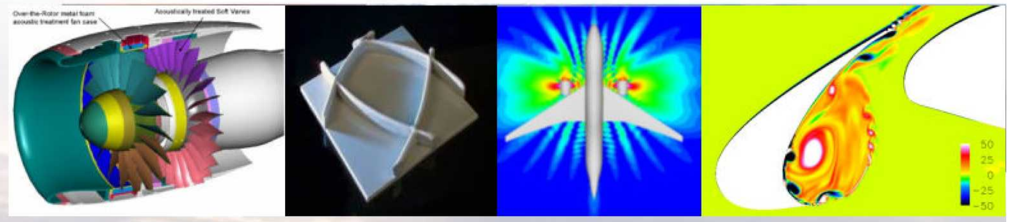
FUNDAMENTAL STUDY OF A JET-IN-CROSSFLOW INTERACTING WITH A VORTEX GENERATOR FOR FILM COOLING APPLICATIONS

Abstract

Results of an experimental study are presented on the effectiveness of a vortex generator (VG) in preventing lift-off of a jet-in-cross-flow (JICF). The study is pertinent to film-cooling applications and its relevance to NASA programs is first briefly discussed. In the experiment, the jet issues into the boundary layer at an angle of 20° to the free-stream. The effect of a triangular, ramp-shaped VG is studied while varying its geometry and location. Detailed flow-field properties are obtained for a case in which the height of the VG and the diameter of the orifice are comparable to the approach boundary layer thickness. The VG produces a streamwise vortex pair with vorticity magnitude three times larger (and of opposite sense) than that found in the JICF alone. Such a VG appears to be most effective in keeping the jet attached to the wall. The effect of parametric variation is studied mostly from surveys ten diameters downstream from the orifice. Results over a range of jet-to-freestream momentum flux ratio ($1<J<11$) show that the VG has a significant effect even at the highest J covered in the experiment. When the VG height is halved there is a lift-off of the jet. On the other hand, when the height is doubled, the jet core is dissipated due to larger turbulence intensity. Varying the location of the VG, over a distance of three diameters from the orifice, is found to have little impact.

National Aeronautics and Space Administration

Fundamental Study of a Jet-in-Crossflow Interacting with a Vortex Generator for Film Cooling Applications



Khairul Zaman[1], David Rigby[2] and James Heidmann[3]
Aerospace Engineer
NASA Glenn Research Center

([1] Inlet and Nozzle Branch
[2] ASRC Aerospace Corporation
[3] Turbomachinery Branch)

2009 Annual Meeting
Fundamental Aeronautics Program
Subsonic Fixed Wing Project
September 29-October 1, 2009

NASA Subsonic Transport System Level Metrics

…. technology for dramatically improving noise, emissions, & performance

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020)*** Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025)*** Technology Benefits
Noise (cum below Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	Better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	Better than -70%
Performance: Field Length	-33%	-50%	Exploit metroplex* concepts

***Technology Readiness Level for key technologies = 4-6
** Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

SFW Approach

- *Conduct Discipline-Based Foundational Research*
- *Investigate Advanced Multi-Discipline-Based Concepts and Technologies*
- *Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes*
- *Enable Major Changes in Engine Cycle/Airframe Configurations*

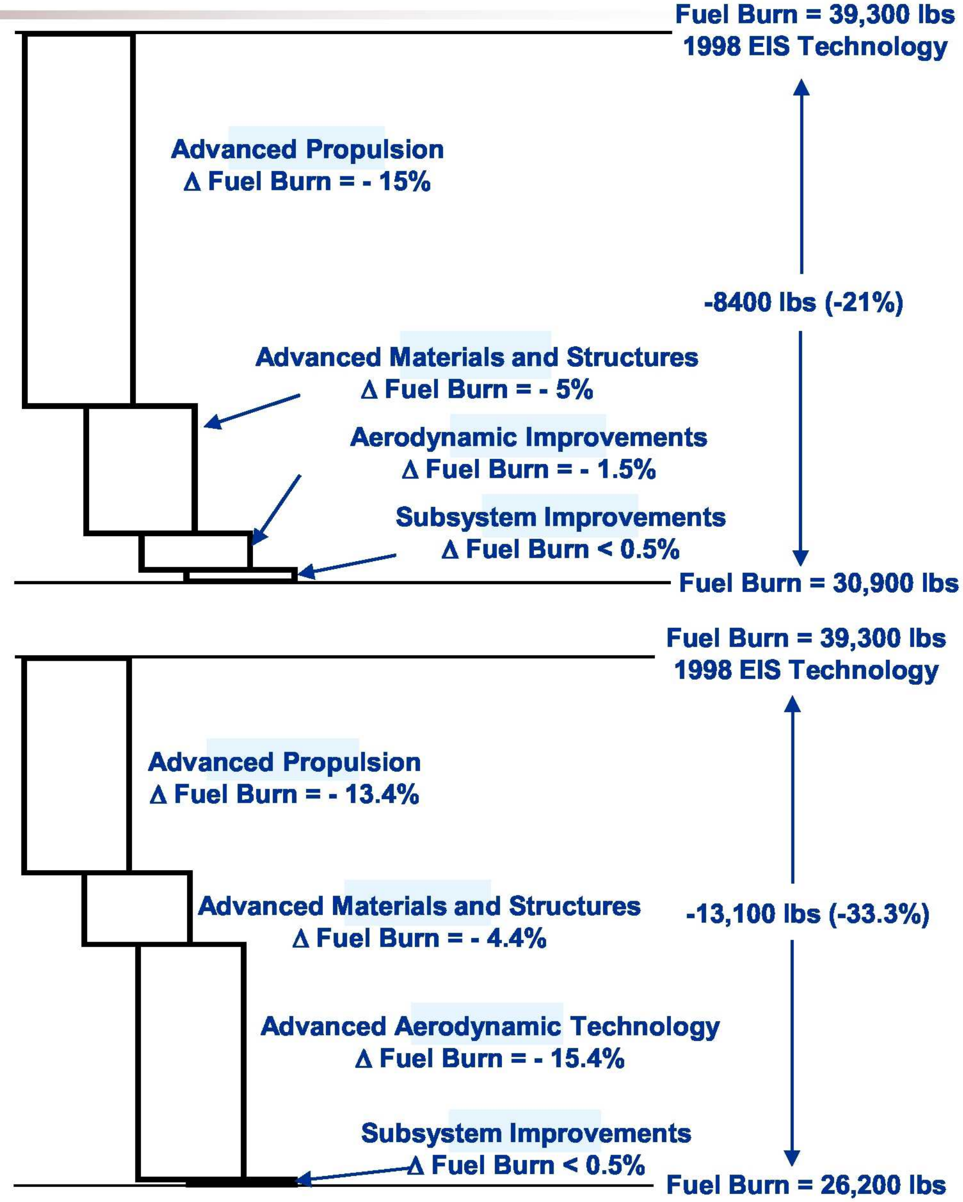
Performance - Fuel Burn - N+1

"N + 1" Conventional Small Twin

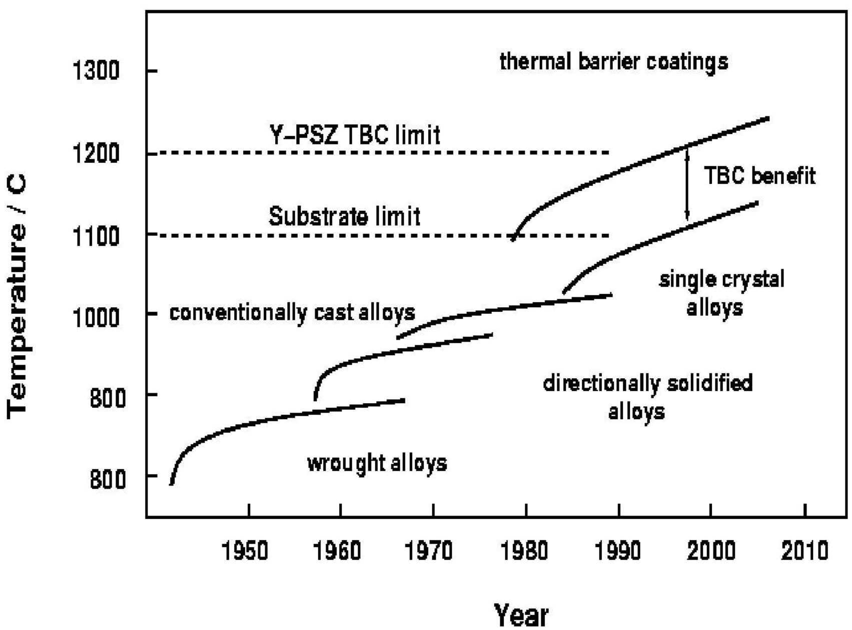
- 162 pax, 2940 nm mission baseline
- Ultra high bypass ratio engines, geared
- Key technology targets:
  - Increase in turbomachinery component effs.
  - -25% turbine cooling flow
  - +50 deg. F compressor exit temp (T3)
  - +100 deg. F turbine rotor inlet temp (T41)
  - -15% airframe structure weight
  - -1% total vehicle drag
  - -15% hydraulic system weight

