INL/MIS-09-16404

Recent Studies with the World's Largest Matched-Index-of-Refraction (MIR) Flow System

Idaho National Laboratory (INL)
Idaho Falls, Idaho 83415-3870

Idaho National Laboratory

Objective ≈ obtain basic and applied measurements of complicated internal and/or external fluid physics for

- Extending fundamental knowledge of generic flow processes
- Assessment of proposed CFD codes
- Guidance for improving CFD codes, e.g., turbulence models

Technique = optical fluid measurements (LDV, PTV) with transparent models using refractive-index matching

Idaho National Laboratory

- ETSci Advisory Committee recommended a central test facility for
  - Complex turbulent flows
  - Flows in porous media
  - Two-phase particulate flows

  using refractive-index-matching techniques

  ➔ INL MIR flow system = World's largest
- Advantages
  - Versatile - internal/external flows, basic/applied research
  - Non-intrusive measurements
  - Good spatial and temporal resolution
  - Benchmark data
- Is an excellent user facility
- Applications from micro-scale to building scale

Idaho National Laboratory

Topics

- Benefits of refractive-index-matching for optical flow measurements
- Characteristics and advantages of INL MIR flow system
- Recent and current experiments
- Potential interactions with INL
- Concluding remarks

Contacts:

INL Thermal Science Dept. manager = J. Philip Sharpe, 208-526-9830 (Phil.Sharpe@inl.gov)

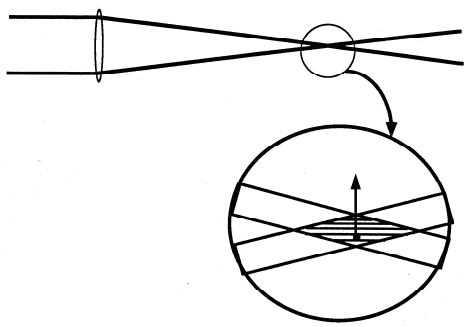
INL technical leader = Donald M. McEligot, 208-526-1732 (dm6@inl.gov)

INL program manager = Hugh McIlroy, 208-526-6176 (Hugh.McIlroy@inl.gov)

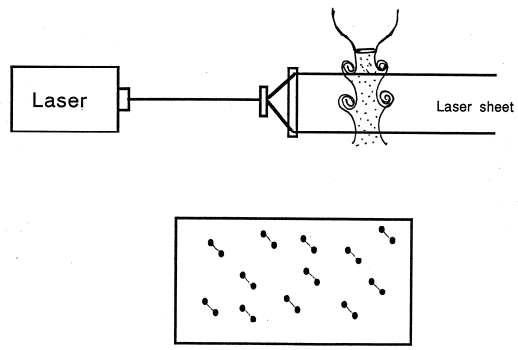
How does refractive-index-matching help?

- Optical techniques avoid disturbing the flow to be measured
- Typical approaches are LDV, PIV, PTV, flow visualization, PLIF, etc.

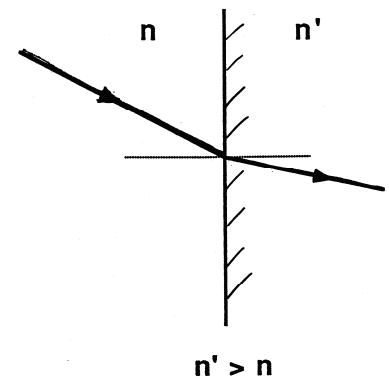
Laser Doppler Velocimetry



Particle Image Velocimetry

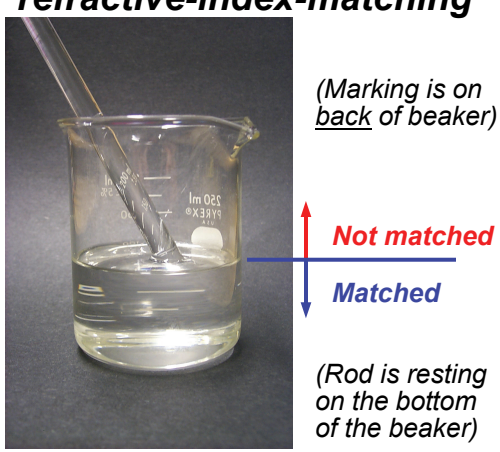


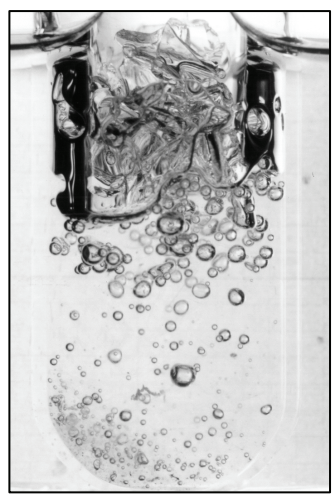
Snell's Law



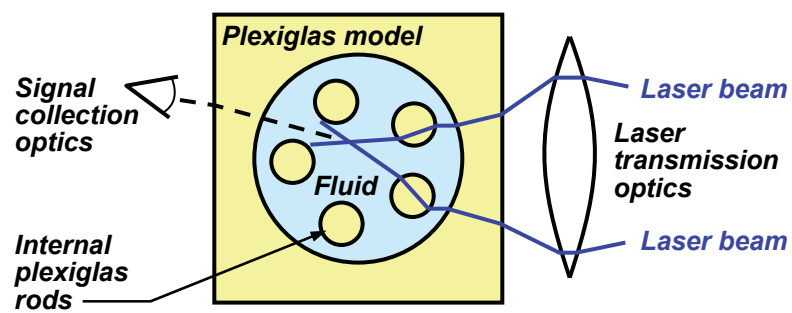
- Unless the refractive indices are matched, the view may be distorted or impossible even with "transparent" materials and position measurements may be incorrect

Example of application of refractive-index-matching

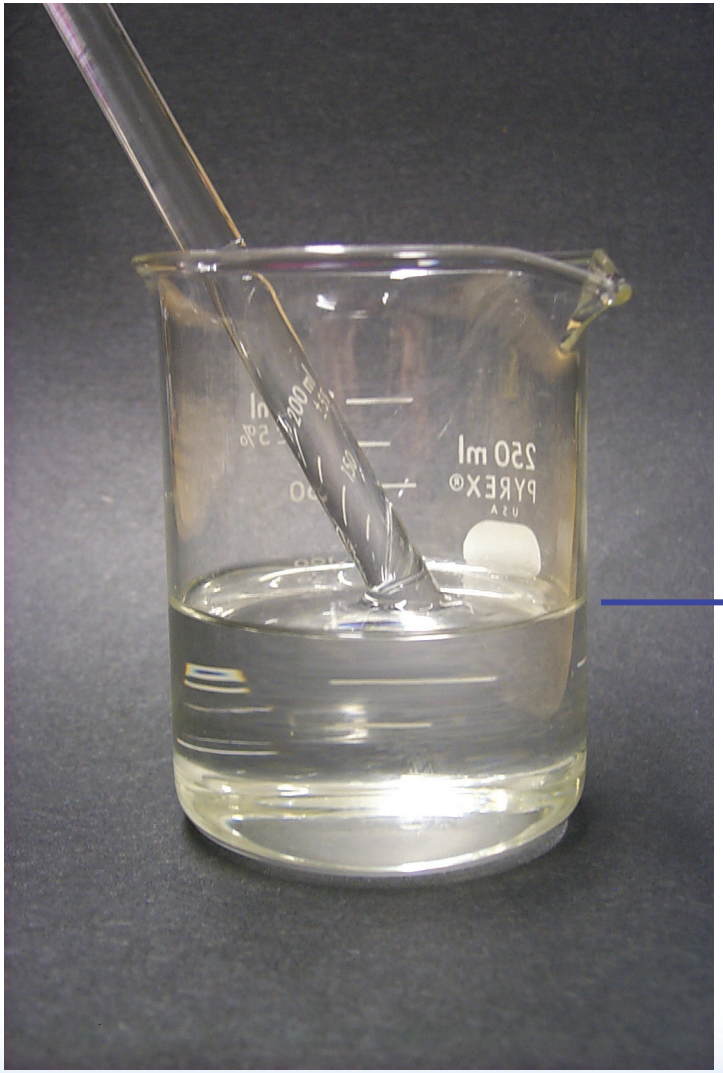




Refractive index not matched



Example of application of refractive-index-matching



Not matched

Matched

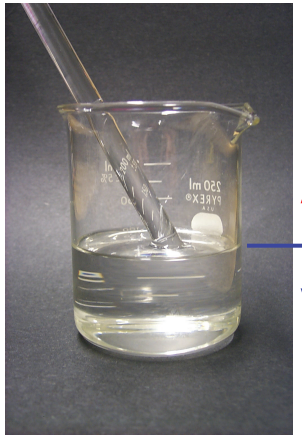
(Rod is resting on the bottom of the beaker)

