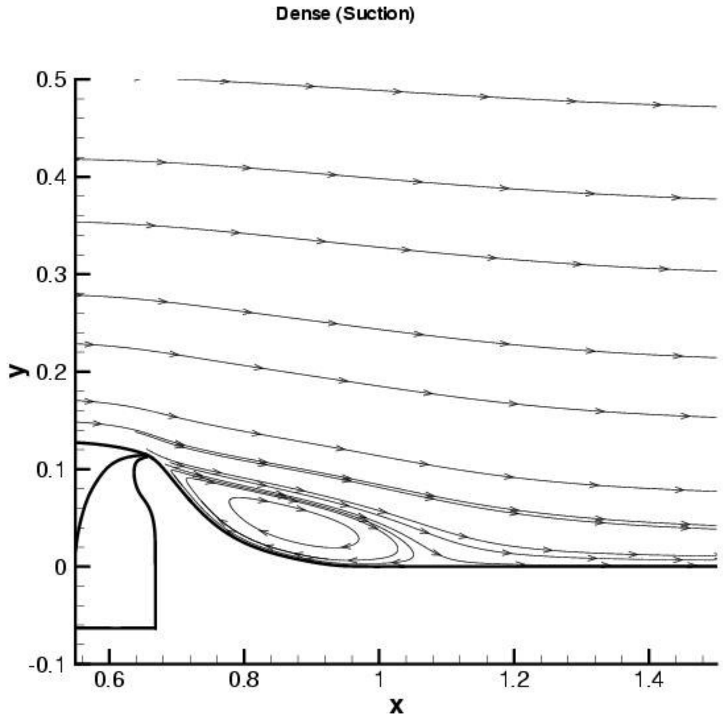


Example suction streamlines

Experiment

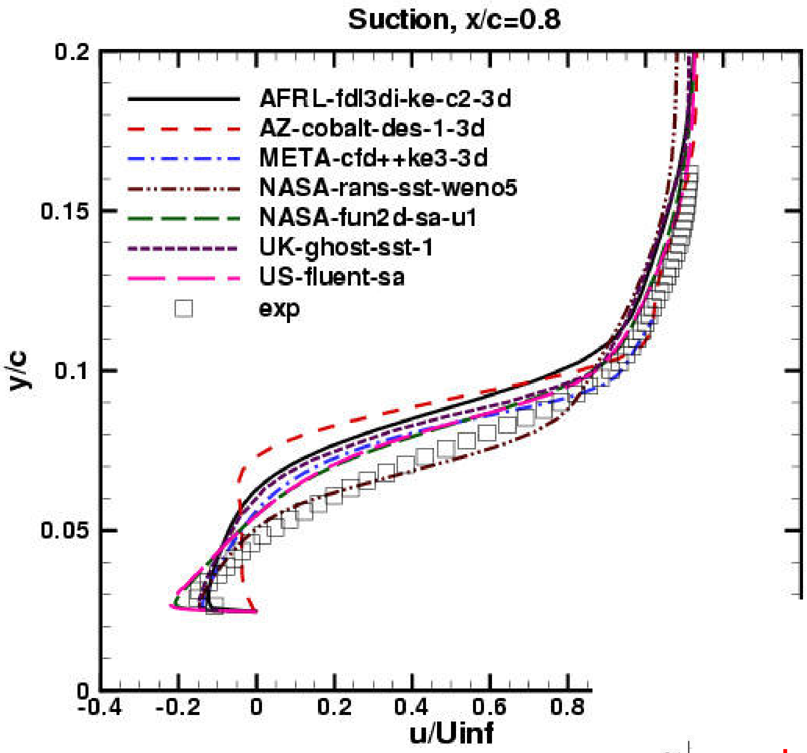


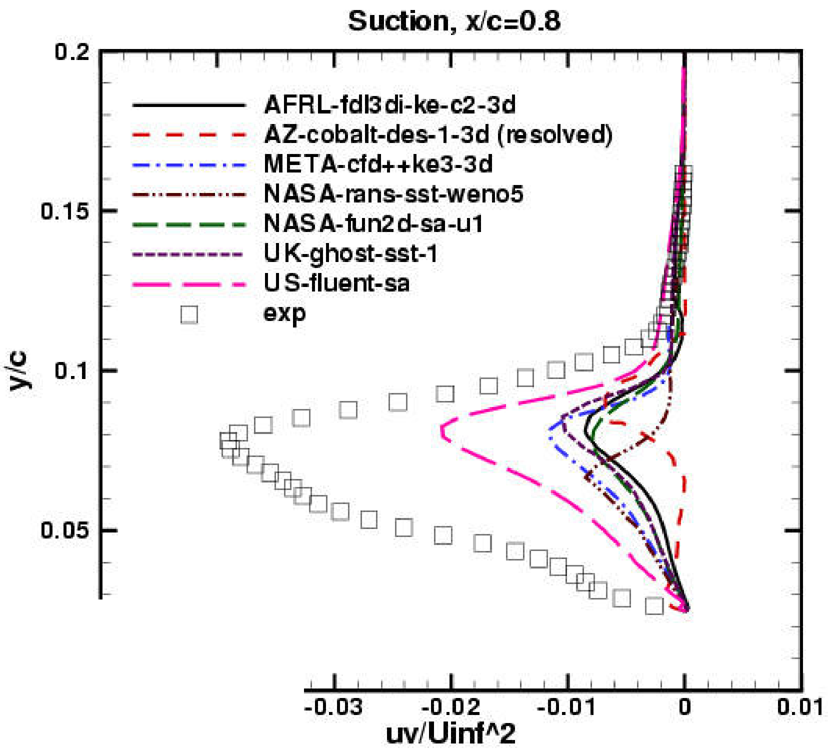
UK-ghost-sst-1

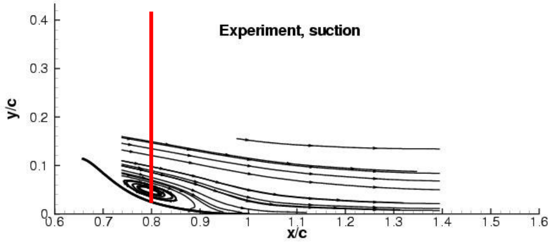


Velocity and turbulent shear stress at x/c=0.8

(inside separation bubble)