"N + 1" Advanced Small Twin

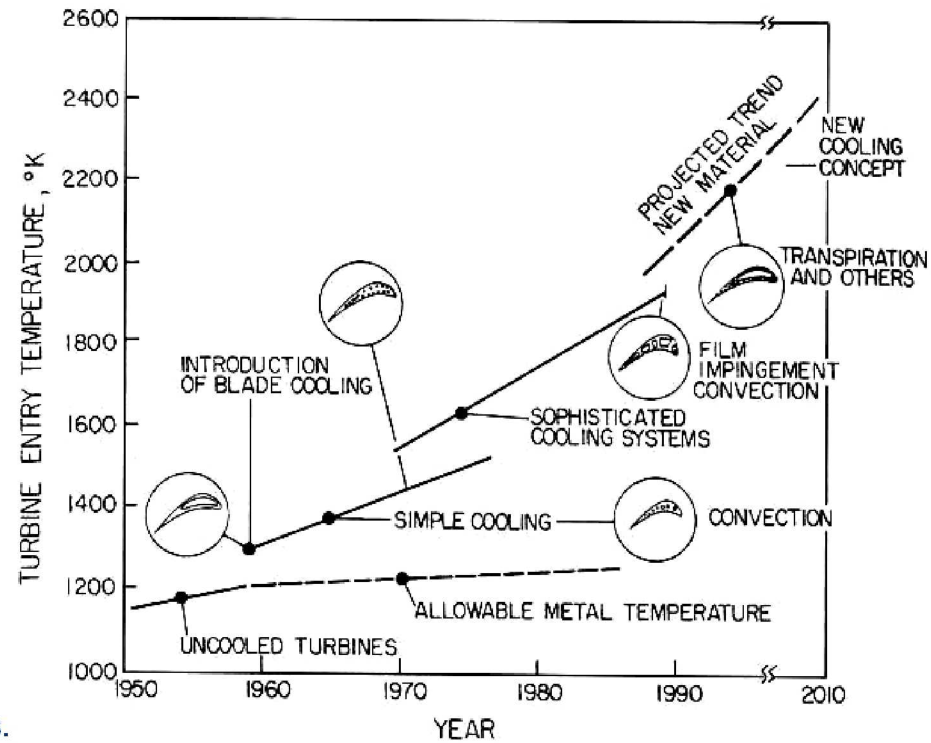
- All technologies listed above plus:
  - Hybrid Laminar Flow Control
    - 67% upper wing,
    - 50% lower wing,
    - tail, nacelle
  - Result = -17% total vehicle drag



Materials and Cooling Improvements



Increase in operational temperature of turbine components.
After Schulz *et al*, Aero. Sci. Techn.7:2003, p73-80.

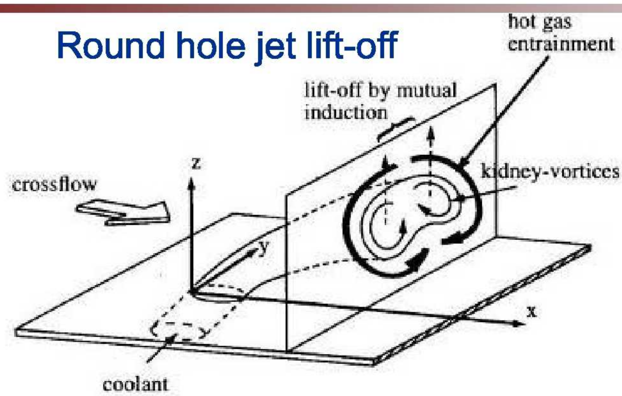


Variation of turbine entry temperature over recent years (Clifford, 1985; AGARD CP 390; collected in Lakshminarayana, 1996).

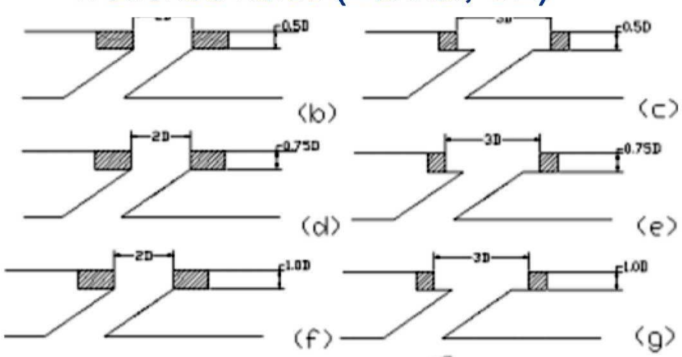
Majority of Turbine Temperature Increase Enabled By Cooling Improvements

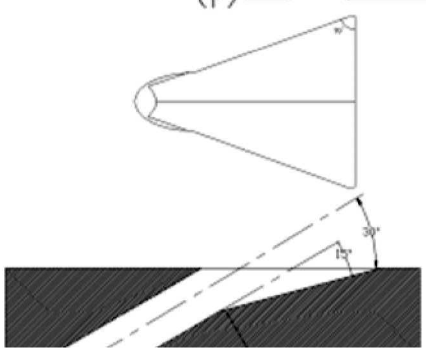
Advanced Film Cooling Concepts

Round hole jet lift-off



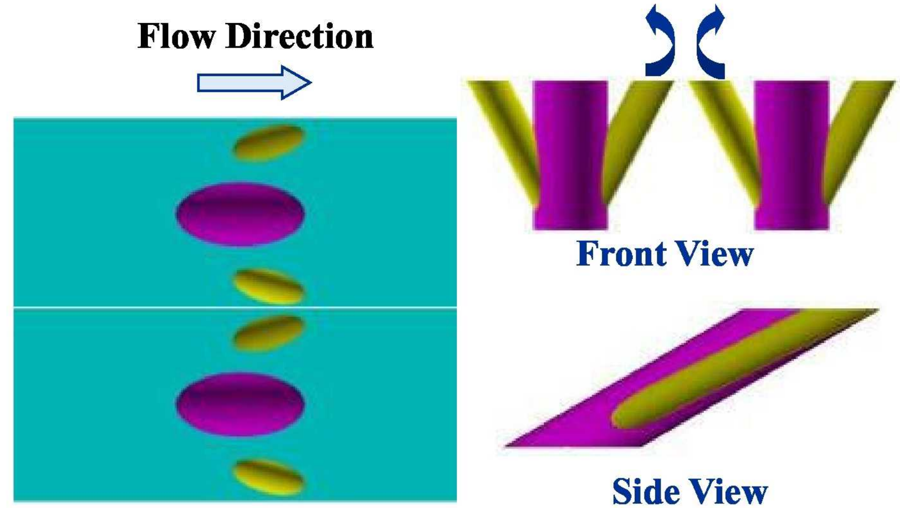
Trenched holes (Bunker, GE)





Shaped holes (standard practice)

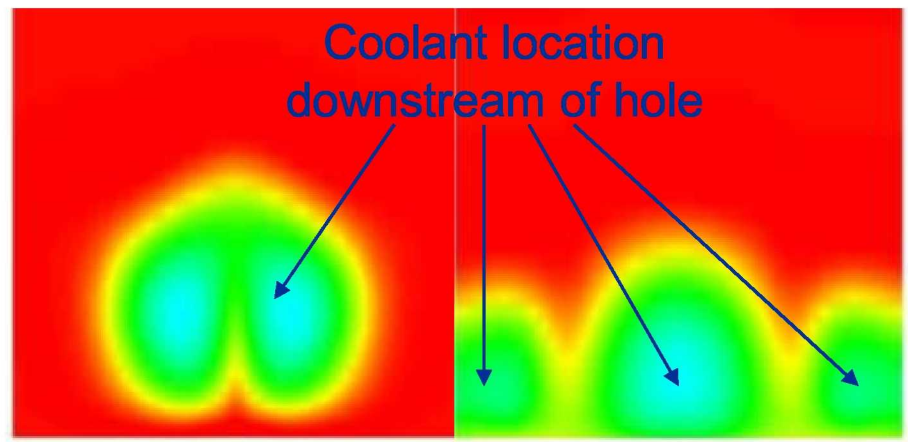
Anti-Vortex Film Cooling Concept (Heidmann, NASA)



Top View

Front View

Side View



Baseline Coolant Coverage (hot wall)

Anti-Vortex Coolant Coverage (cool wall)

Inclined Jet-in-Crossflow Interacting with a Vortex Generator

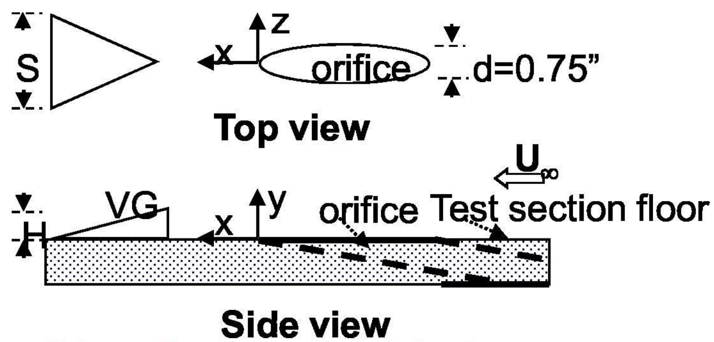
Objective:
-- Fundamental study of a vortex generator (VG) concept to prevent liftoff of jet-in-cross-flow (JICF)
-- Explore concept for advanced turbine film cooling
-- VG is robust in design and may be alternative to expensive shaped holes

Rationale:
-- VG produces a pair of streamwise vortices opposite in sign to that of bound-vortex-pair of JICF;
-- Jet liftoff delayed through vorticity cancellation