(Marking is on <u>back</u> of beaker)

Benefits of INL MIR flow system

- Most previous MIR experiments have been cm-scale; INL test section is about 0.6 m x 0.6 m x 2.5 m

Example of application of refractive-index-matching

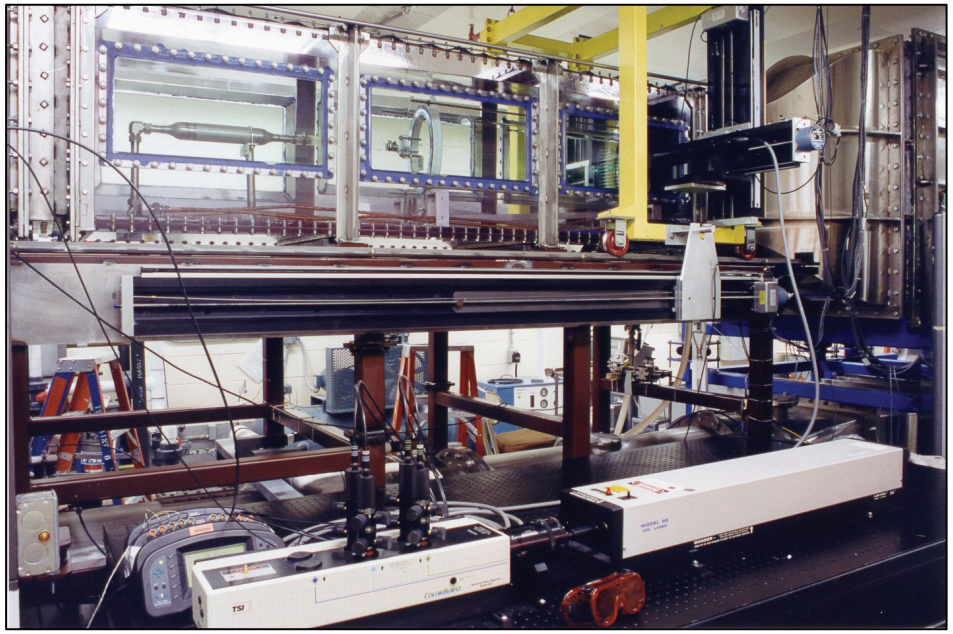


(Marking is on back of beaker)

Not matched

Matched

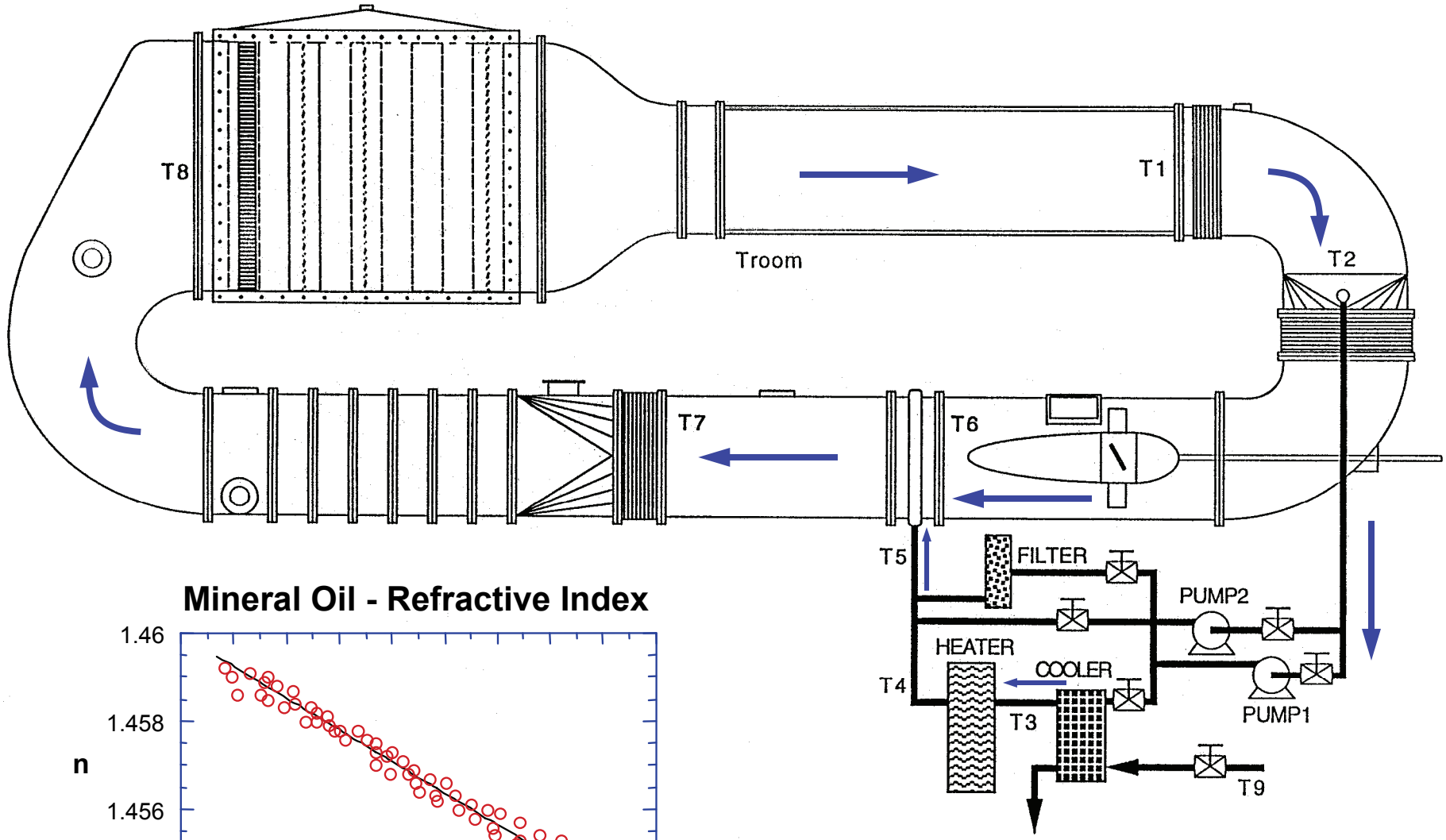
(Rod is resting on the bottom of the beaker)

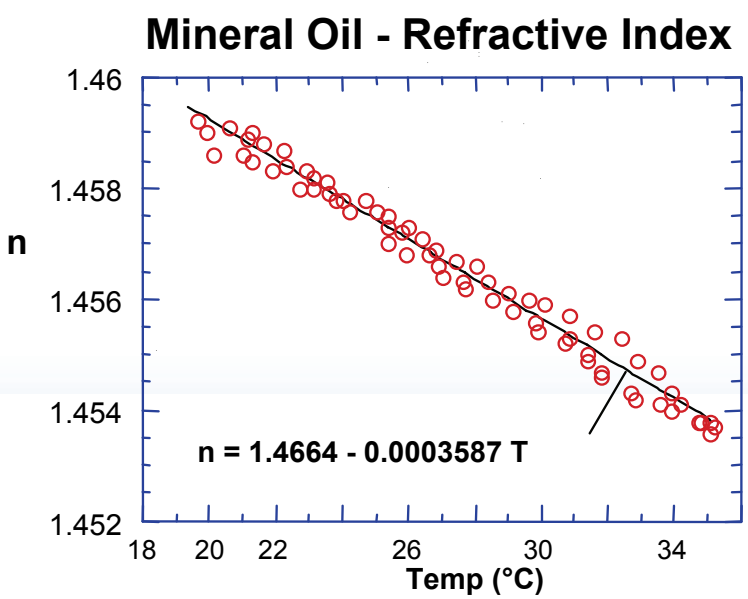


Apparatus to study fluid physics phenomena in idealized SNF canister for EM Science project