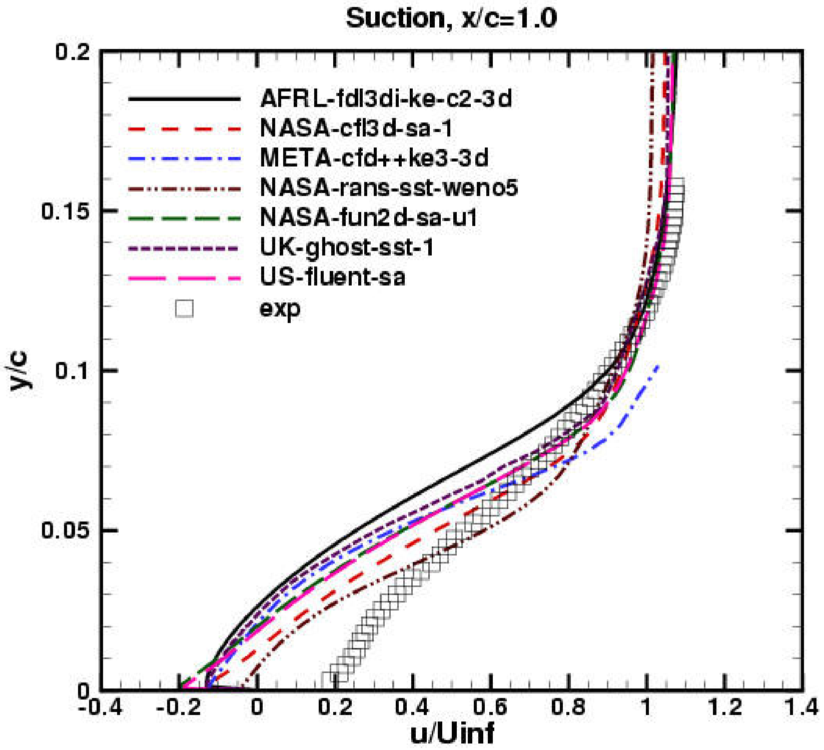


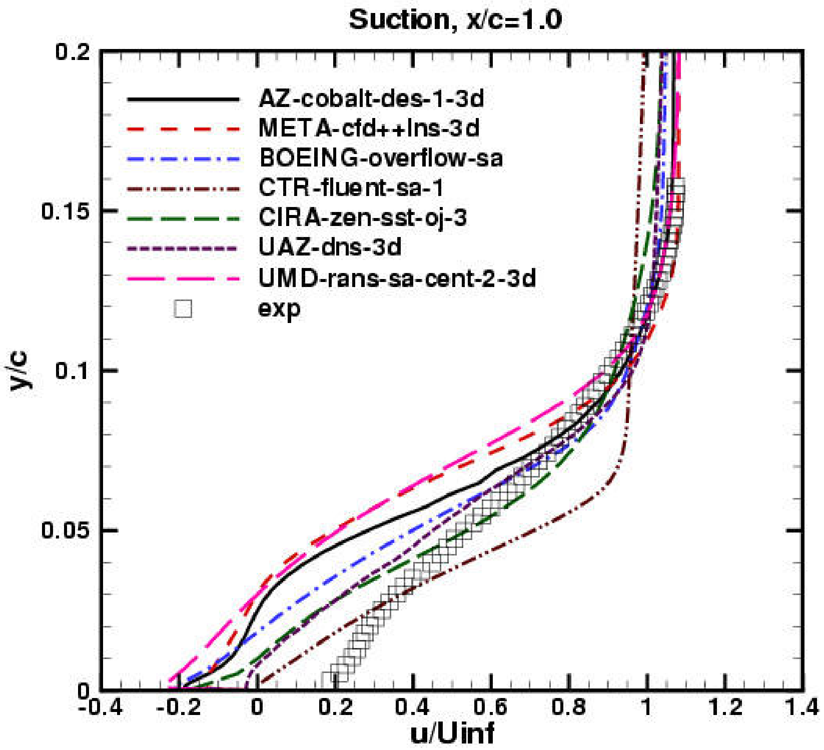


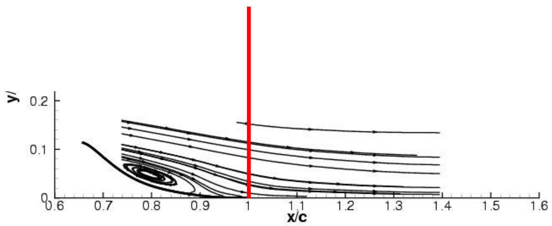


Sample u-velocity profiles at x/c=1.0

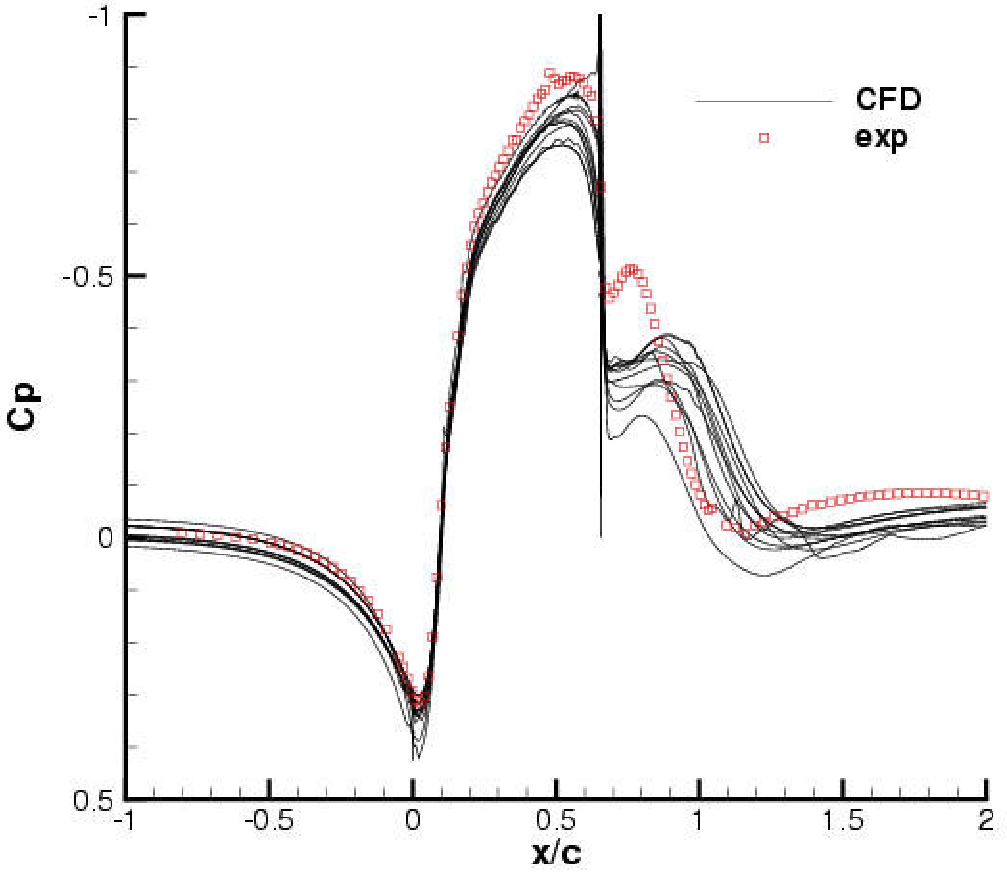
(downstream of experimental reattachment)







Mean oscillatory-case Cp's



11th ERCOFTAC/IAHR Turbulence Modeling Workshop Results for Hump Model Case

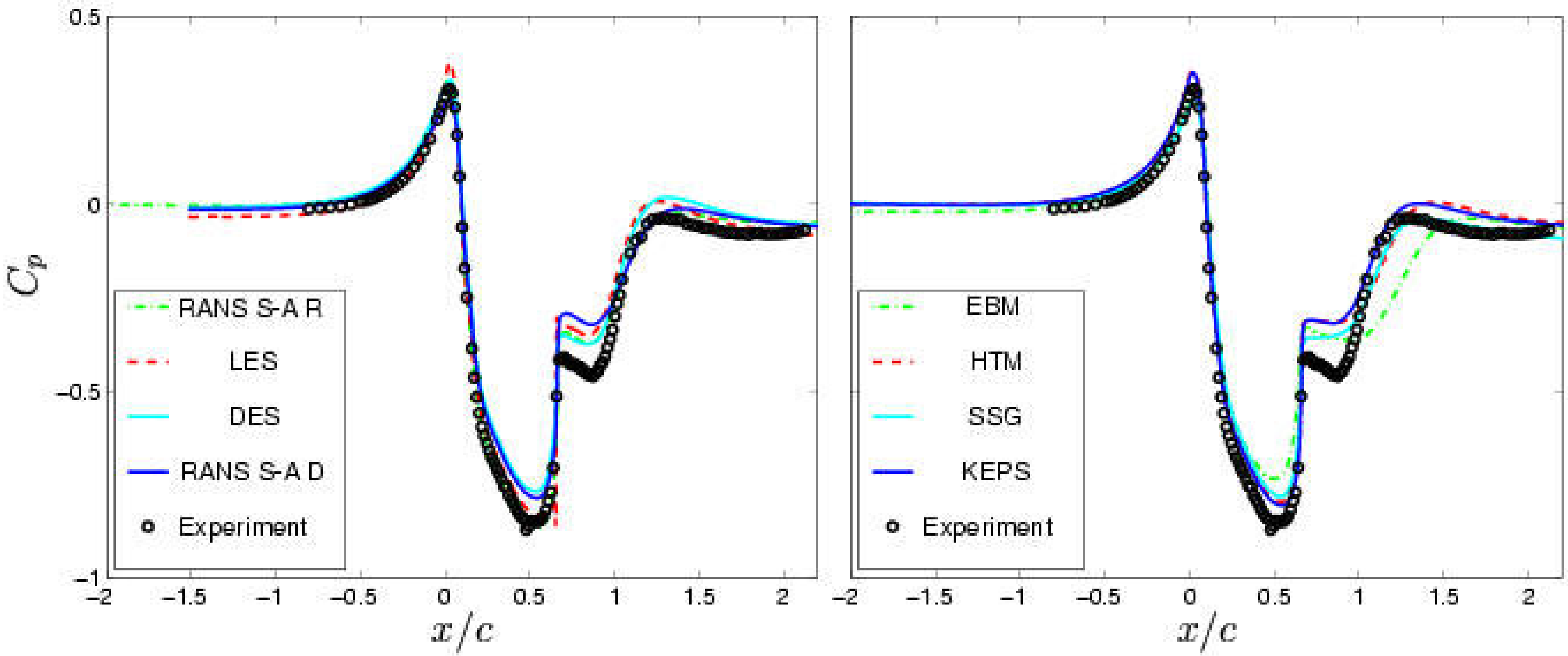
April 2005

Methodologies

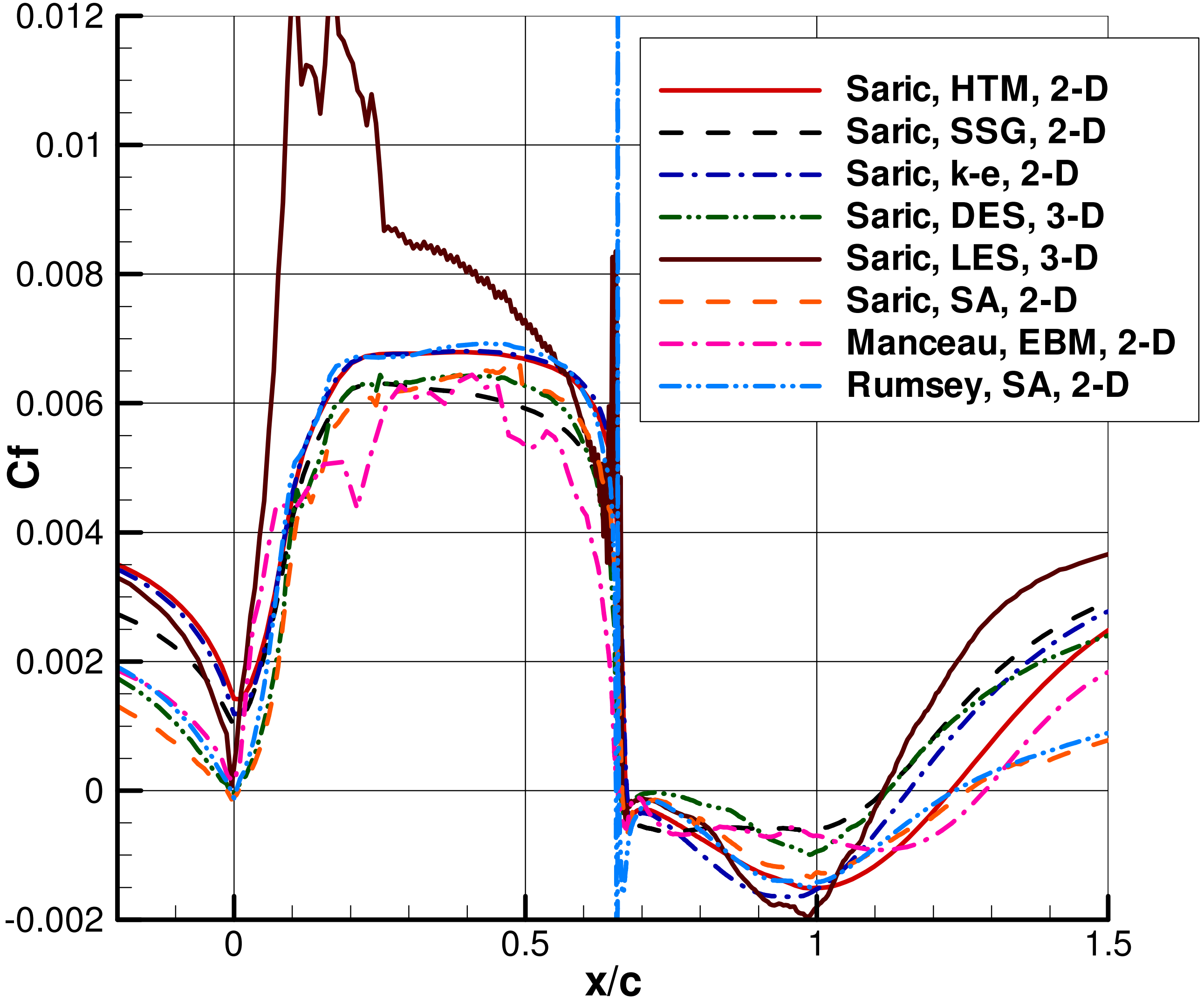
- RANS
  - S-A
  - k-epsilon
  - hybrid k-epsilon+SSG
  - RSM (elliptic blending model)
  - RSM (SSG)
- 3-D DES
- 3-D LES (Smagorinsky)

(BLUE means new category of method, not used at CFDVAL2004)

Noflow, C_p

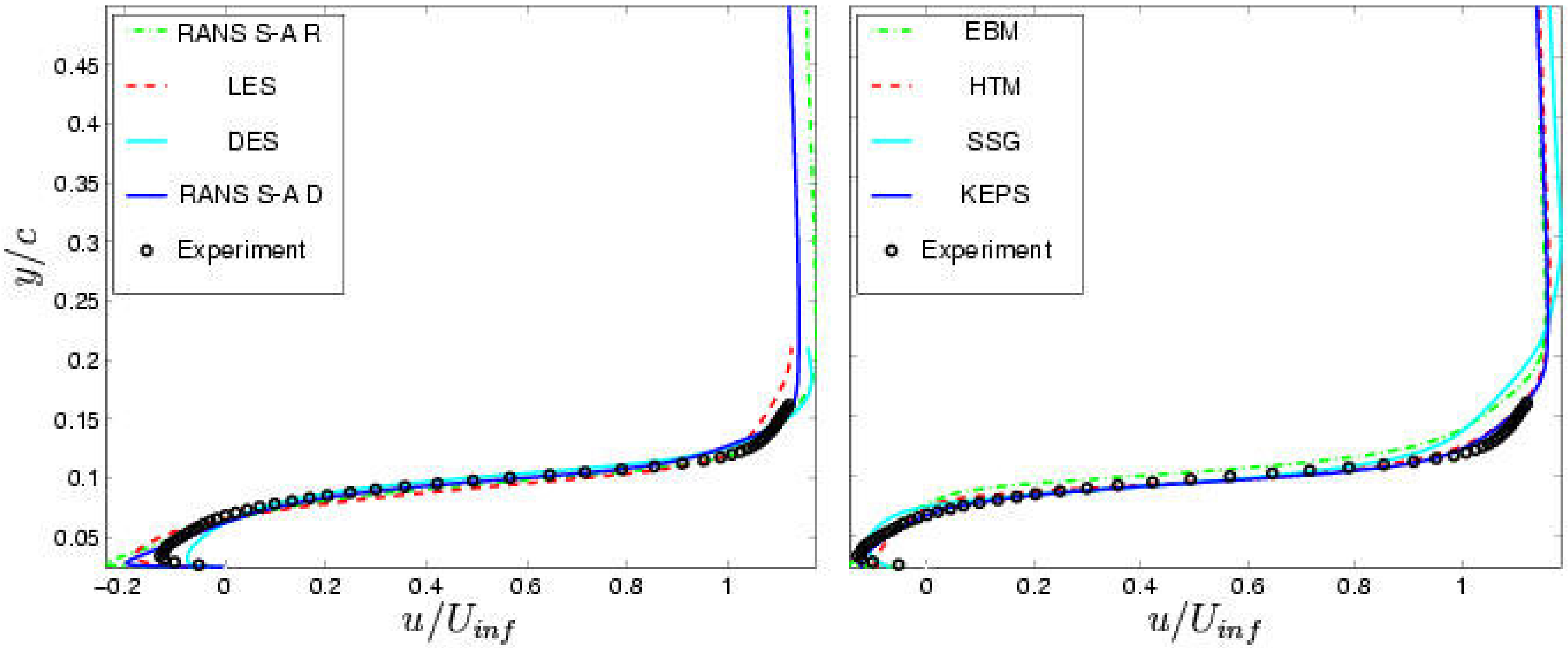

0.5
0
−0.5
−1
C_p
RANS S-A R
LES
DES
RANS S-A D
Experiment
EBM
HTM
SSG
KEPS
Experiment
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
x/c
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
x/c