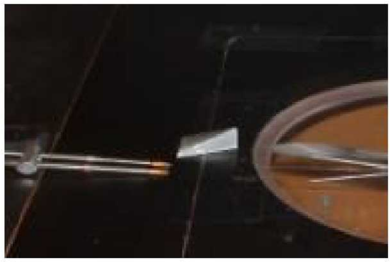
Approach:
-- Obtain detailed flowfield data including all components of mean velocities, turbulence intensities, and streamwise vorticity
-- Optimize VG geometry and location through experiment and accompanying CFD

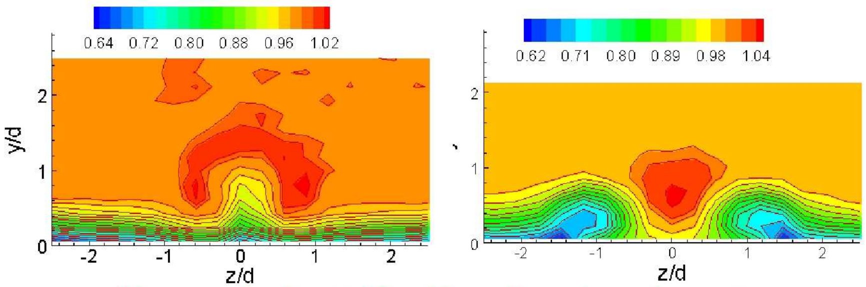
Result:
-- Data on bottom right demonstrate 'coolant flow' successfully pulled towards wall

Research team: Khairul Zaman, David Rigby, James Heidmann



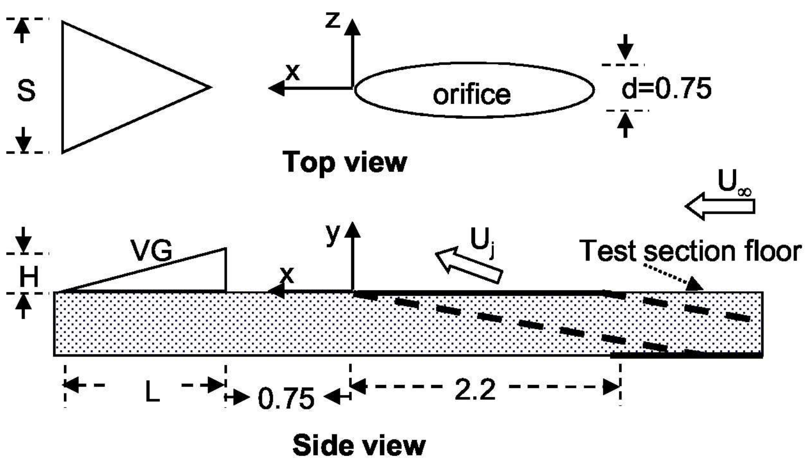
Schematic of experimental set-up


Picture with two crossed hot-wires on left



Mean velocity at 10 orifice diameters downstream
left: baseline flow, right: with VG

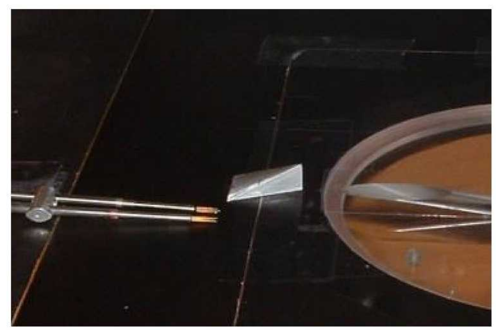
Experimental Facility



Schematic of Orifice and VG

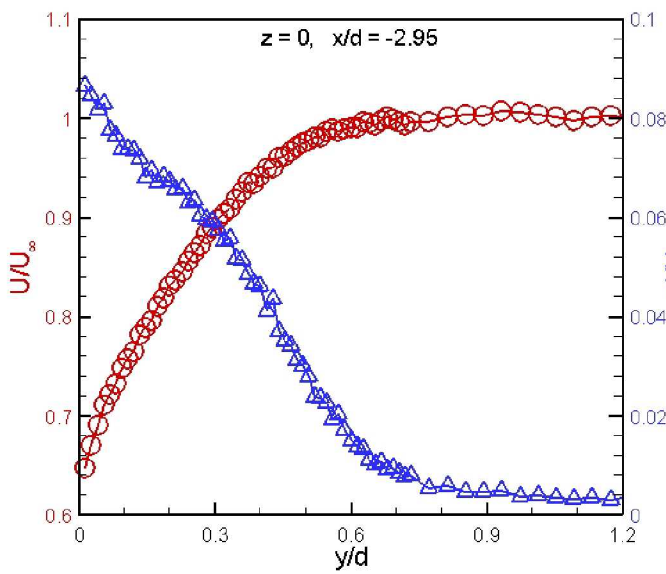
Data to be presented are for:
$L = 1.91d$, $S=1.57d$ and $H=0.75d$
$J = (U_j/U_\infty)^2 = 2$

Single-wire set-up



X-wire set-up

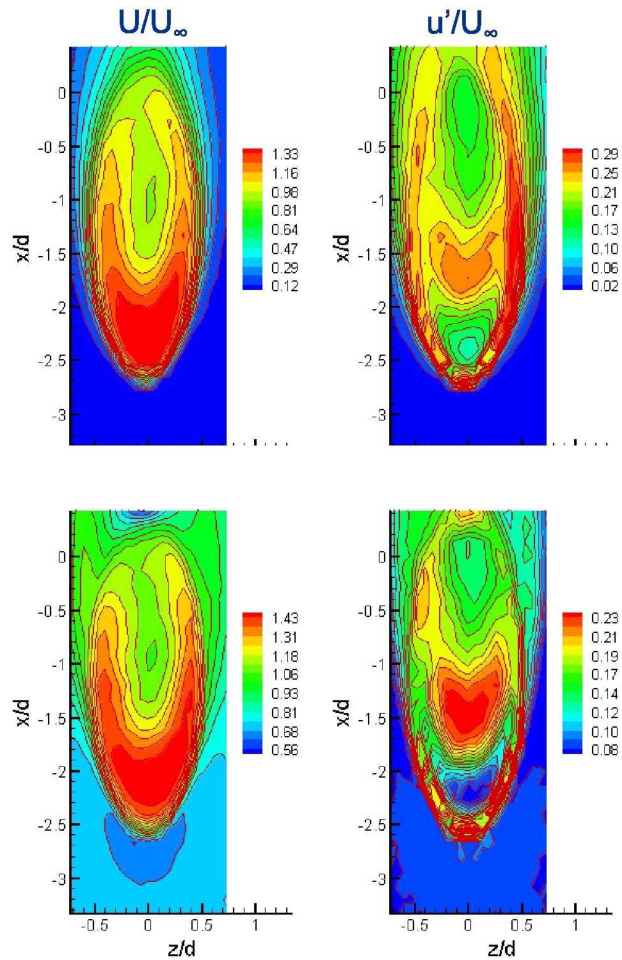
Approach boundary layer and orifice exit conditions