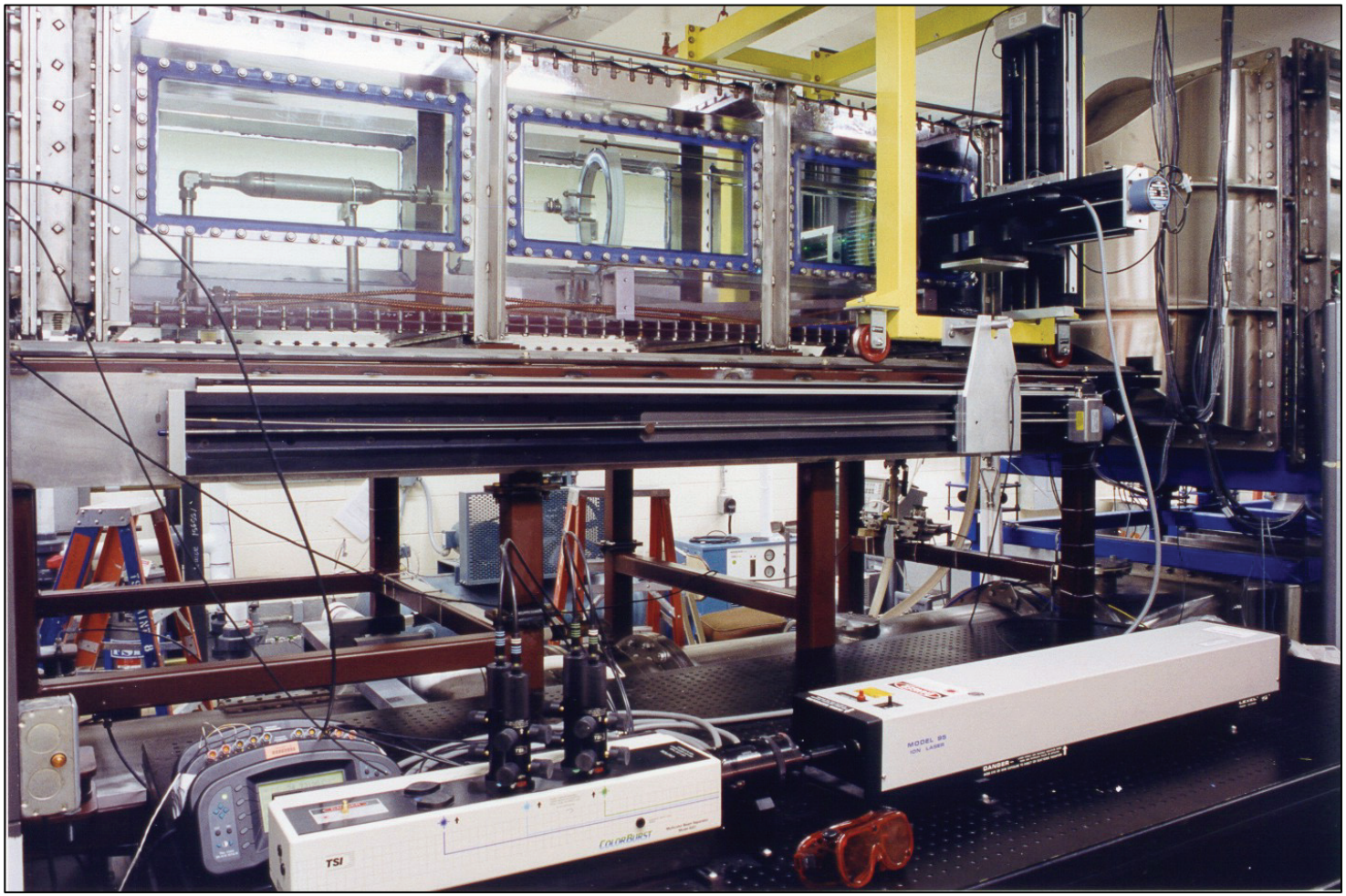
- **Advantages**
  - Versatile - basic/applied research, internal / external / coupled flows
  - Non-intrusive, undistorted measurements of flow and transport
  - μ-scale to building scale experience
  - Good spatial and temporal resolution
  - Benchmark measurements

The Large INL MIR Flow System





MIR Test Section [Stoots et al., Exp. Fluids, 2001]



Idaho National Laboratory

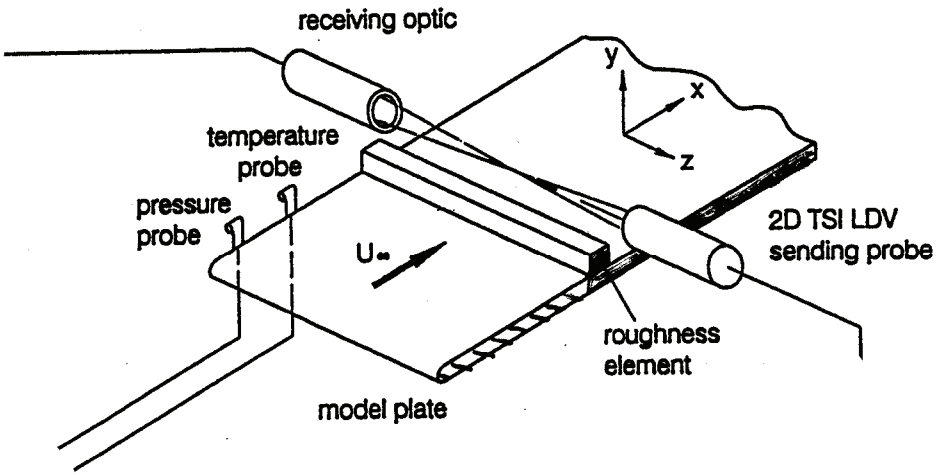
Recent and current collaboration

Prof. F. Durst, Uni. Erlangen, Germany	Structure of transitional flow*
DoE EM Science program	Fundamental flow in SNF canisters*
DoE NERI program	Fundamental thermal fluid physics of advanced reactors*
Bechtel R&D	Flows around buildings
Prof. R. S. Budwig, U. Idaho	Basic measurements of transitional and turbulent flows with favorable pressure gradients*
DoE/Korea I-NERI program	Advanced computational thermal fluid physics and its assessment
Prof. D. R. Smith, U. Wyoming	Structure of transient synthetic jet flows*
DoE EM Science program	Multiphase flow in complex fracture apertures*
DoE NE NGNP program	Experiments to assess CFD tools
Prof. B. L. Smith, Utah State	Non-symmetric swirling jet experiments

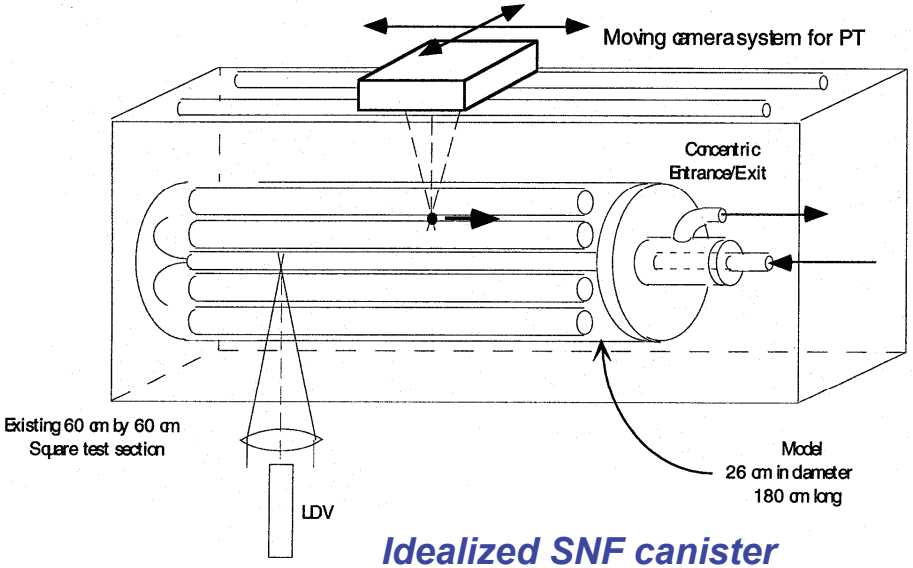
* Basic research -- addressing science issues