Noflow, C_f

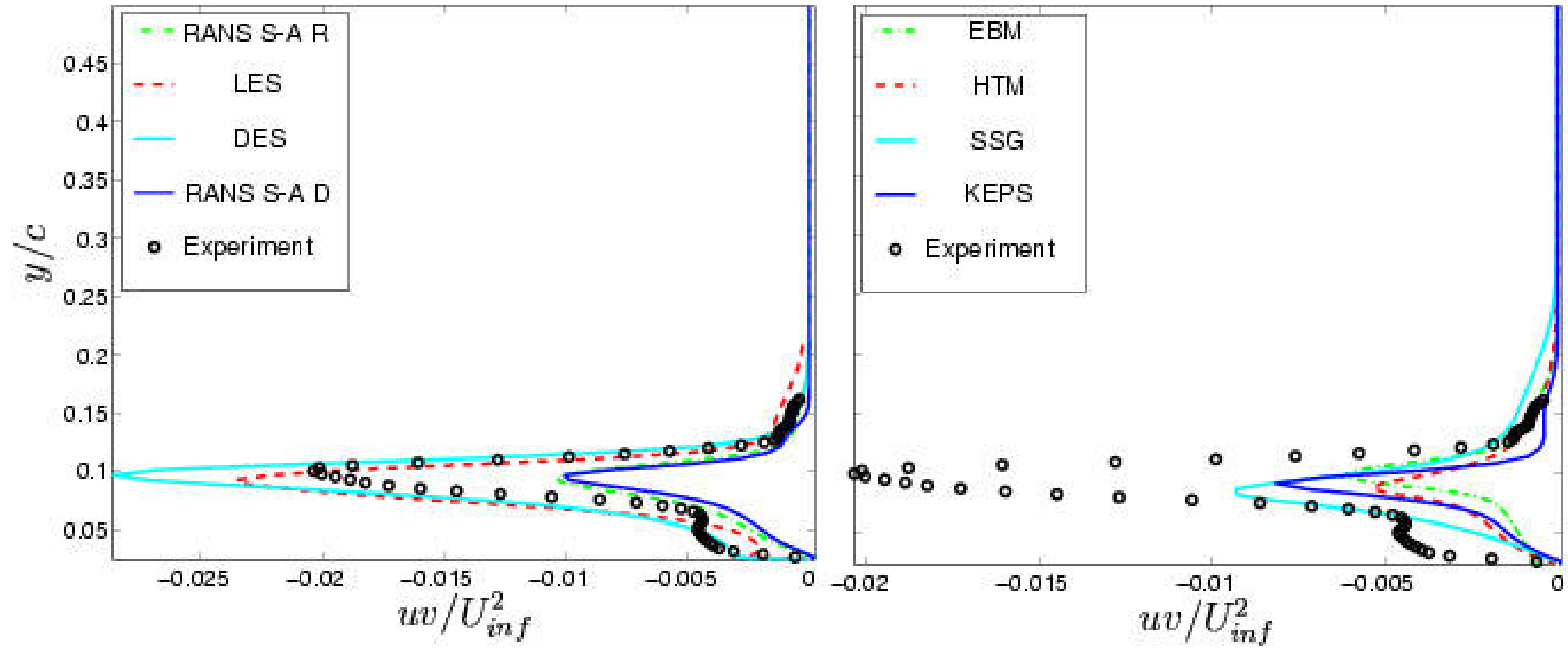


0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
Cf
0
0.5
1
1.5
x/c
Saric, HTM, 2-D
Saric, SSG, 2-D
Saric, k-e, 2-D
Saric, DES, 3-D
Saric, LES, 3-D
Saric, SA, 2-D
Manceau, EBM, 2-D
Rumsey, SA, 2-D

Noflow, $x/D = 0.8$

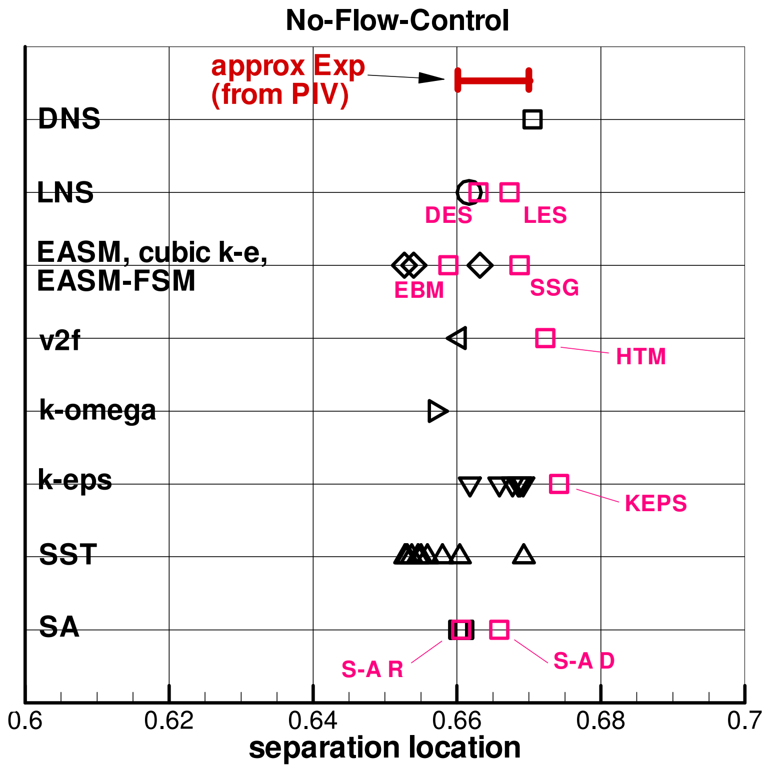

RANS S-A R
LES
DES
RANS S-A D
Experiment
y/c
u/U_inf
EBM
HTM
SSG
KEPS
Experiment
u/U_inf

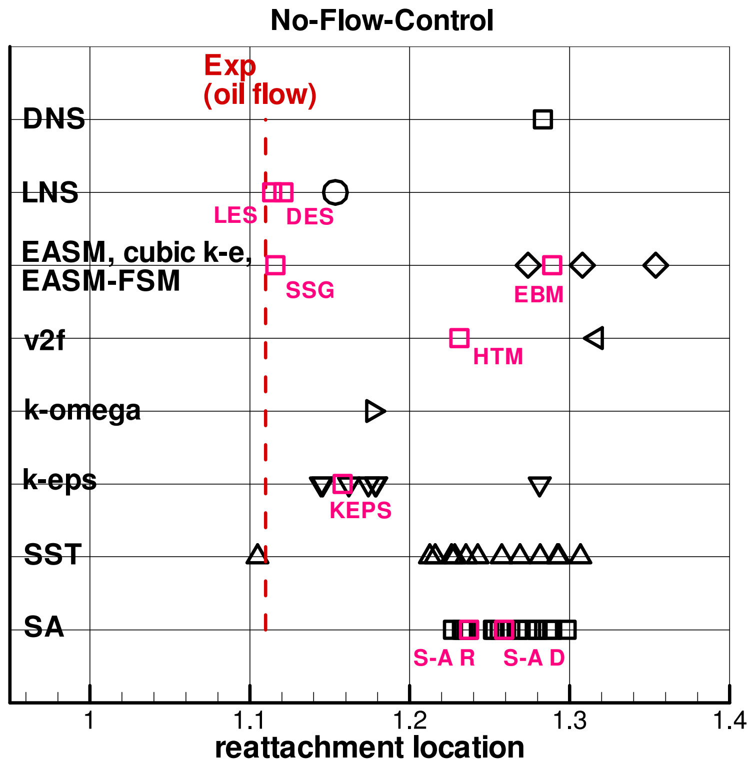
Noflow, $x/D = 0.8$


RANS S-A R
LES
DES
RANS S-A D
Experiment
EBM
HTM
SSG
KEPS
Experiment
y/c
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
−0.025
−0.02
−0.015
−0.01
−0.005
0
uv/U²_inf
−0.02
−0.015
−0.01
−0.005
0
uv/U²_inf

Separation and reattachment locations

no-flow-control case





Sample u-velocity profiles at x/c=1.2

(downstream of experimental reattachment)