Approach B.L. profiles

B.L. thickness ~ VG height

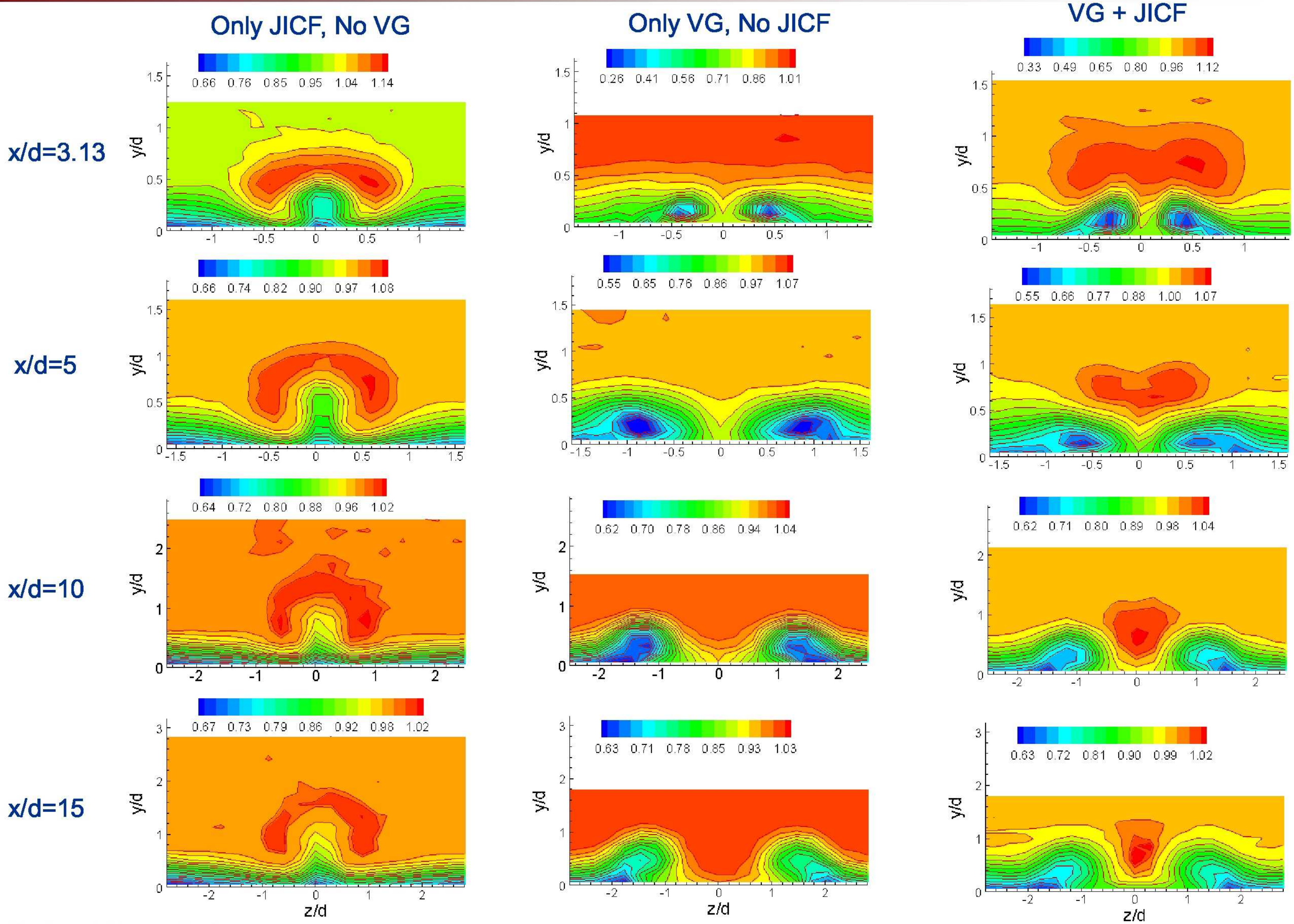
Velocities at exit of Orifice



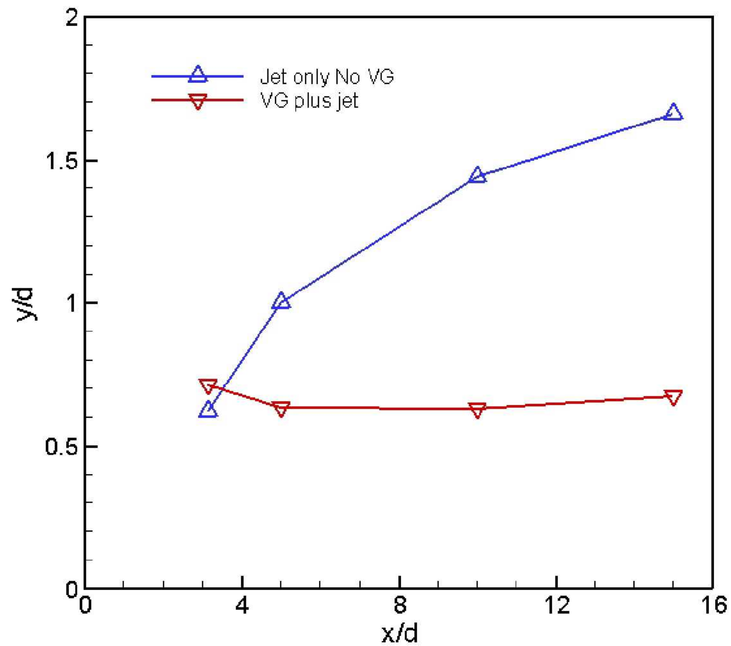
$U_\infty = 0$
$U_j \approx 41 f/s$

$U_\infty \approx 29 f/s$
$U_j \approx 41 f/s$

Mean velocity (U/U_∞) contours on x-sectional planes

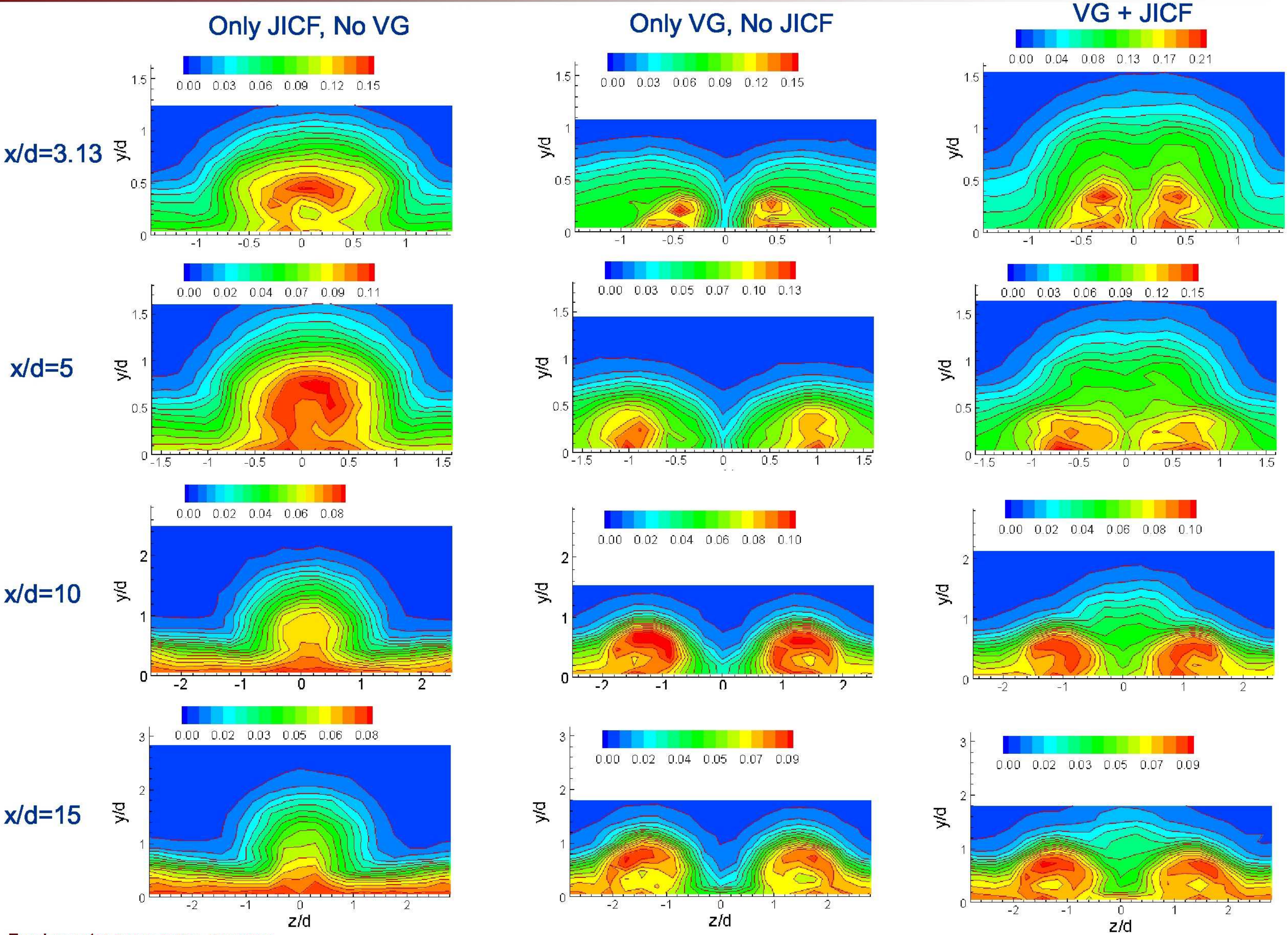


Jet penetration
Trajectory of U-peak at z=0