Idaho National Laboratory

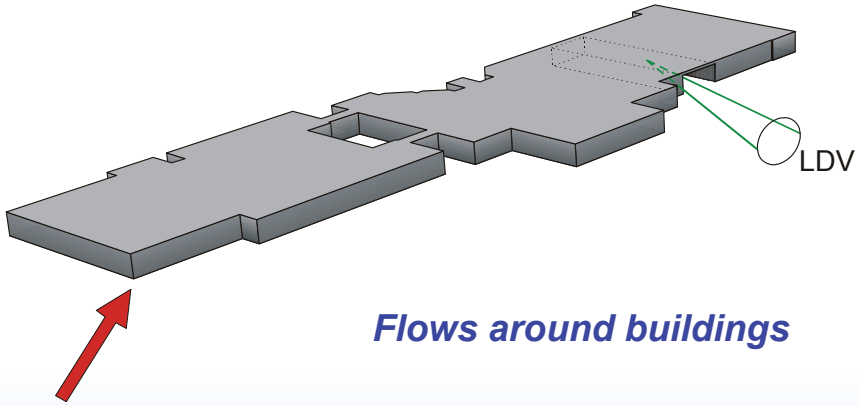
Recent Experiments



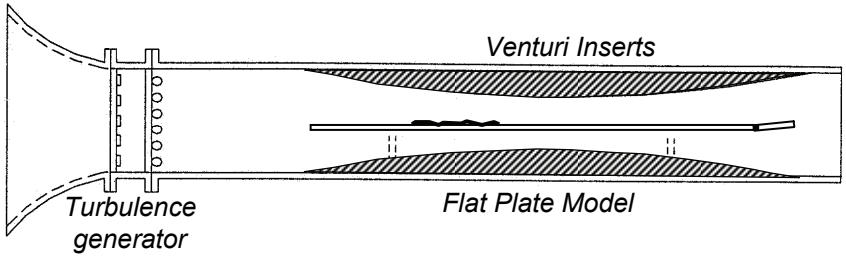
Boundary layer transition



Idealized SNF canister



Flows around buildings

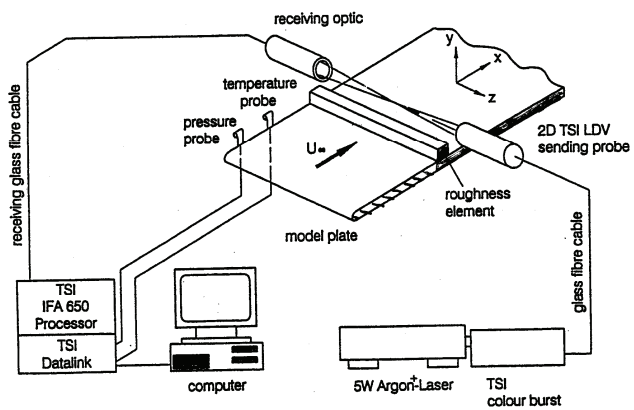


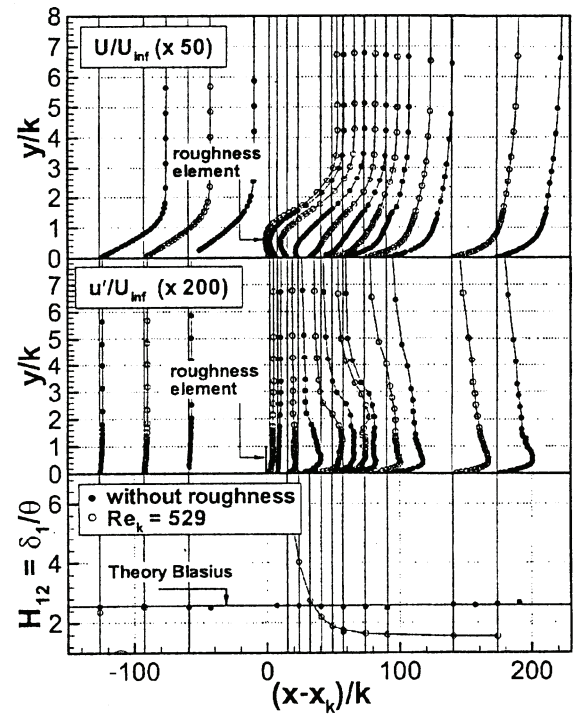
Realistic rough surfaces in turbomachinery

Reynolds stress development in a transitioning boundary layer

Fundamental question = How does the turbulent contribution evolve in a transitional boundary layer?

User = Lehrstuhl für Strömungsmechanik, Uni. Erlangen 1998-2001

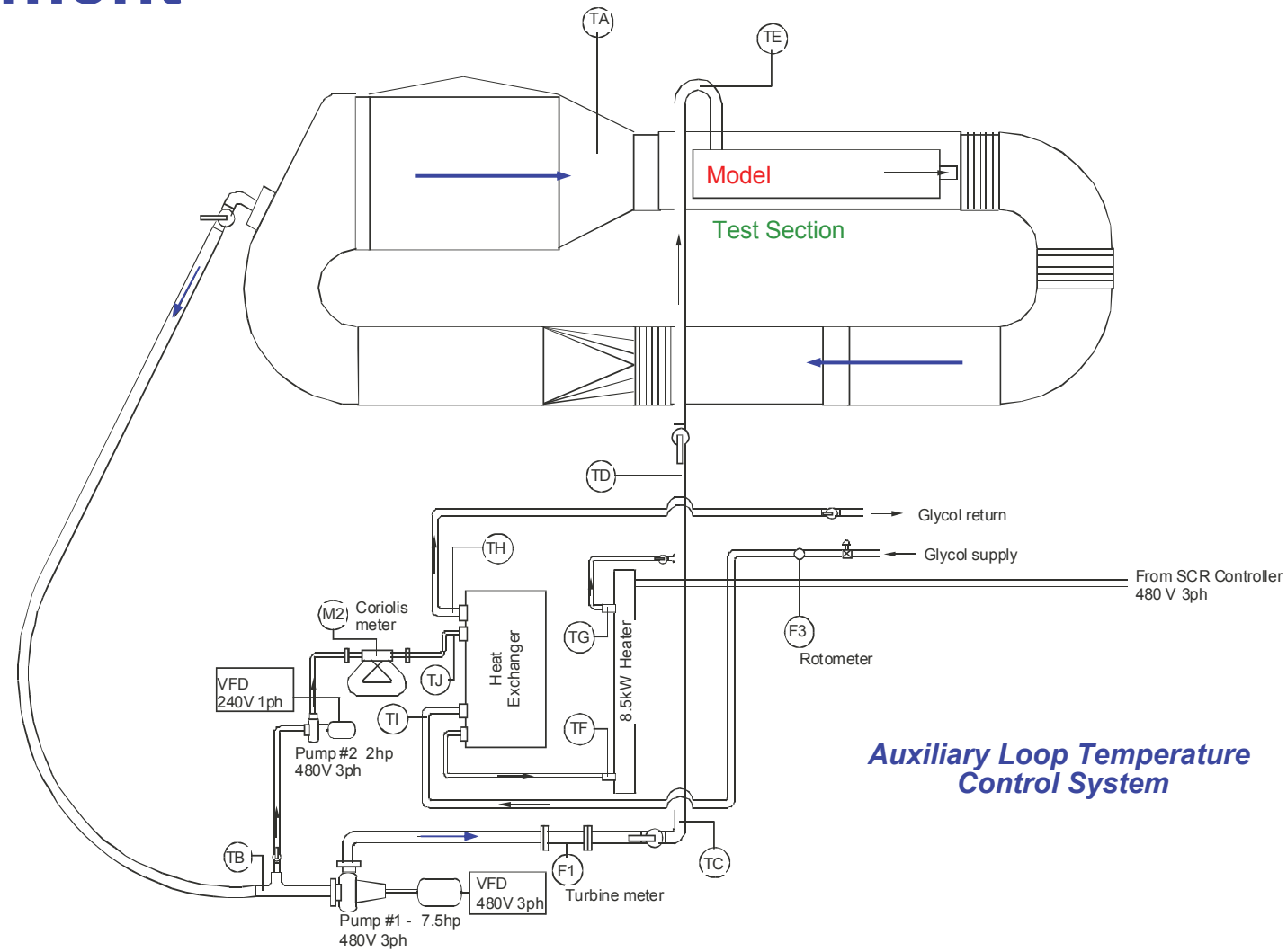




Ref: Becker, S., C. M. Stoots, K. G. Condie, F. Durst and D. M. McEligot, 2002. LDA-measurements of transitional flows induced by a square rib. J. Fluids Engr., *124, pp. 108-117.*