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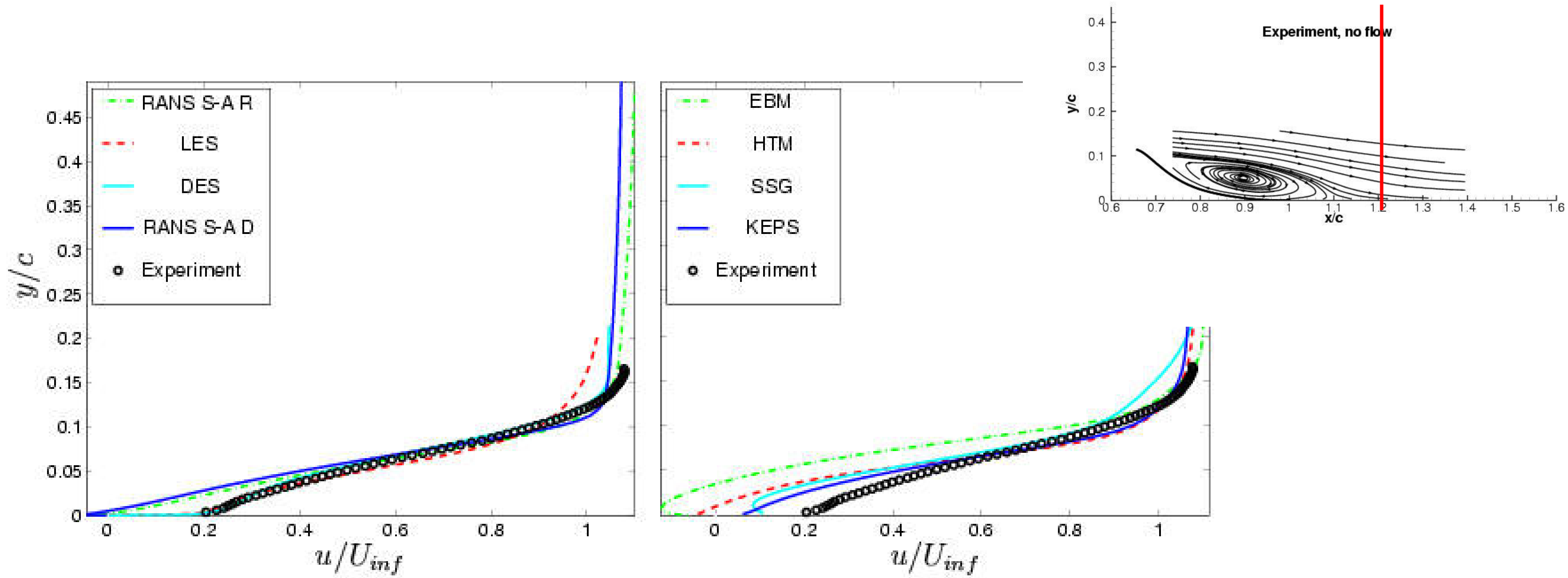
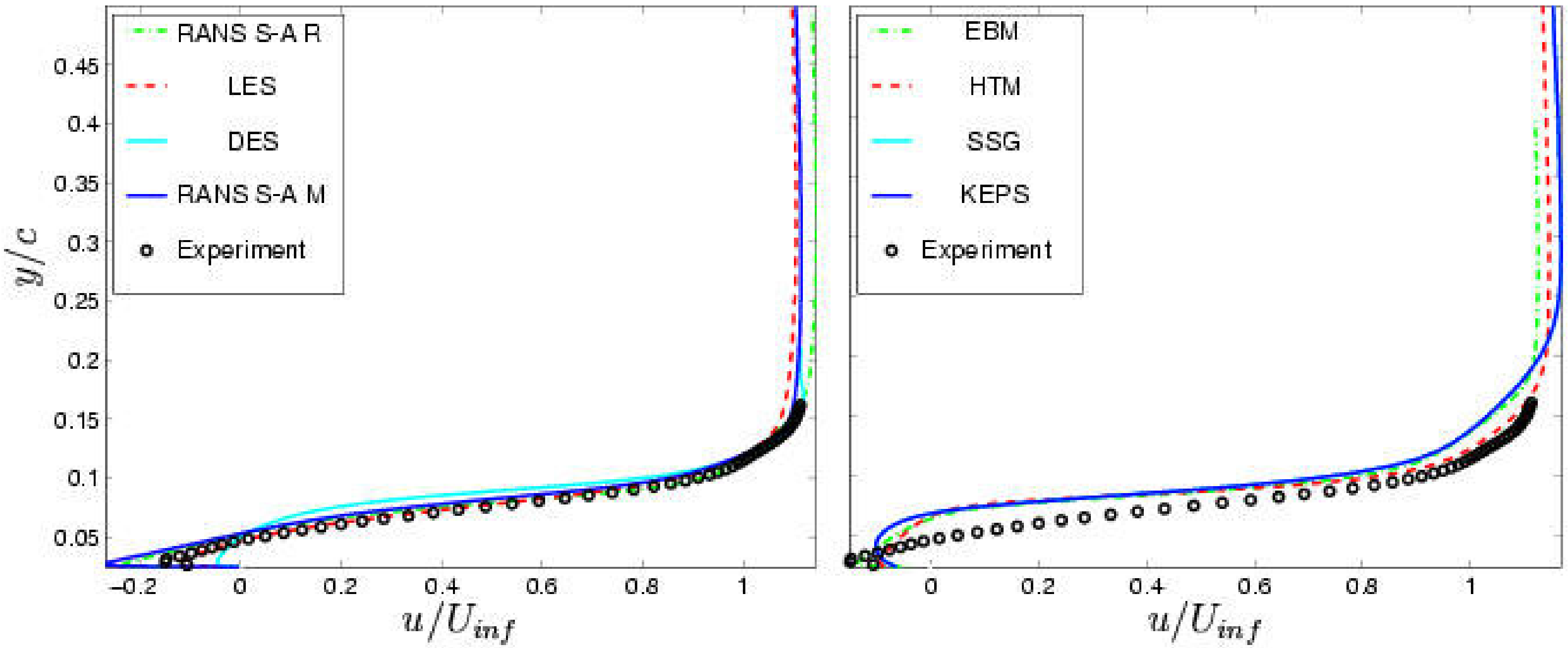
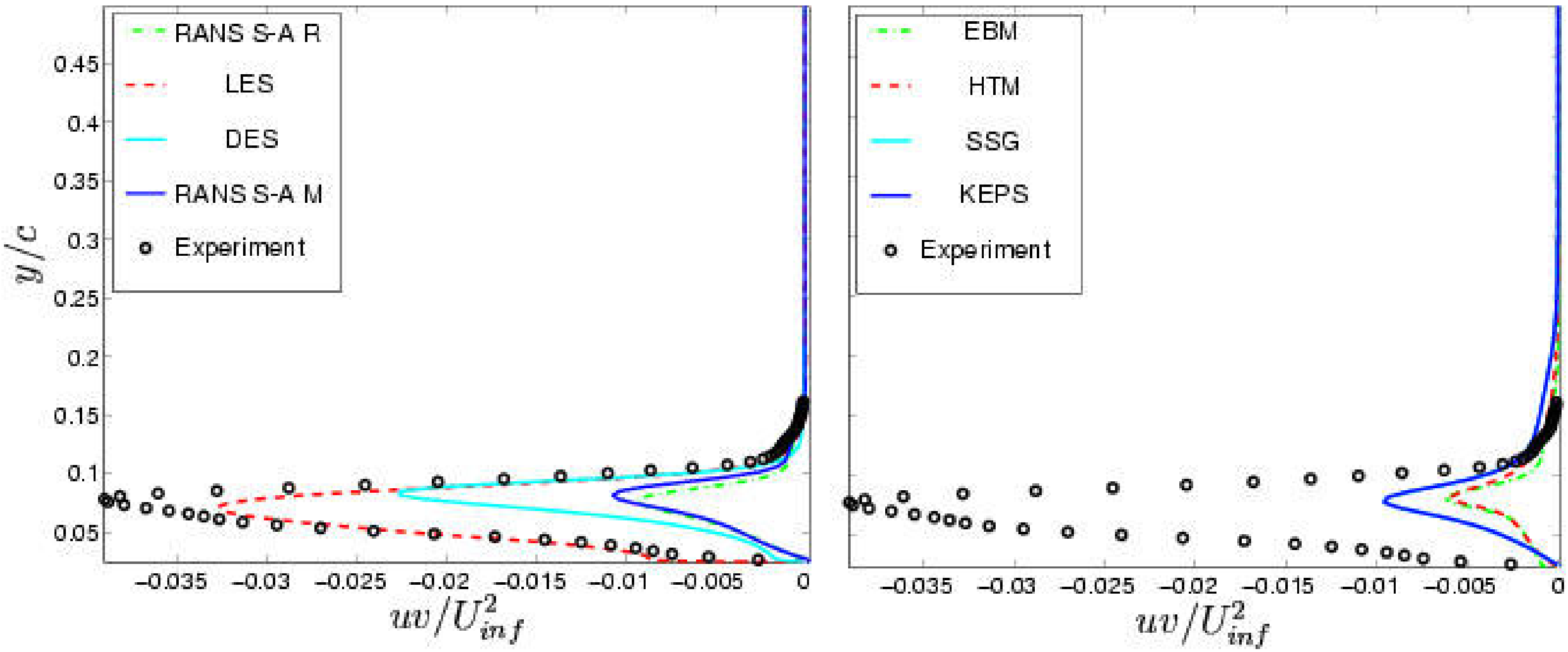
Noflow, $x/D = 1.2$