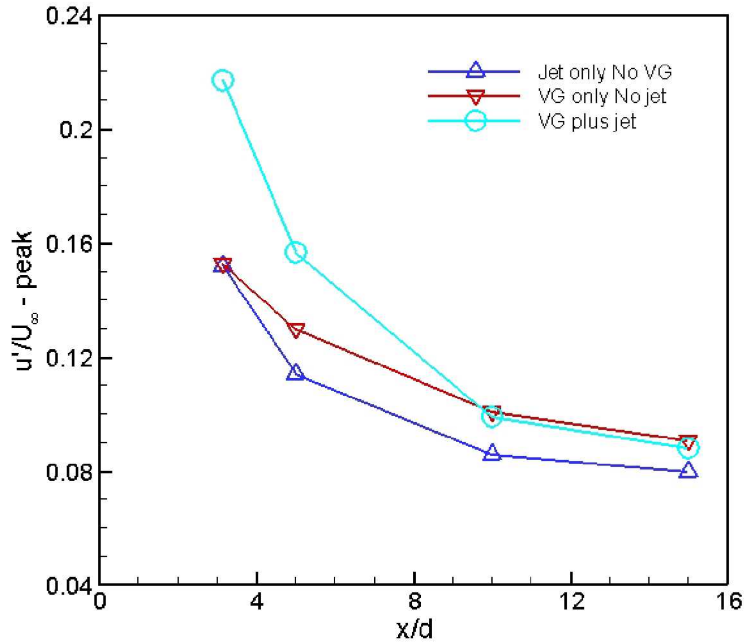


VG effectively pulls and retains the JICF (coolant) close to wall

Turbulence intensity (u'/U_∞) contours on x-sectional planes

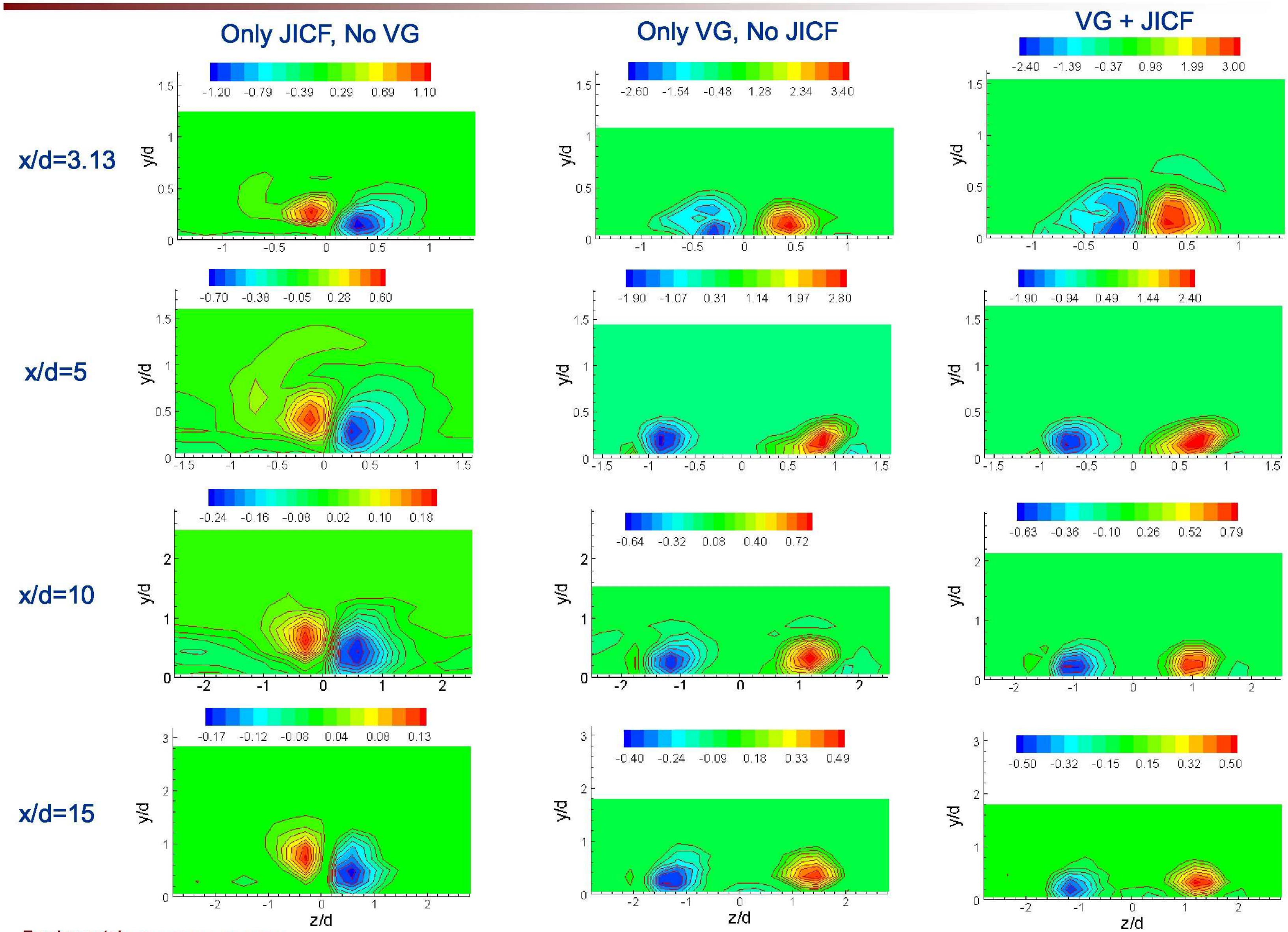


Streamwise variation of peak turbulence intensity



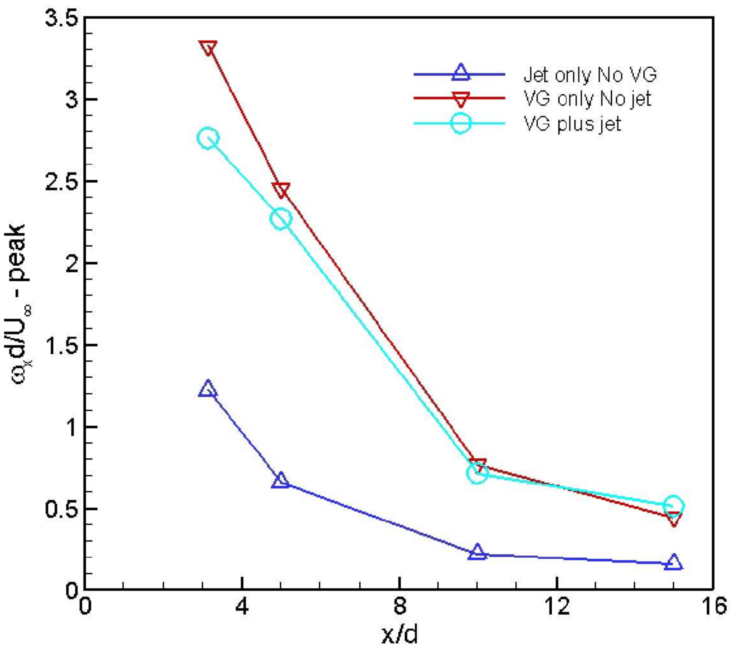
Turbulence is high for combination of VG and JICF
Causes a faster mixing of the JICF (coolant) as evidenced from U-contours