Stoots, C., S. Becker, K. Condie, F. Durst and D. M. McEligot, 2001. A large-scale matched index-of-refraction flow facility for LDA studies around complex geometries. Exp. Fluids, *30, pp 391-398.*

Schematic diagram of typical internal flow experiment



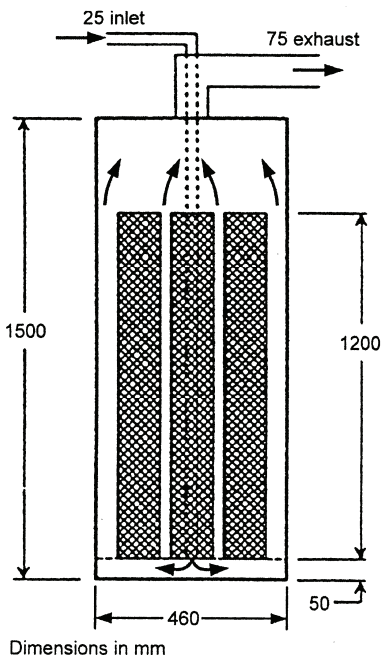
Temperatures of main flow and flow through the model are controlled independently to match the refractive indices of the fluid and transparent model

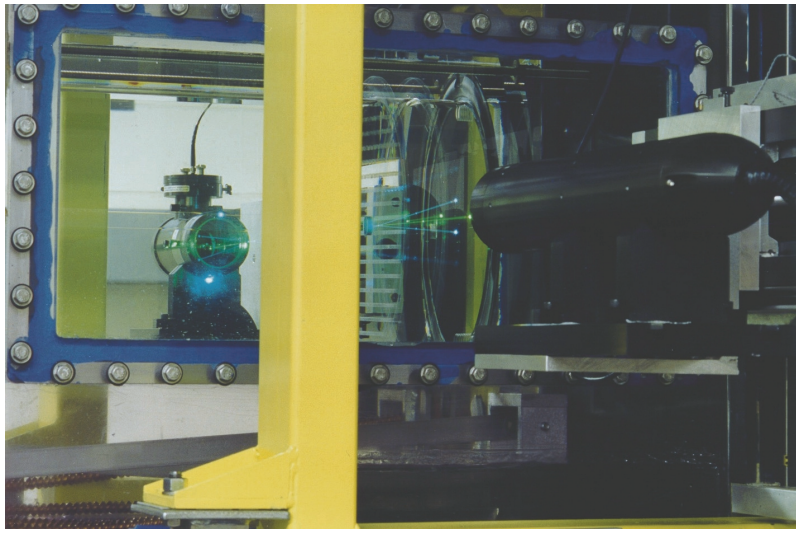
Measurements of fundamental fluid physics of SNF storage canisters

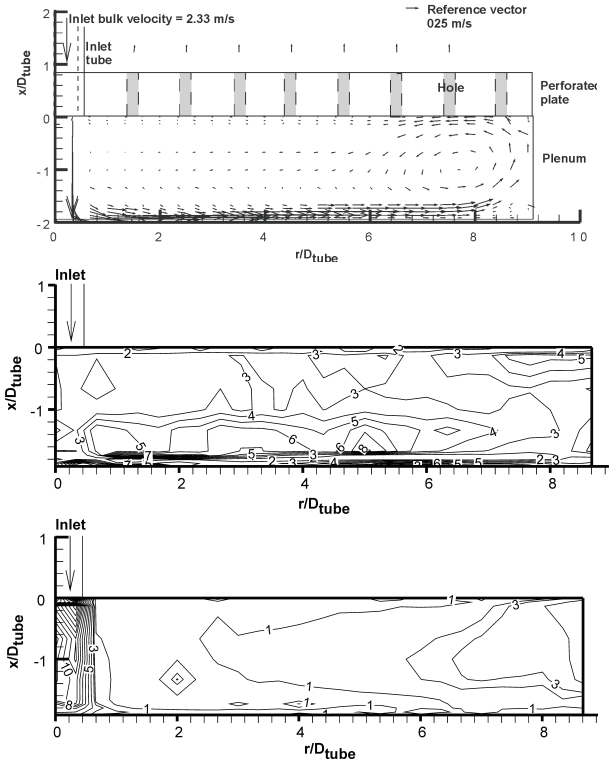
Objective = obtain fundamental measurements of generic flow phenomena occurring during drying applications

Customer = DoE EM Science program, 1997-2001

Collaboration = Prof. J. C. Crepeau, U. Idaho (PI), Prof. R. S. Brodkey and Y. G. Guezennec, Ohio State and Dr. R. C. Clarksean, Leading Technology Designs





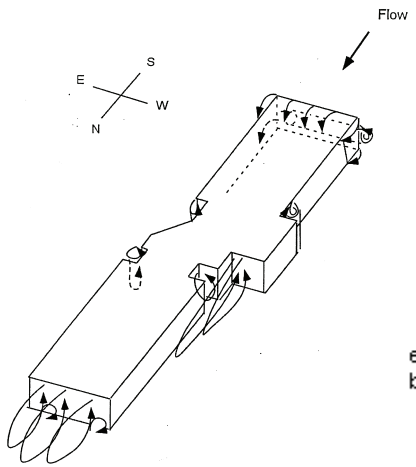


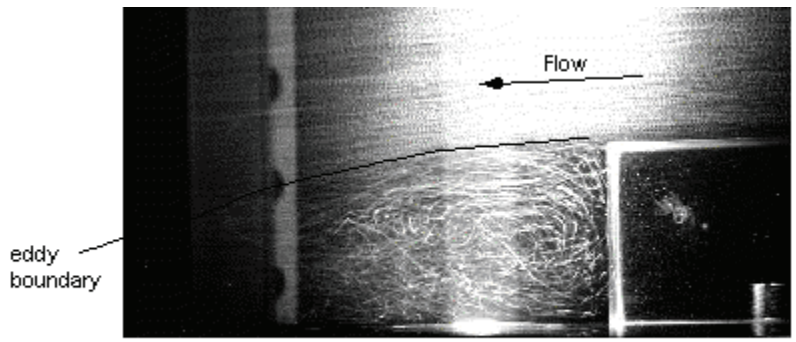
Ref: McCreery, G. E., K. G. Condie, R. C. Clarksean and D. M. McEligot, 2002. Convective processes in spent nuclear fuel canisters. Heat Transfer 2002 *(Proc., 12th International Heat Transfer Conf., Grenoble) Vol. 4, pp 663-668.*

Computational and physical modeling collaboration for DARPA Chem/Bio program application

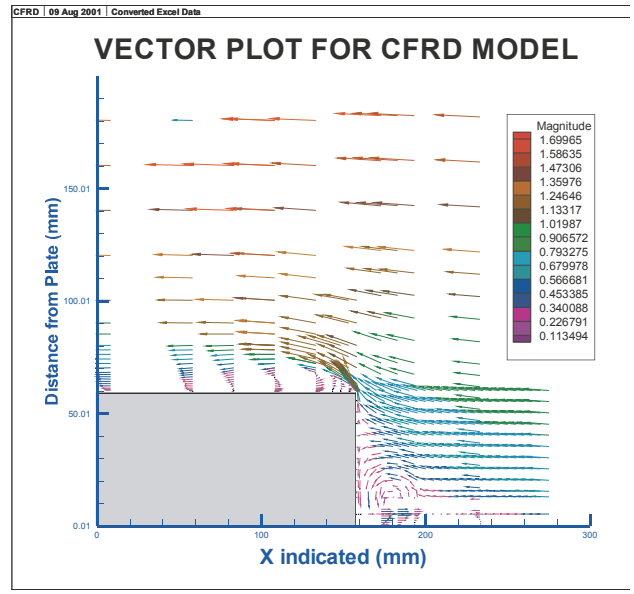
Objective = obtain measurements to assess CFD models for simulation of flow around buildings, particularly separated flow regions