Suction, $x/D = 0.8$

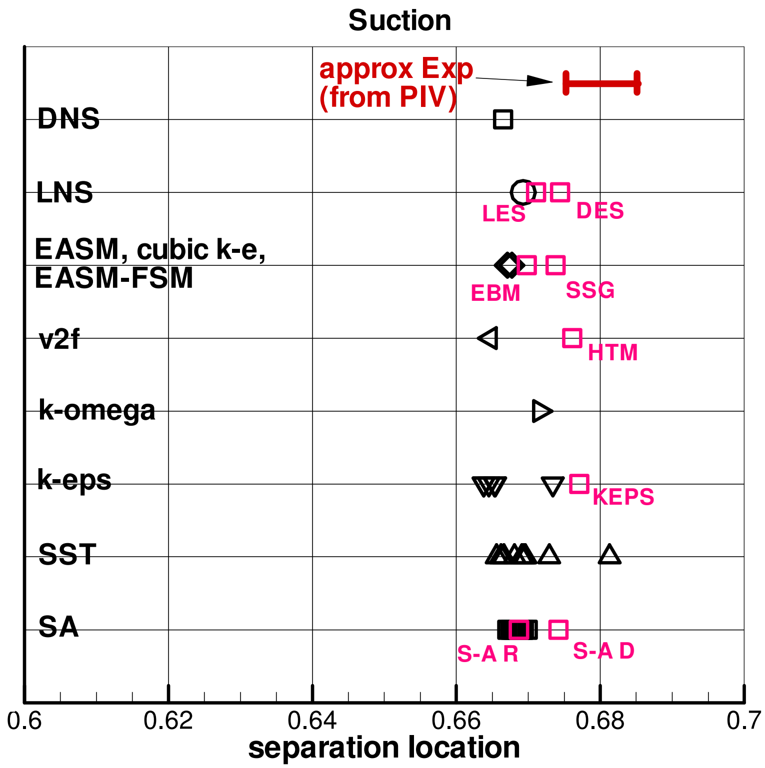


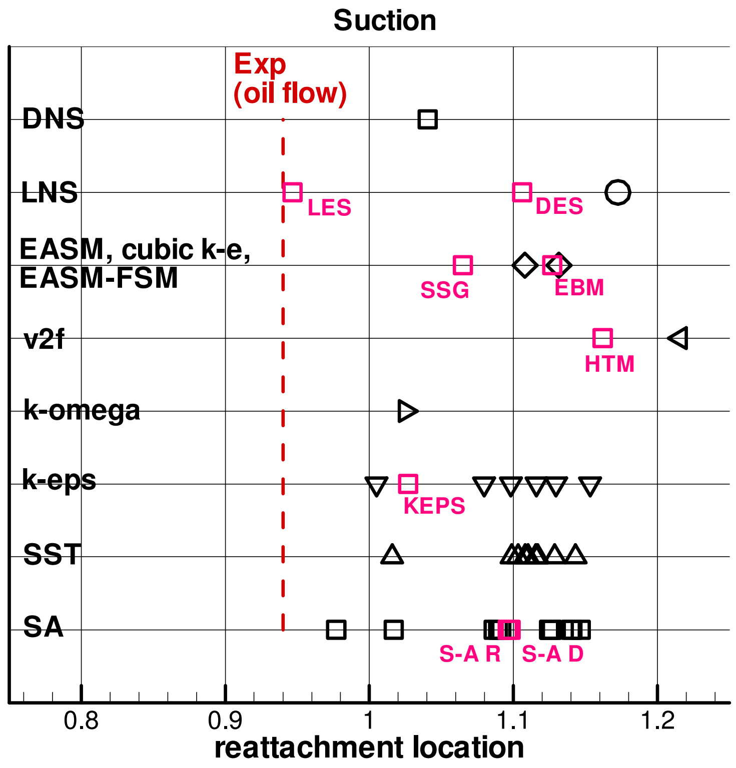
Suction, $x/D = 0.8$



Separation and reattachment locations

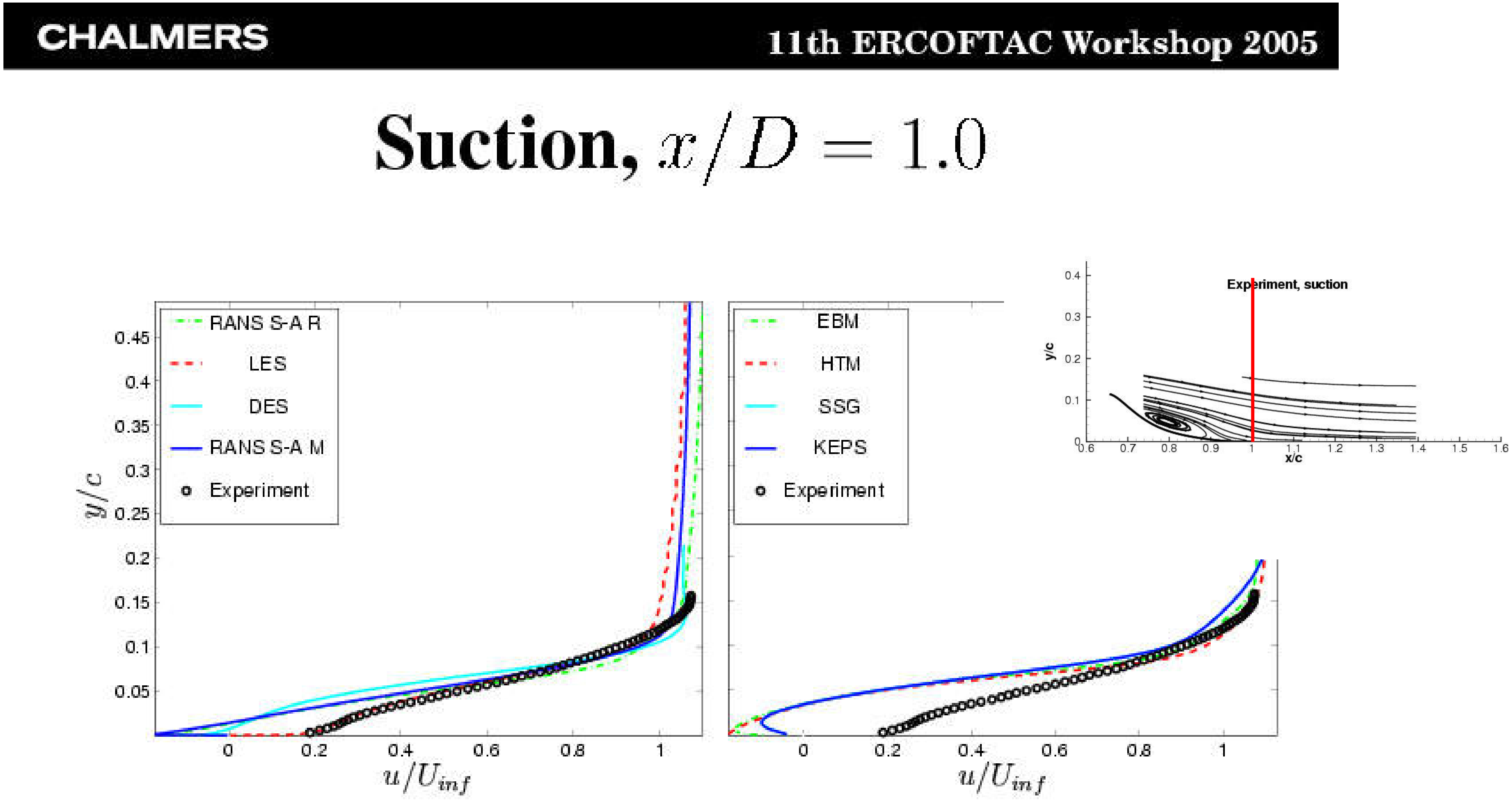
suction case





Sample u-velocity profiles at x/c=1.0

(downstream of experimental reattachment)



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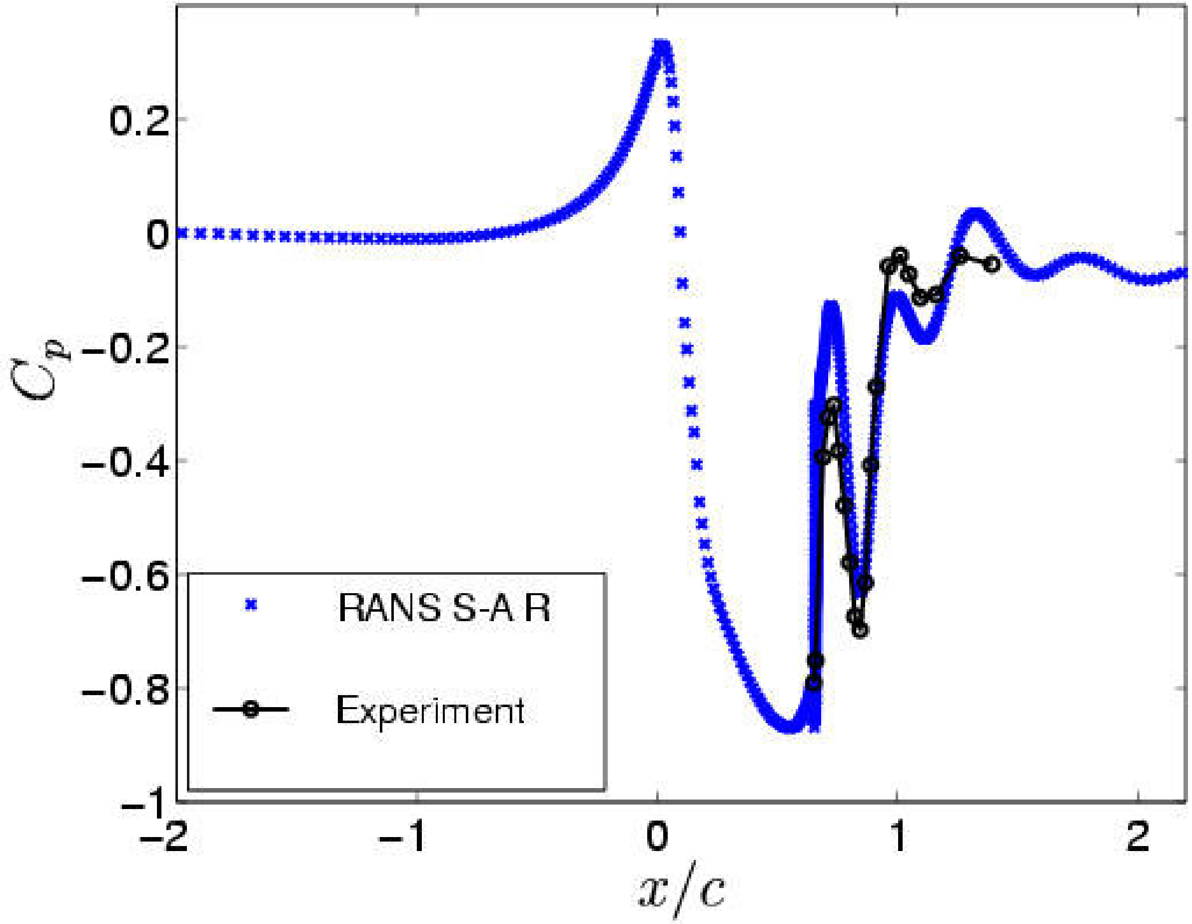
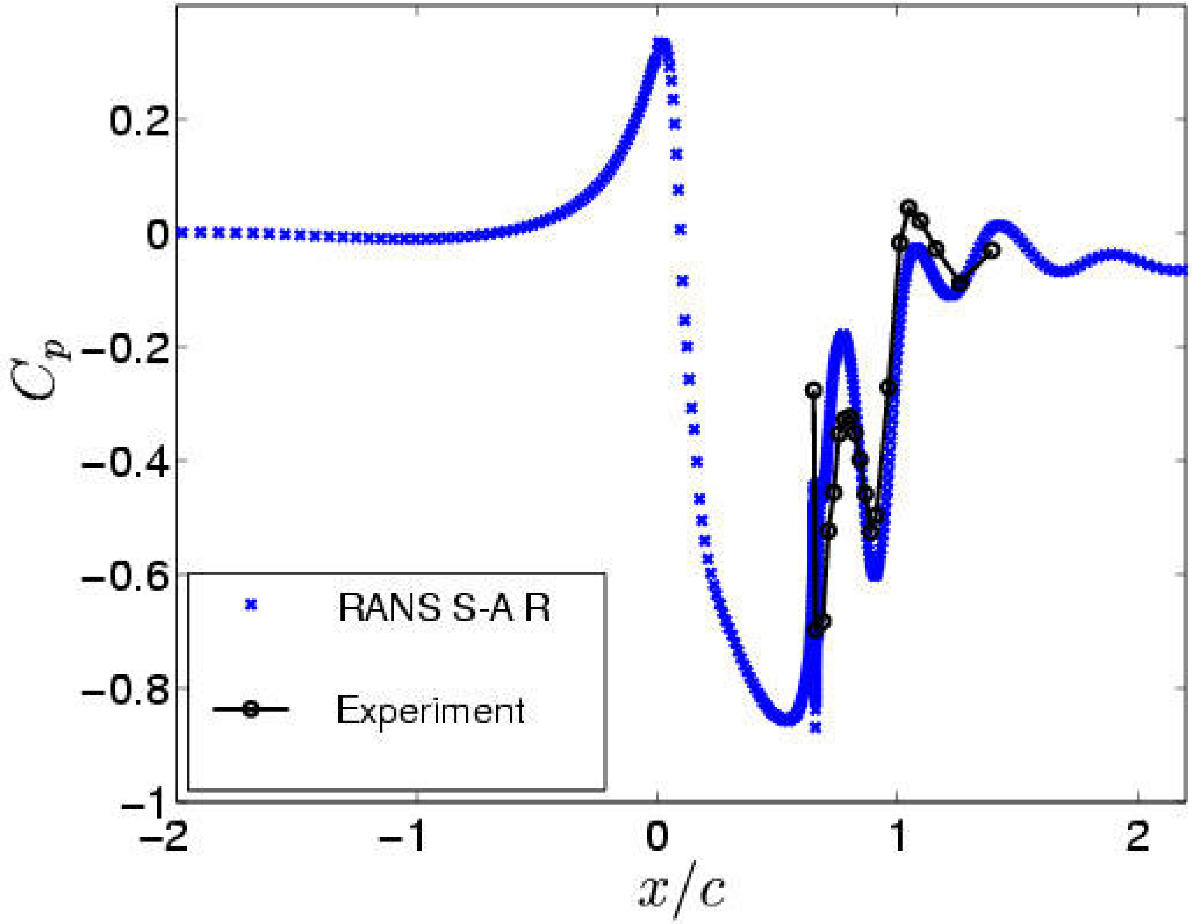
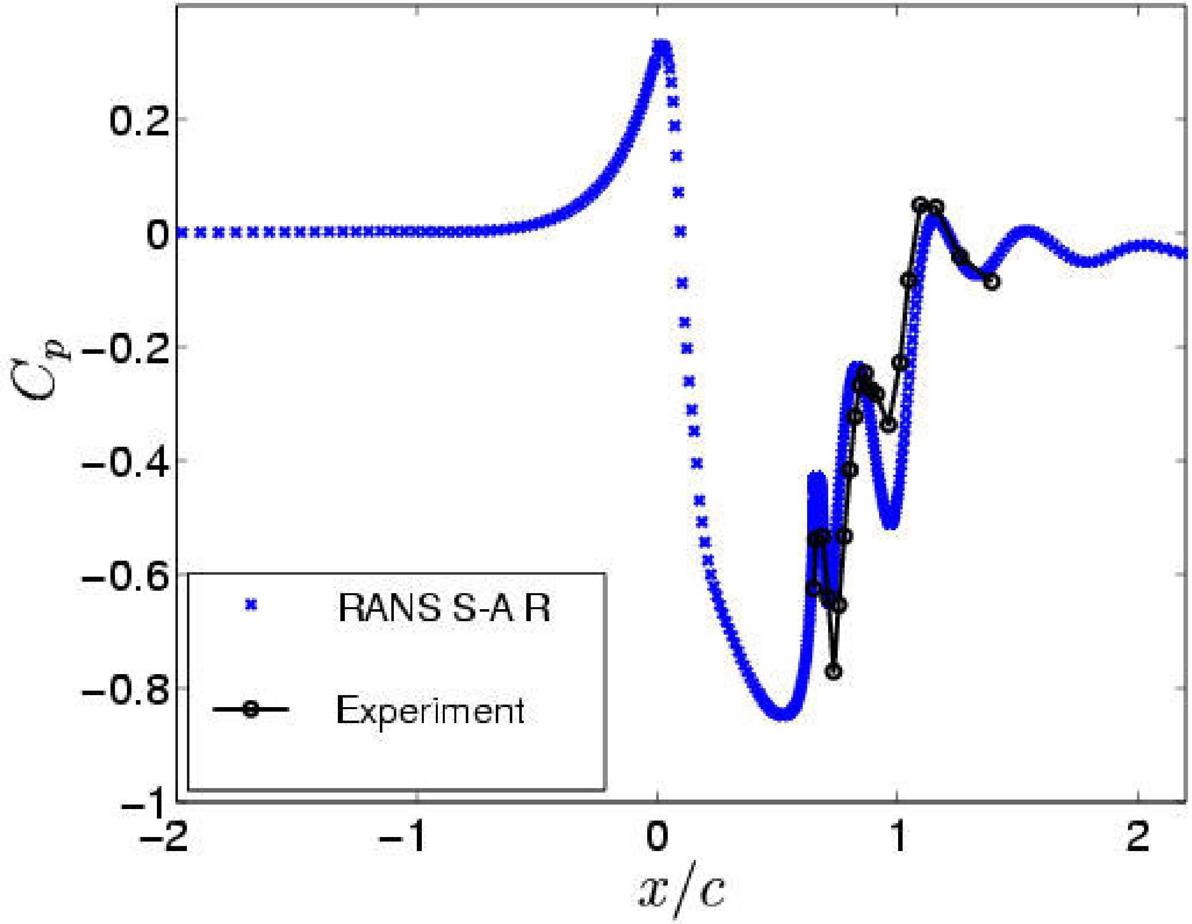
Oscillatory 80^o, C_p