Streamwise vorticity ($\omega_x d/U_\infty$) contours on x-sectional planes

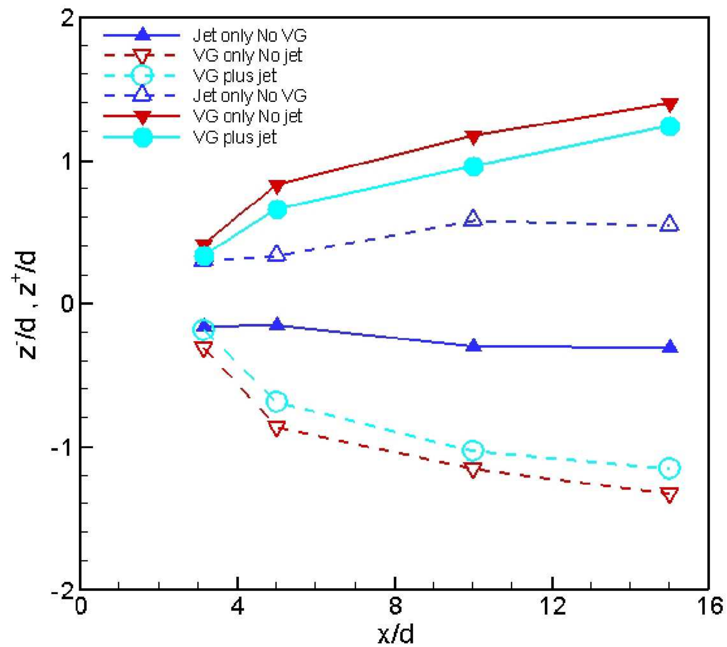


Variation of streamwise vorticity properties with axial distance

Variation of peak vorticity



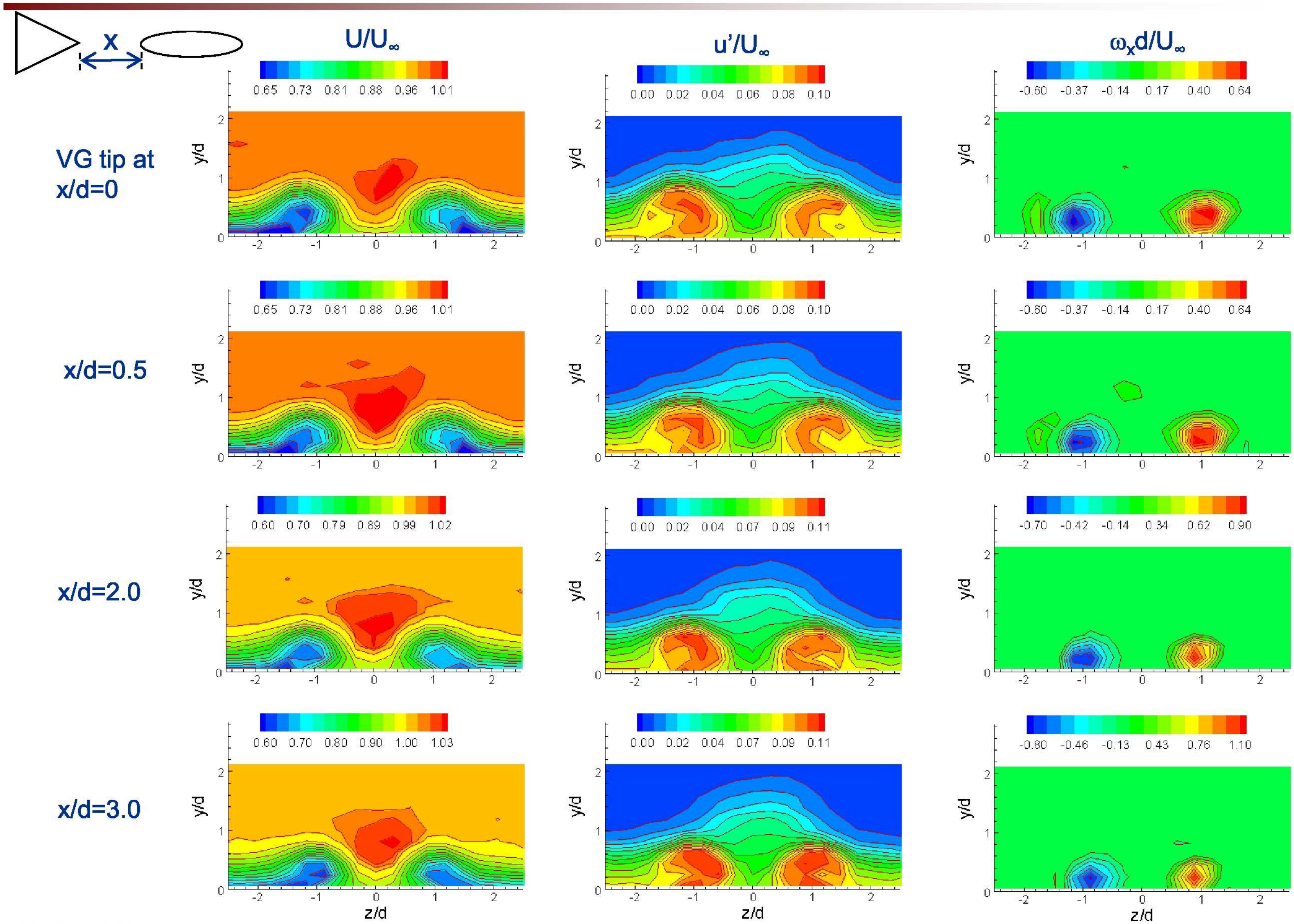
Trajectory of vortex core



VG dominates streamwise vorticity
ω_x–peak about 3 times larger for VG relative to JICF
The job could be done with a smaller VG ?

Effect of varying location of VG relative to orifice

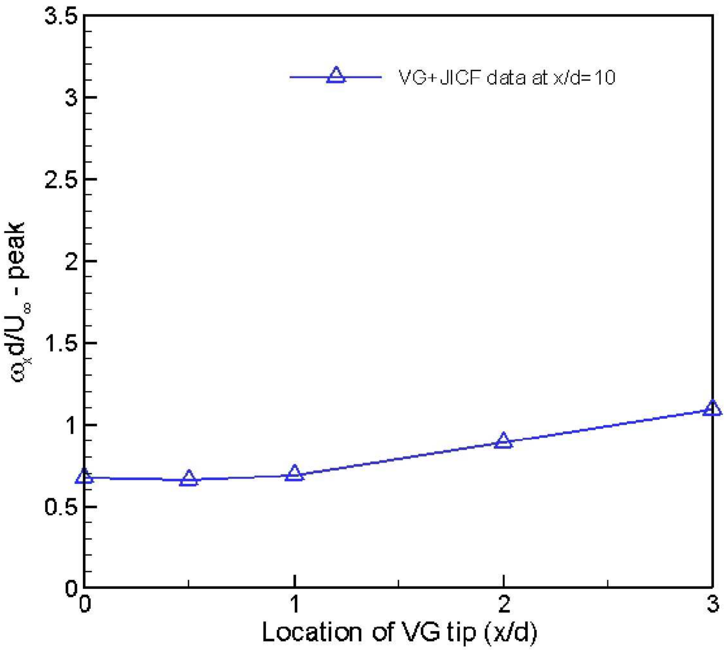
U, u' and ω_x contours on x-sectional plane at x/d=10



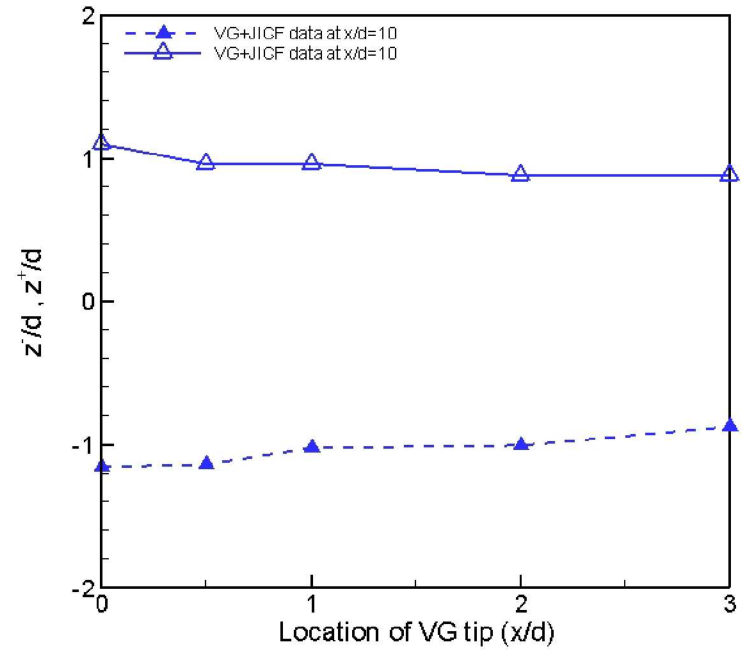
Variation of streamwise vorticity properties at x/d=10