Customer = Bechtel R&D group via CFRD program, 2000-2001





Trailing eddy downstream of model



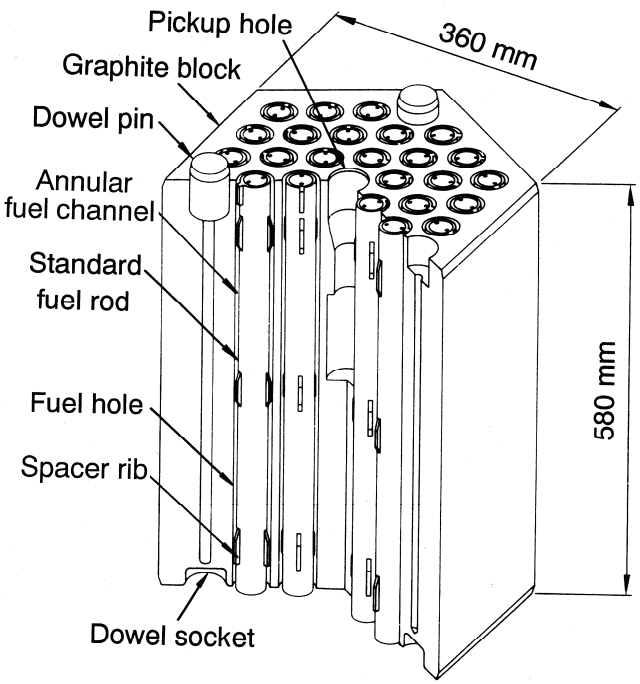
Products:

- Excel files of velocity and turbulence distributions
- Videos of flow visualization
- Knight, K. J., et al., 2002. ASME paper IMECE-2002-34451.

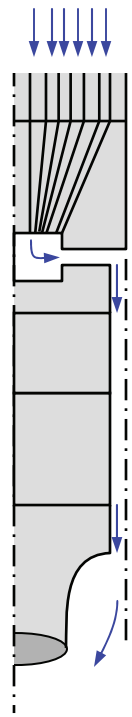
Fundamental thermal fluid physics of high temperature flows in advanced reactor systems

Objective = provide fundamental thermal fluid physics knowledge and measurements necessary for the development of improved predictive methods for application to high temperature flows for advanced reactor systems (primarily GCHTRs)

Customer = DoE NERI program, 1999-2002



HTTR



MHTGR

Gas Temperature Range (K)		
GT-MHR	**573**	**1873**
HTTR	**673**	**1873**
GC-FBR	**723**	**1323**
Fusion blanket	**563**	**973**

Emphases =

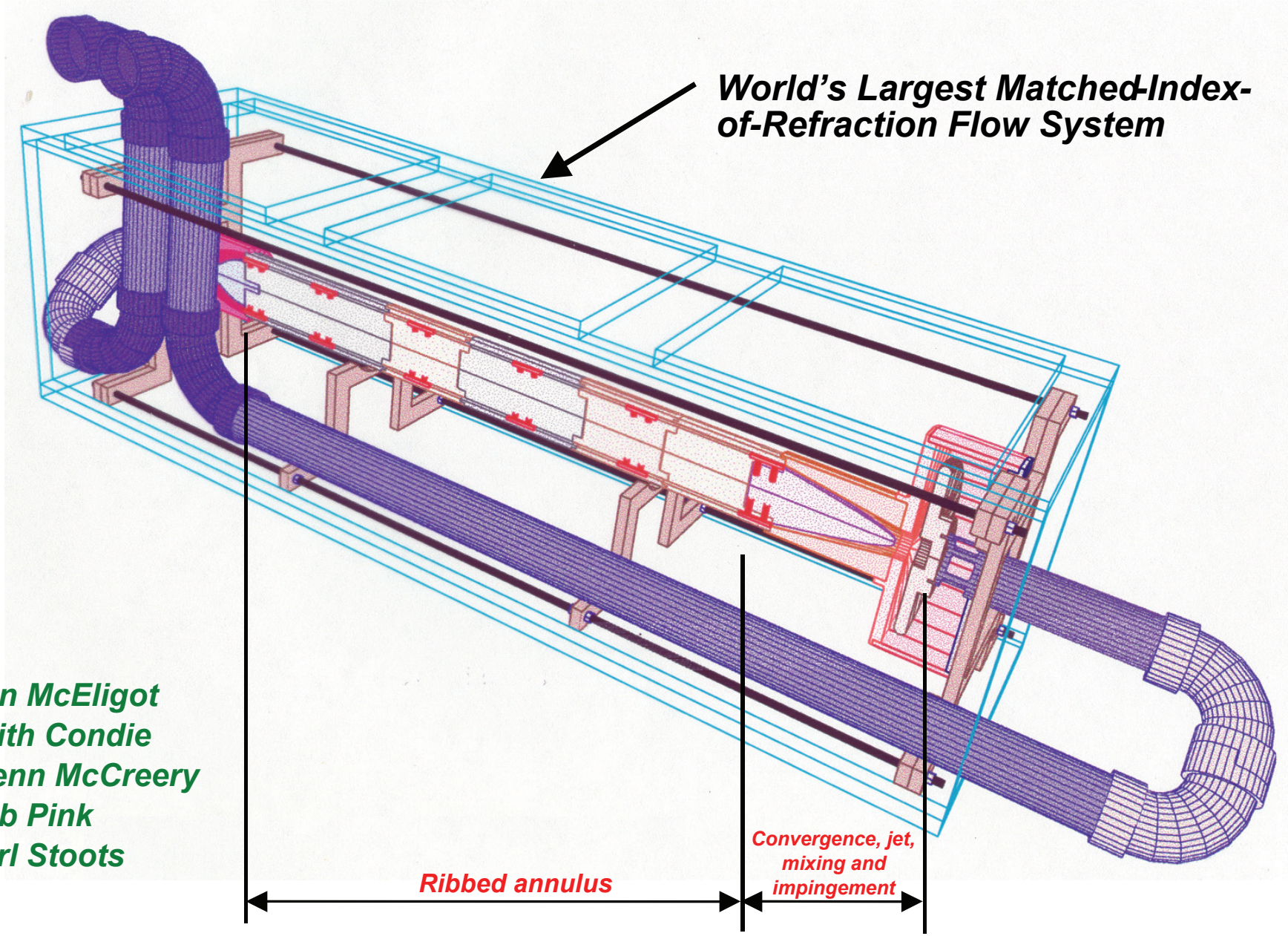
- **Complex geometries**
- **Gas property variation**

Tasks/Participants/Organizations

HT/FF in advanced reactors	Drs. Arkal Shenoy and Guido Baccaglini / GA
Measurements for complex geometries	Donald M. McEligot, Keith G. Condie, Glenn E. McCreery and Robert J. Pink / INL
LES development	Prof. Richard H. Pletcher / Iowa State U.
DNS development	Profs. Shin-ichi Satake / Toyama U. and Tomoaki Kunugi / Kyoto U.
Multi-sensor probe development	Profs. James M. Wallace and Petar Vukoslavcevic / U. Maryland
Measurements for buoyancy and gas property variation	Prof. J. Derek Jackson / U. Manchester

Idaho National Laboratory

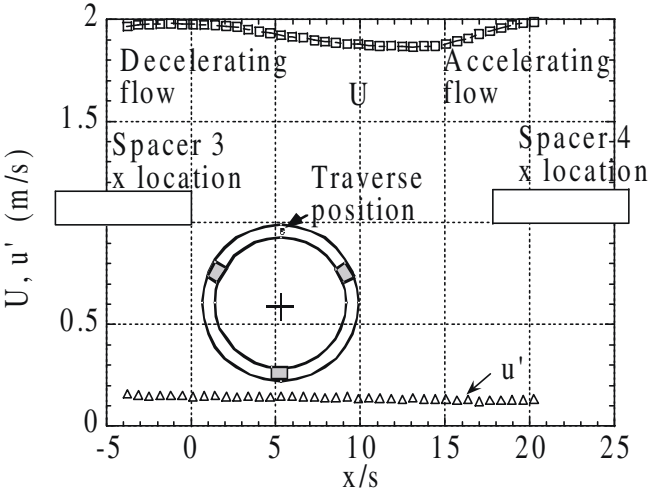
INL – Experiment for Assessment of Computer Codes for Complex Reactor Flow Phenomena