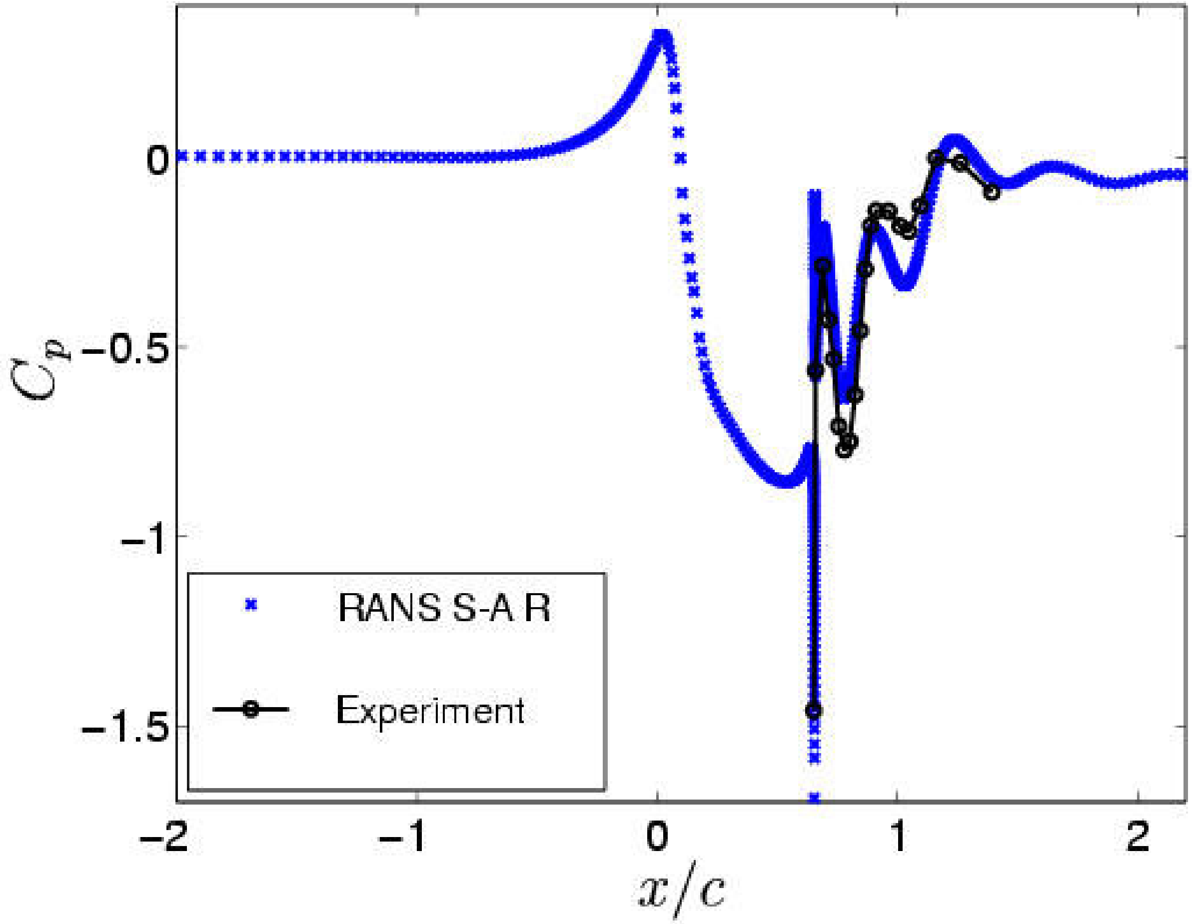
Oscillatory 170^o, C_p



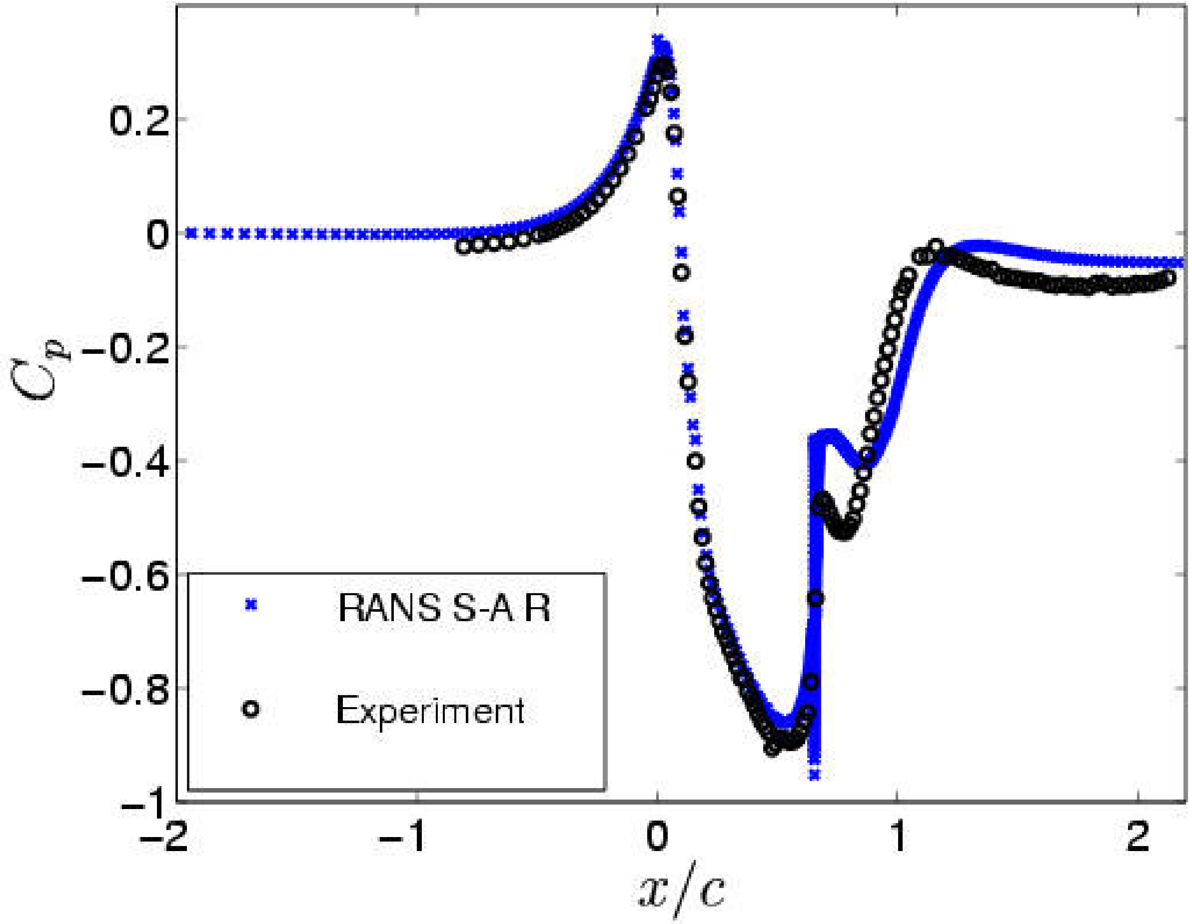
Oscillatory 260^o, C_p



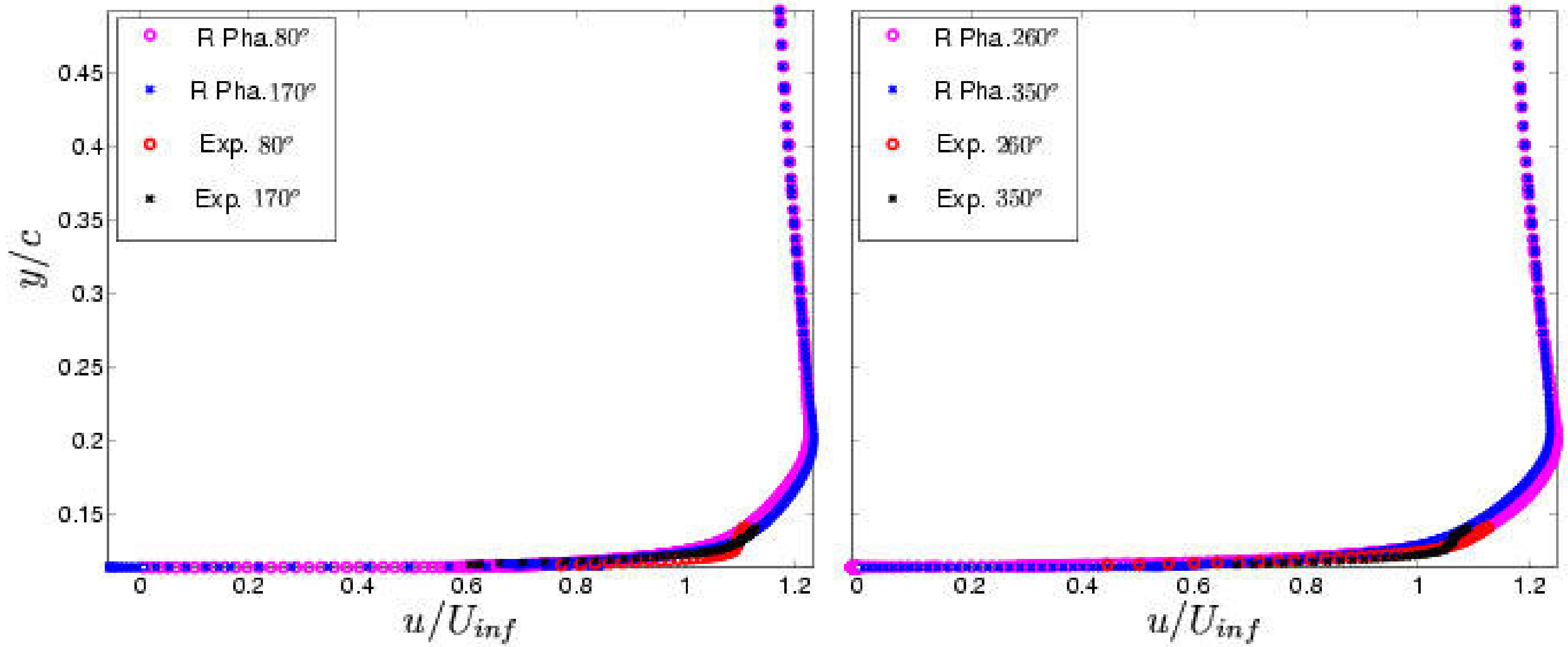
Oscillatory 350^o, C_p



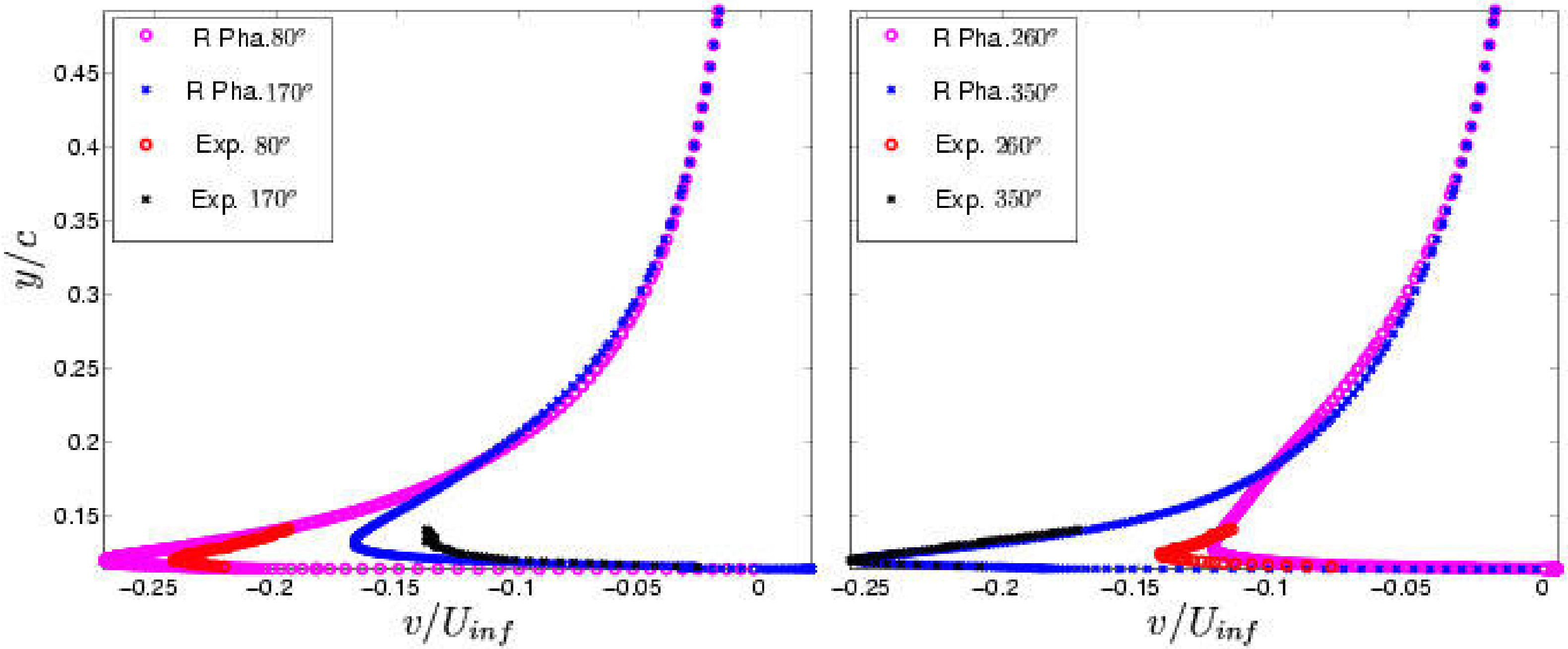
Oscillatory, C_p
(long-time average)