for varying location of VG

Variation of peak vorticity



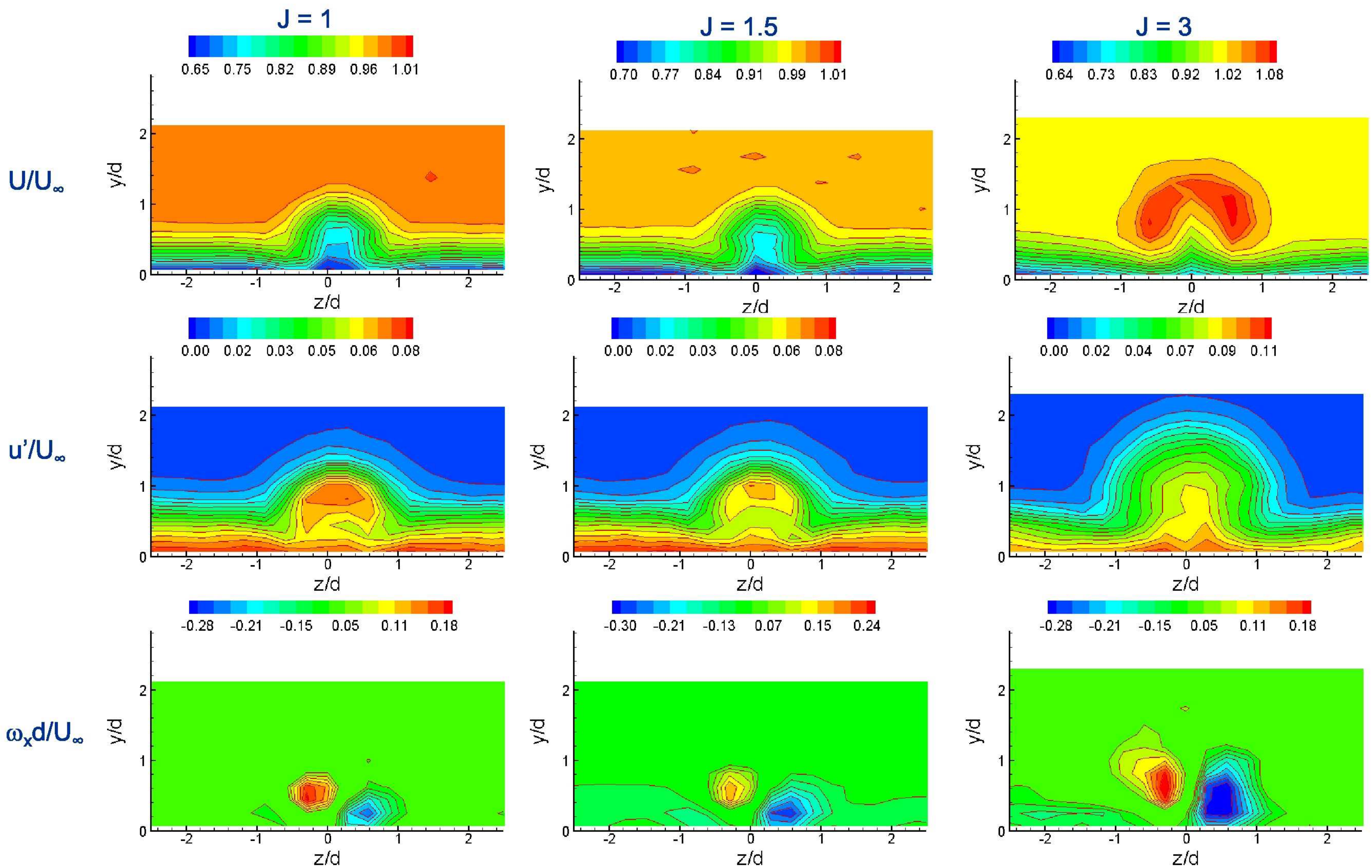
Trajectory of vortex core



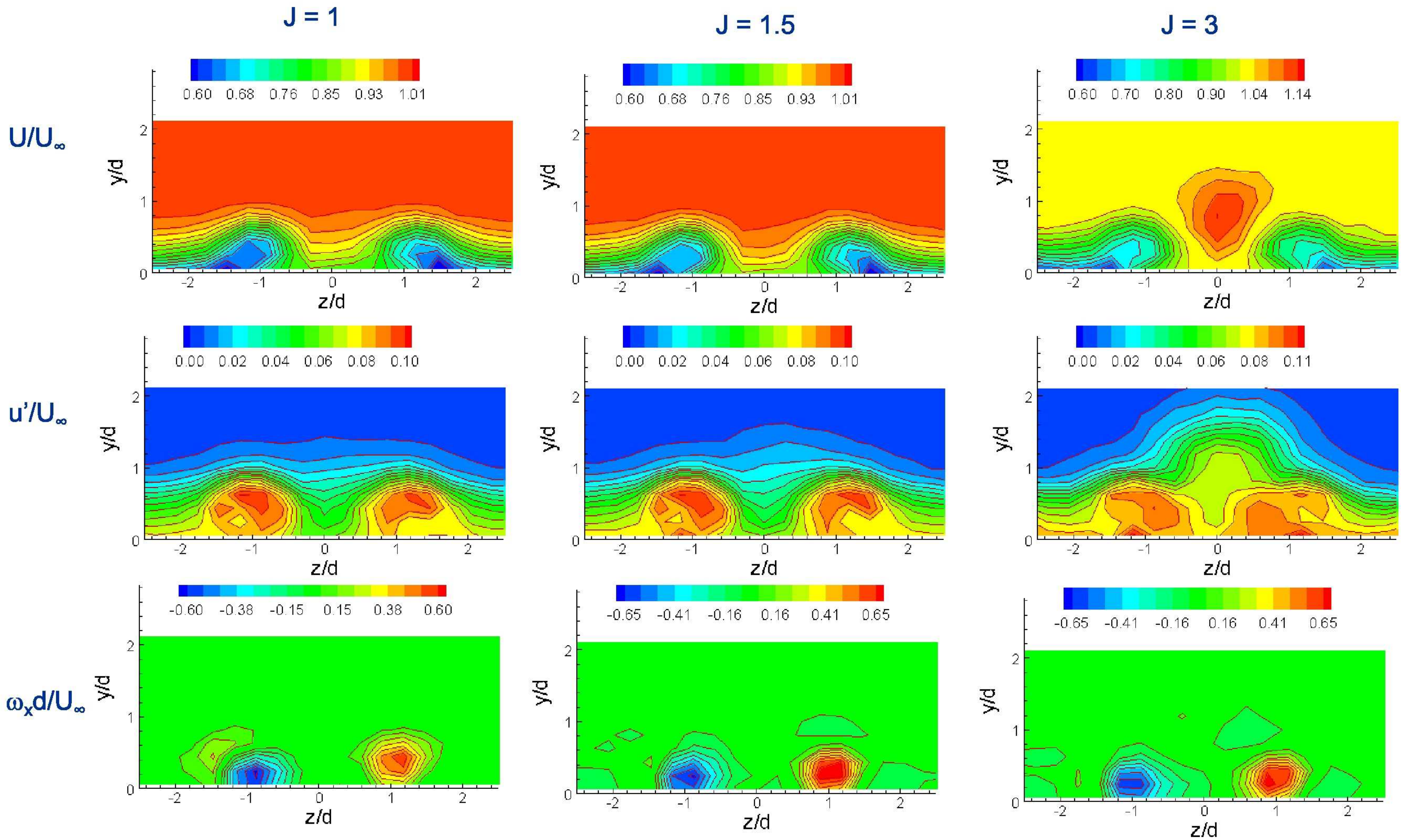
When VG is moved downstream, ω_x–peak increases and spanwise separation of the pair decreases, expected since VG moves closer to measurement location

Placement of VG at different x/d made only small difference

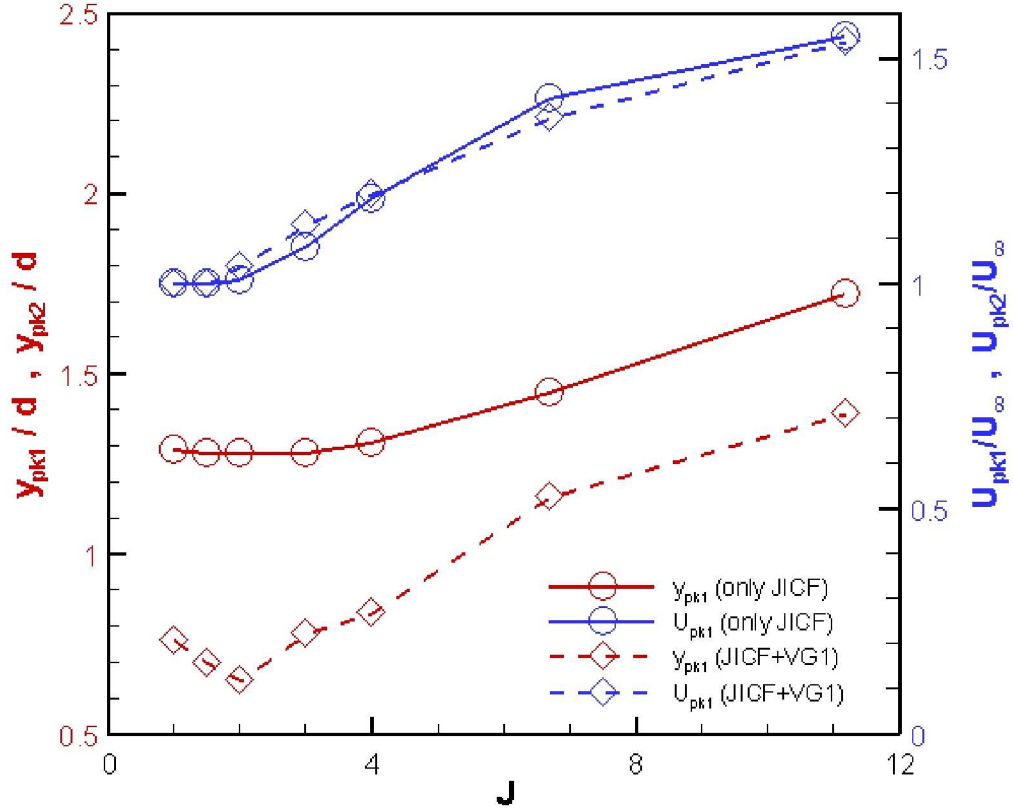
U, u' and ω_x contours at x/d=10
For different J ($(U_j/U_\infty)^2$); Only JICF, no VG case