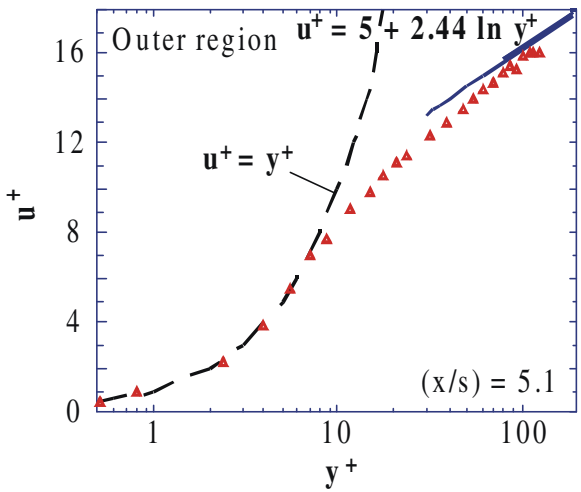
Don McEligot
Keith Condie
Glenn McCreery
Bob Pink
Carl Stoots

Streamwise mean velocity measurements by LDV

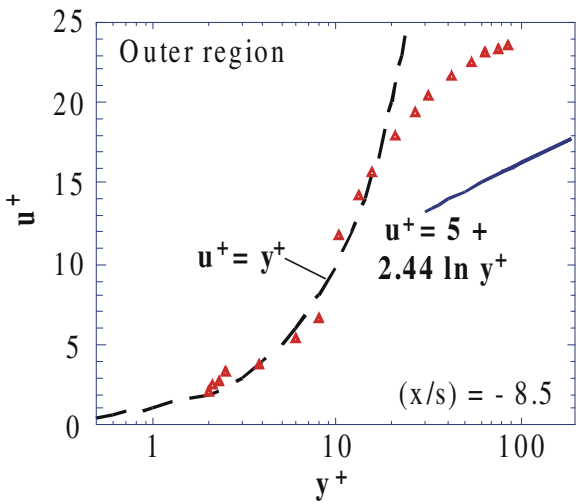
Axial profiles



Decelerating region



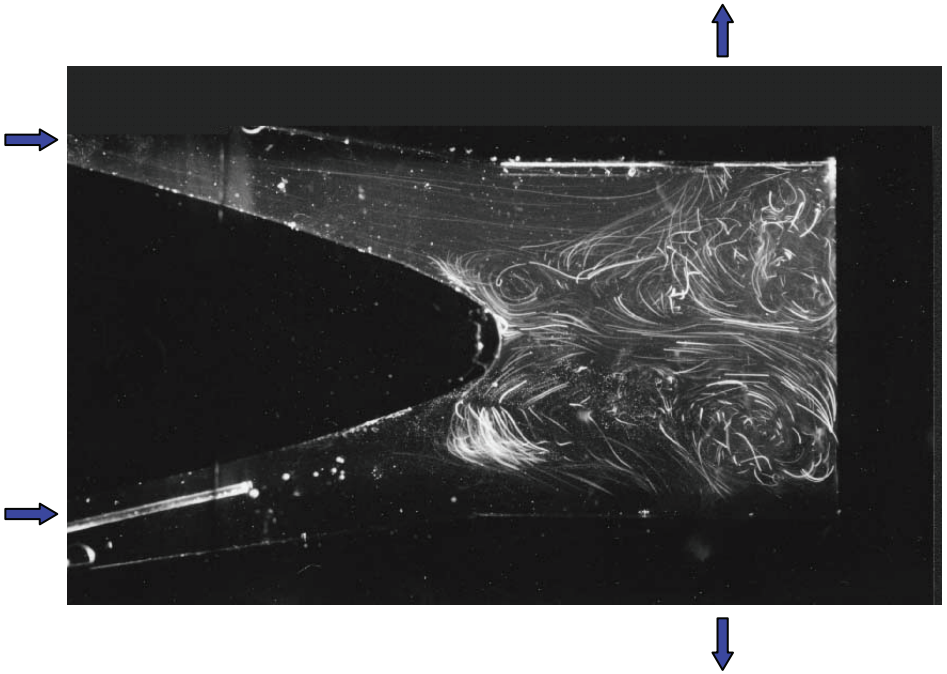
Accelerating region



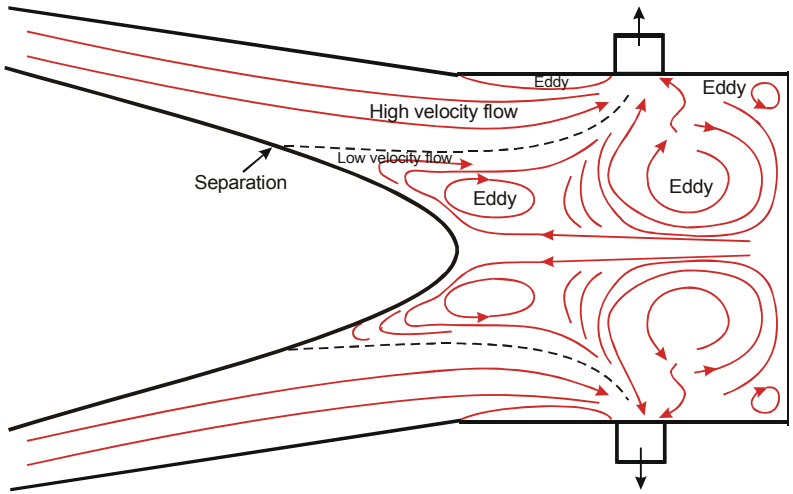
Ref: McCreery, G. E., R. J. Pink, K. G. Condie, 2003. Fluid dynamics of ribbed annuli. NuReth-10 paper J00203, Seoul, October.

Idaho National Laboratory

Preliminary flow visualization for exit convergence



Typical streak-line visualization



Deduced streamlines

Key results of collaborations

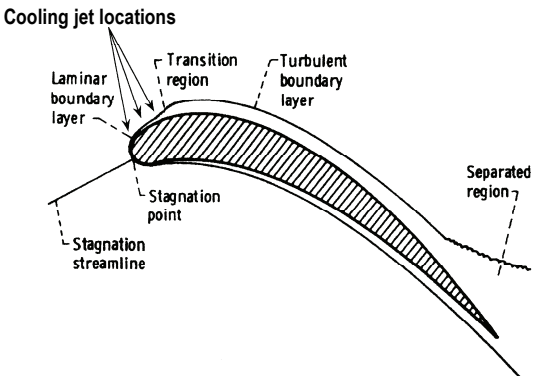
- 13 archival papers published or in press
- 35 conference publications
- 13 invited presentations
- 31 publications and presentations on other topics

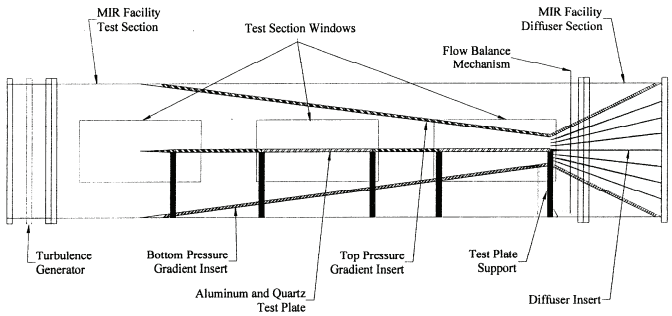
Related to this NERI project

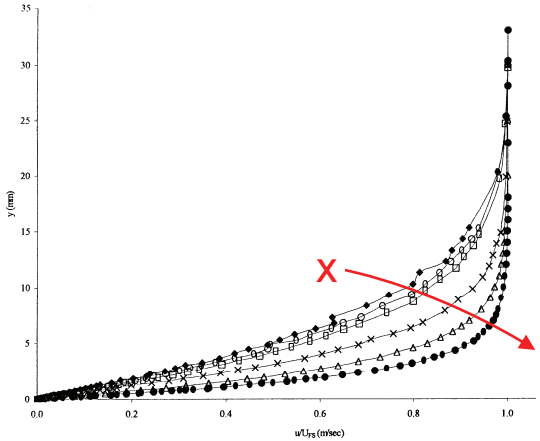
Boundary layers on turbine blades with rough surfaces

Objective = conduct basic measurements that will reveal the influences of realistic surface roughness on the near-wall behavior of the boundary layer