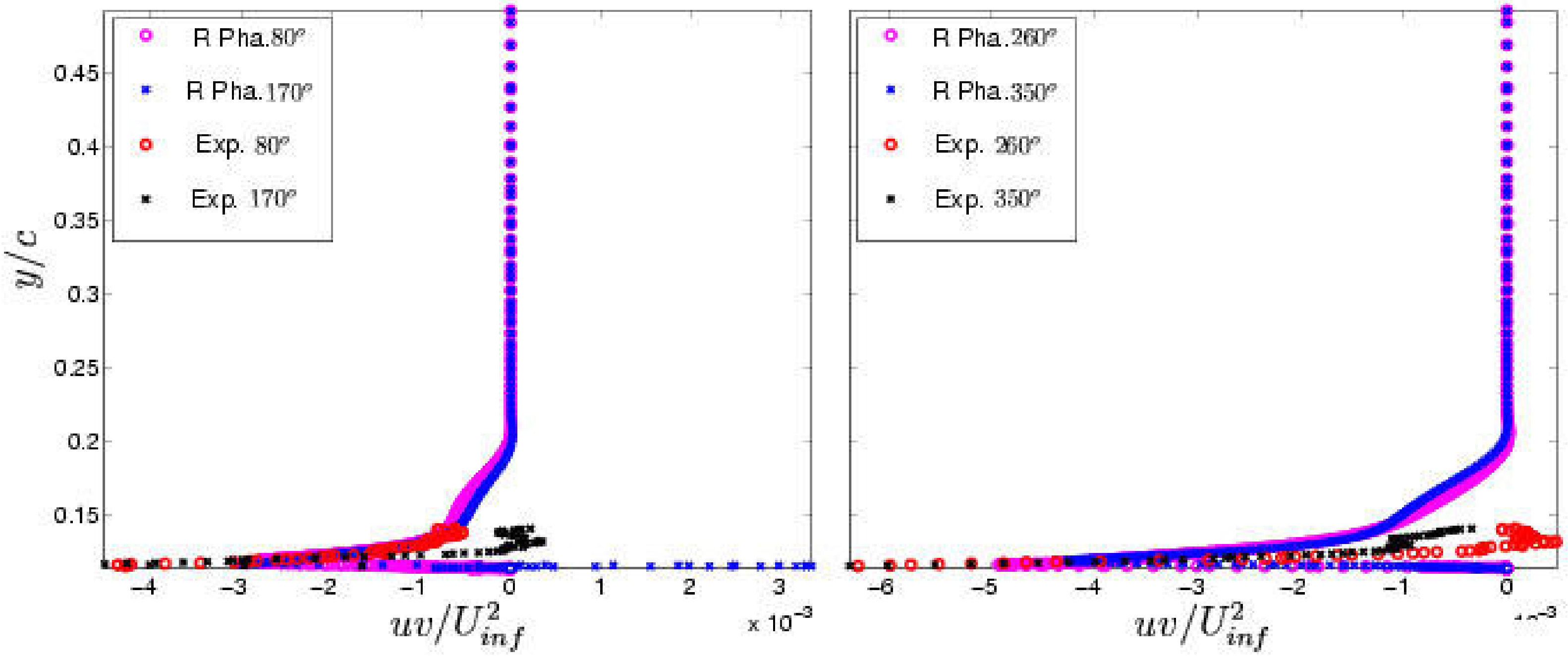
Oscillatory Slot, $x/c = 0.66$



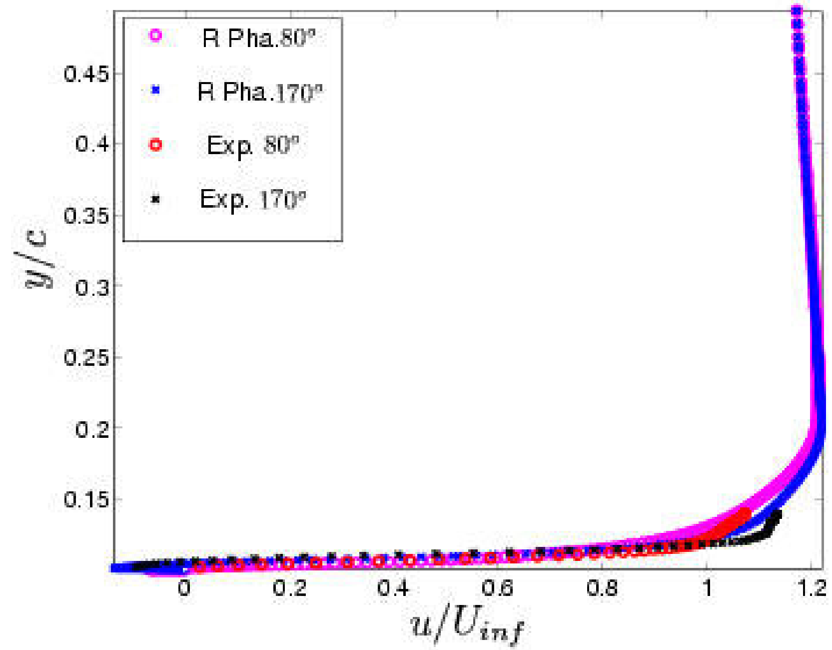
Oscillatory Slot, $x/c = 0.66$

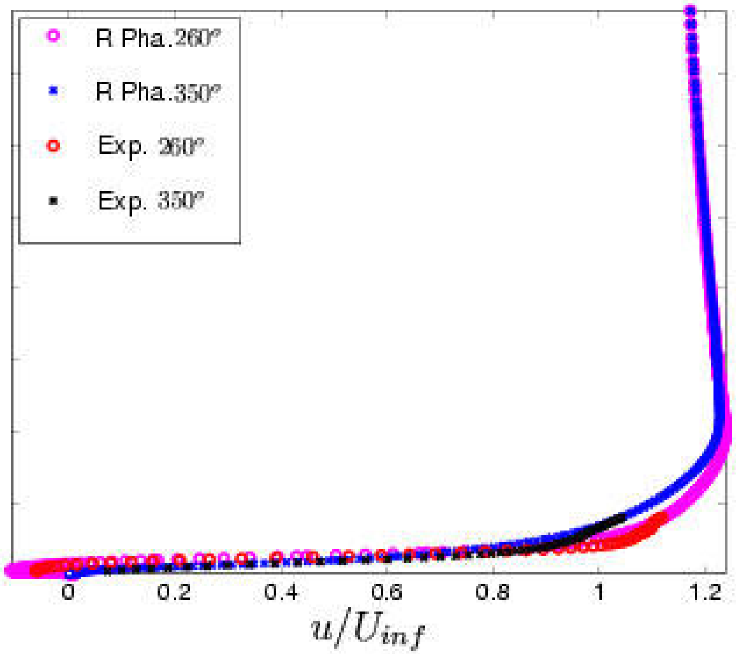


Oscillatory Slot, $x/c = 0.66$

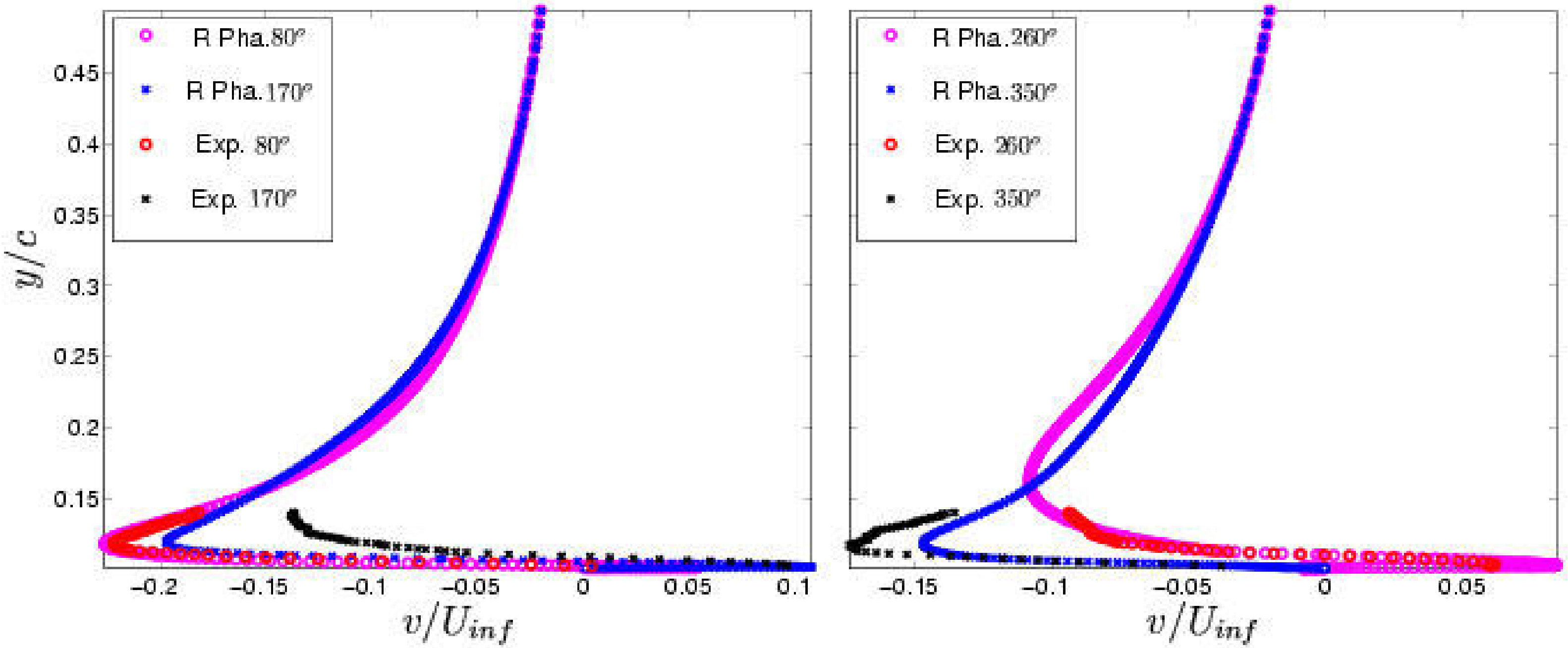


Oscillatory Slot, $x/c = 0.68$

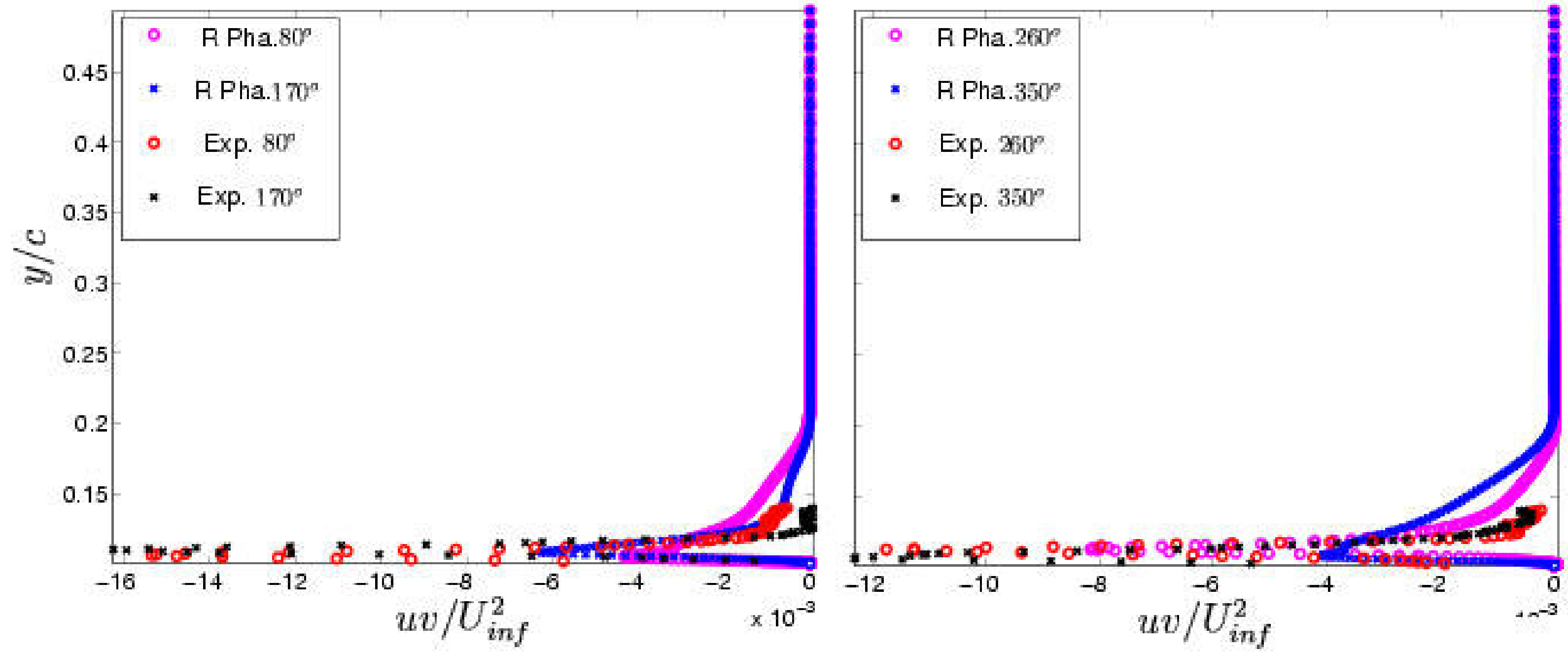




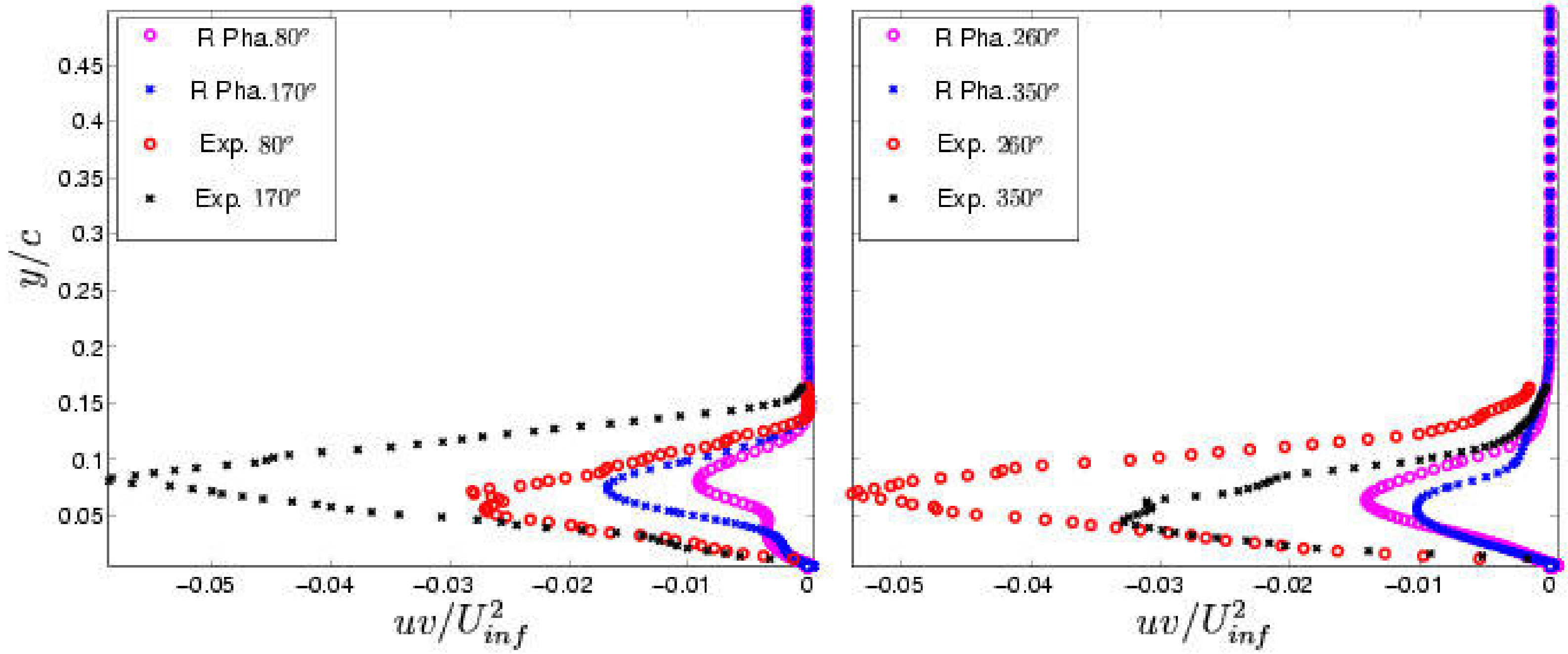
Oscillatory Slot, $x/c = 0.68$



Oscillatory Slot, $x/c = 0.68$



Oscillatory Slot, $x/c = 0.9$



Hump reattachment point (CFL3D)

	Exp.	CFD (fine)	CFD (med)
No-Flow	1.11	1.24	1.23
Suction	0.94	1.10	1.11
Osc.	≈0.98	1.22	n/a

Case 3 Summary

- Overall, results from Sweden ERCOFTAC/IAHR workshop were consistent with results from CFDVAL2004 workshop:
  - RANS models (including full RSM) generally overpredict separation length (underpredict magnitude of u'v' in separated region)
  - DES (blended LES-RANS) predicts correct separation length for no-flow-control, but overpredicts length for suction
  - Differences in upstream and downstream BCs probably responsible for some of the variation among CFD results (e.g., Cf's in front of hump)
  - To get Cp's, side-plate blockage generally must be accounted for
  - Modeling the cavity itself does not appear to be crucial for steady cases
- New LES results exhibited some odd behavior, but appear promising with regard to predicting separation correctly
- For oscillatory case, RANS captures general unsteady character (vortex strength & convection) well, but again overpredicts separation length

Conclusions

Case 1 Conclusions

- Wide CFD variation exhibited
- Computing internal cavity problematic and did not appear to produce any significant benefit