U, u' and ω_x contours at x/d=10
For different J; VG + JICF case

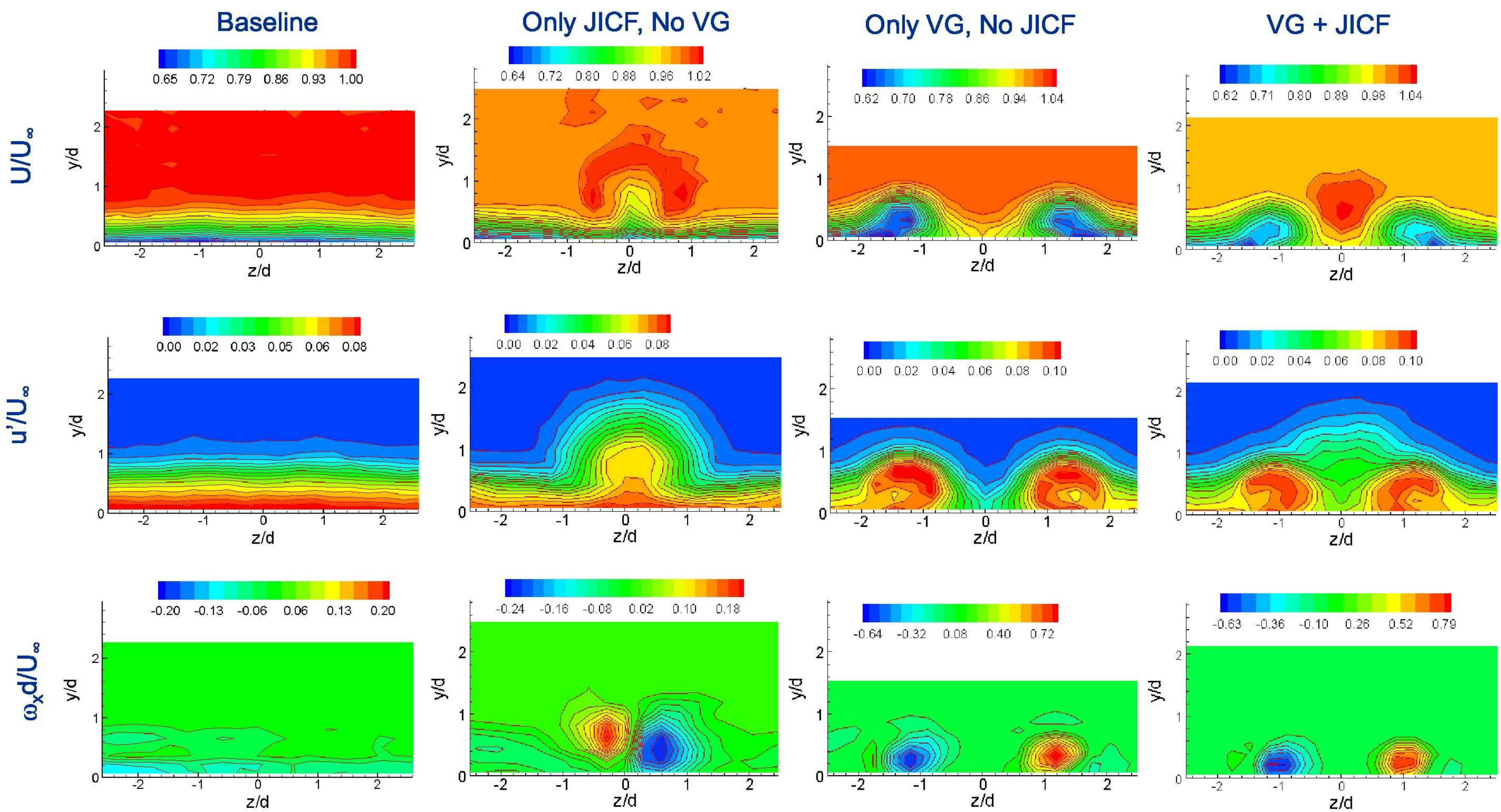


Effect of J on magnitude and location of U-peak with and w/o VG

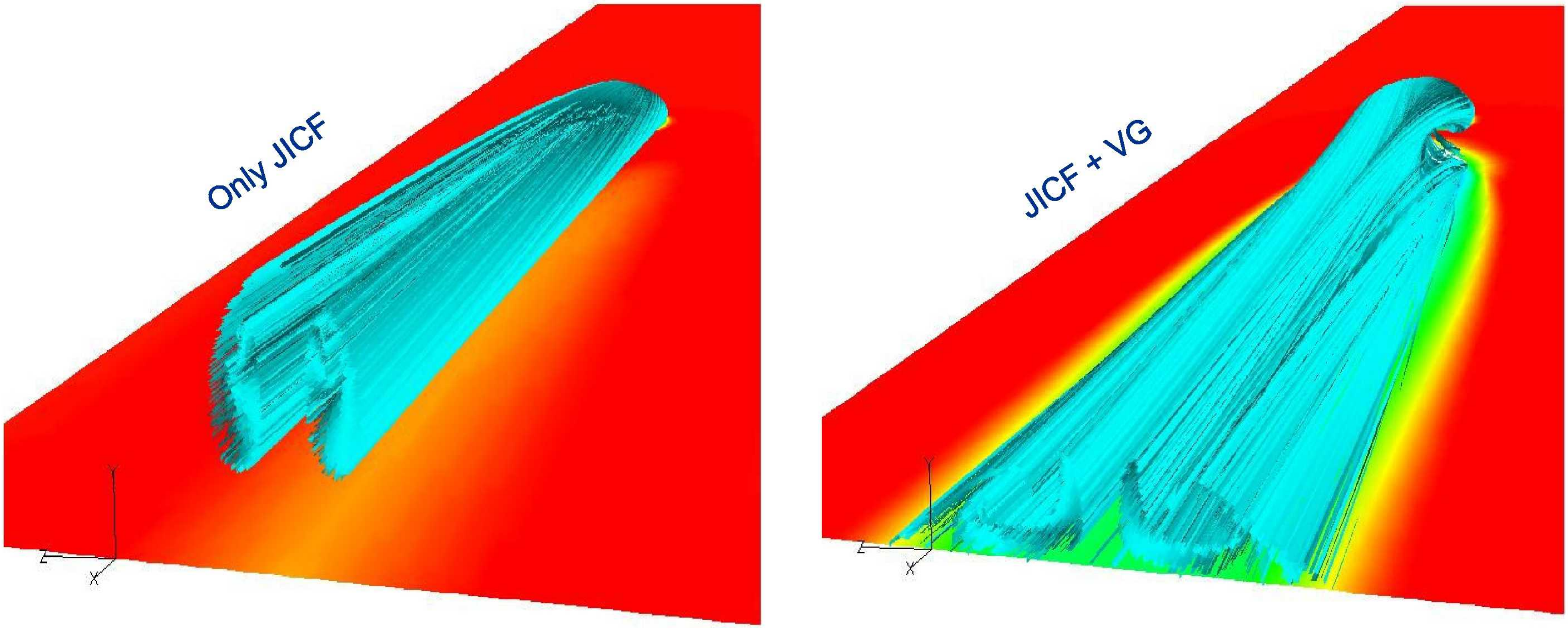


Magnitude of U-peak changes little in presence of VG
But location is drawn toward wall even at highest J

Recap: Contours of various properties at x/d = 10; J=2



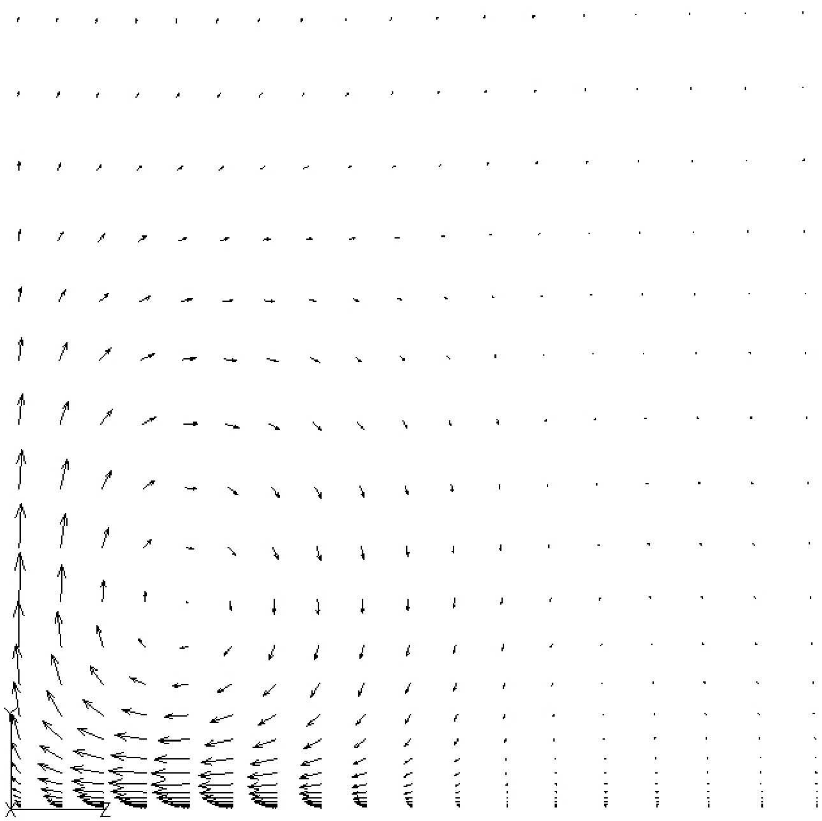
CFD: Coolant streamlines - Surface colored by effectiveness
Blowing ratio=1.5, Density ratio=2, J=1.125



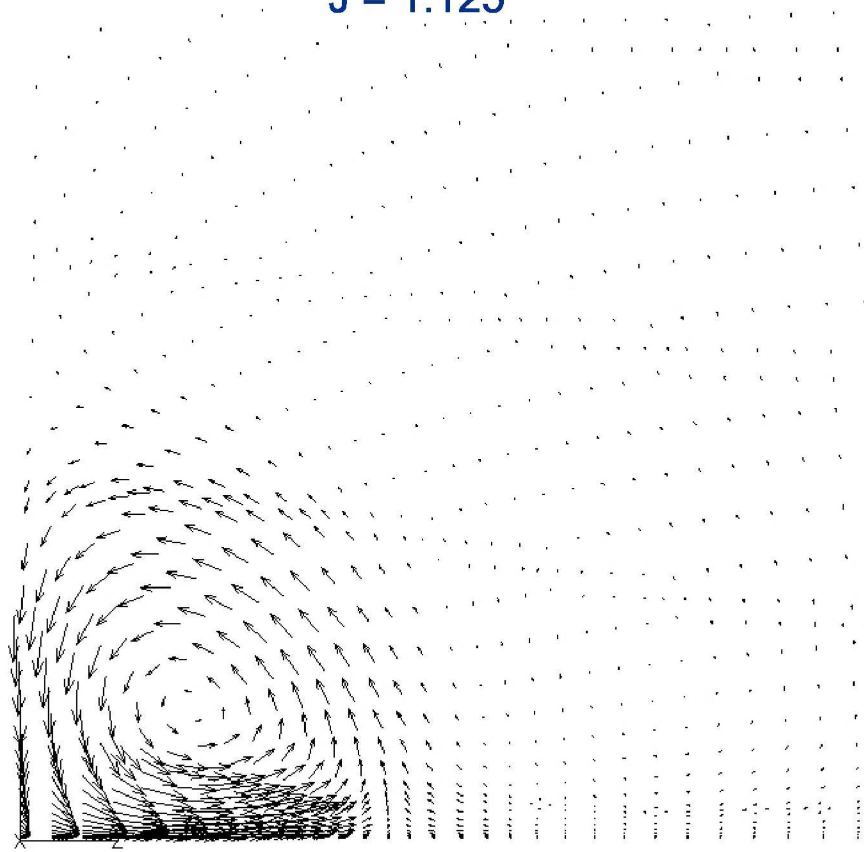
- JICF without VG lifts off
- JICF with VG is drawn to the surface and spreads

CFD: Secondary momentum vectors at x/D=5

JICF Alone
Blowing ratio = 1.5
Density ratio = 2.0
J = 1.125



JICF + VG
Blowing ratio = 1.5
Density ratio = 2.0
J = 1.125



Addition of VG reverses and strengthens vortices as in experiment

Concluding Remarks

VG used effectively pulls and retains the JICF (coolant) close to the wall

Placement of VG at different axial location made only small difference in the effect

VG used dominates streamwise vorticity; ω_x–peak about 3 times larger for VG only relative to JICF only

It may be possible to keep the coolant close to the wall with a smaller VG.

Further combined experimental and CFD effort will focus on optimization by varying geometric parameters of VG.