- Difficult experiment to simulate
  - Case probably mostly laminar / transitional
  - Piezo-electric driver and its effects (e.g., non-sinusoidal jet velocity at exit) difficult to model in CFD
  - Ring vortices (3-D effect) formed from slot ends probably influence flowfield away from wall

Case 2 Conclusions

- Wide CFD variation exhibited
- LES and URANS on similar-sized grids yielded similar results (in mean-flow quantities)
- CFD missed some aspects of flow at cavity exit
  - Experiment produced large cross-flow velocity component at orifice exit (not modeled by CFD)
  - Need additional documentation of experimental orifice exit BCs
- Different turbulence models had relatively small impact

Case 3 Conclusions

- CFD must account for blockage to match Cp's
- RANS CFD generally overpredicted separation length and underpredicted turbulent shear stress in separated region
  - This is a turbulence modeling issue
    - CAN RANS TURBULENCE MODELS BE FIXED?
  - But even DNS, LES, and blended RANS-LES were not *consistently* better
    - ONE GUESS: THIS MAY BE BECAUSE THESE METHODS ARE NOT EASY TO RUN CORRECTLY (grid resolution, spanwise extent, sufficient time, blending issues)

Next Steps / Future Directions

- For synthetic jets, reduce CFD uncertainty by employing identical BCs.
- For hump, turbulence models (for RANS) need to be improved to increase mixing in separated region to bring about earlier reattachment and recovery.
- Possible further validation against hump model with oscillatory (synthetic jet) control at next (12^{th}) ERCOFTAC turb. modeling workshop.
- Note: the Hump case is now officially a part of the ERCOFTAC Database (Classic Collection). It is listed as Case C.83.