User = U.Idaho for AFOSR/D-EPSCoR project, doctoral thesis, 2000-2003





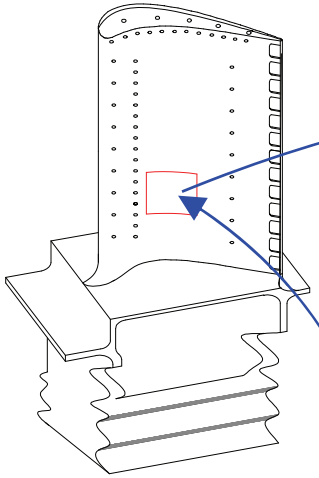


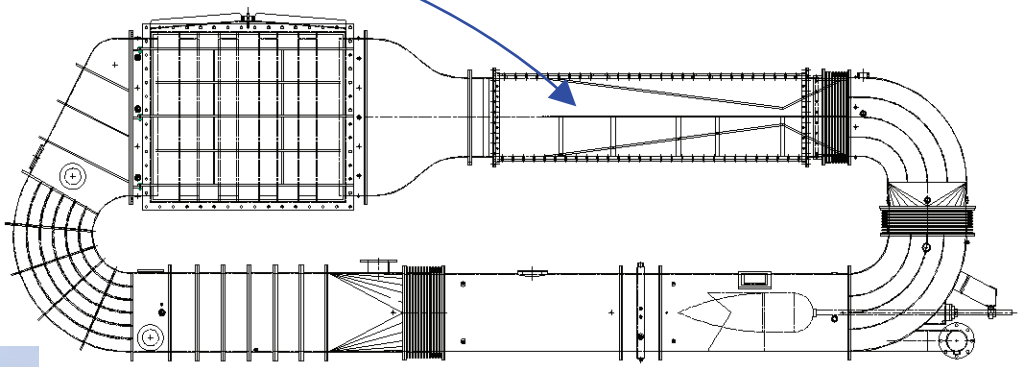
Phase I: Smooth plate, II. Realistic roughness

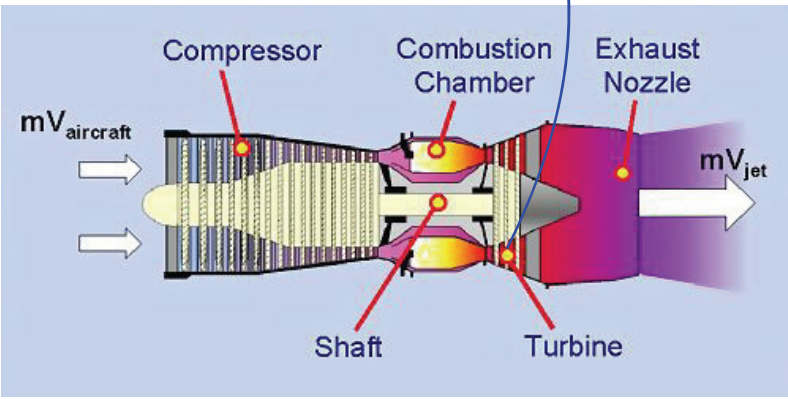
McIlroy, H. M., R. S. Budwig and D. M. McEligot, 2003. Scaling of turbine blade roughness for model studies. ASME paper IMECE-2003-42167.

McIlroy, H. M. and R. S. Budwig, 2007. The boundary layer over turbine blade models with realistic rough surfaces. *J. Turbomachinery* 129, pp 318-330.

Rough surface model scaling



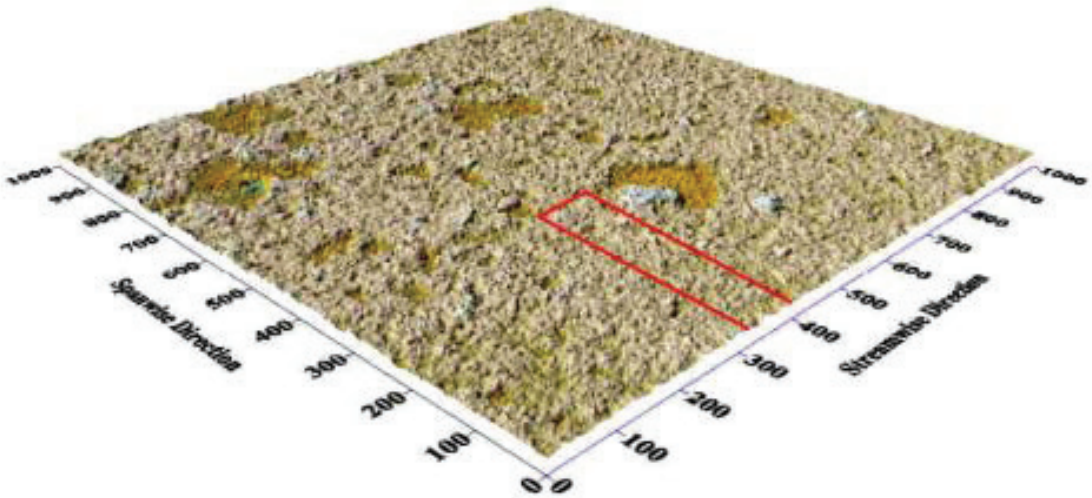




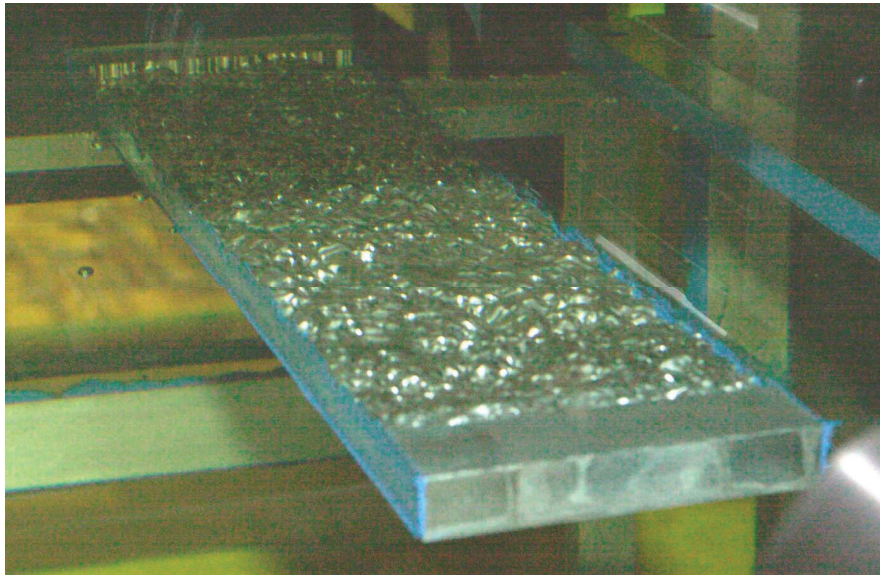
University of Idaho

Model of a rough “spall” in a smoother surface

Data of Bons et al.



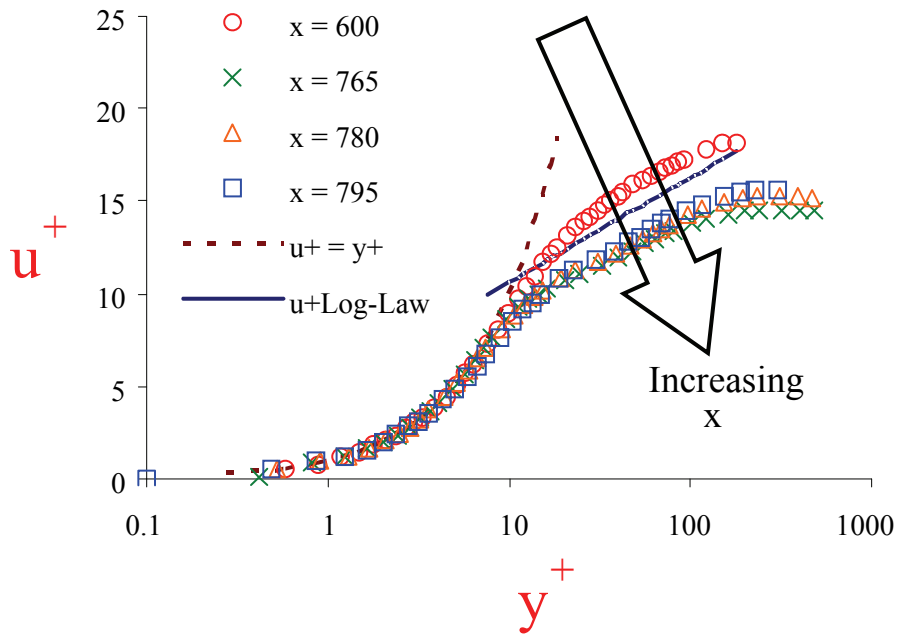
~100x scale model installed



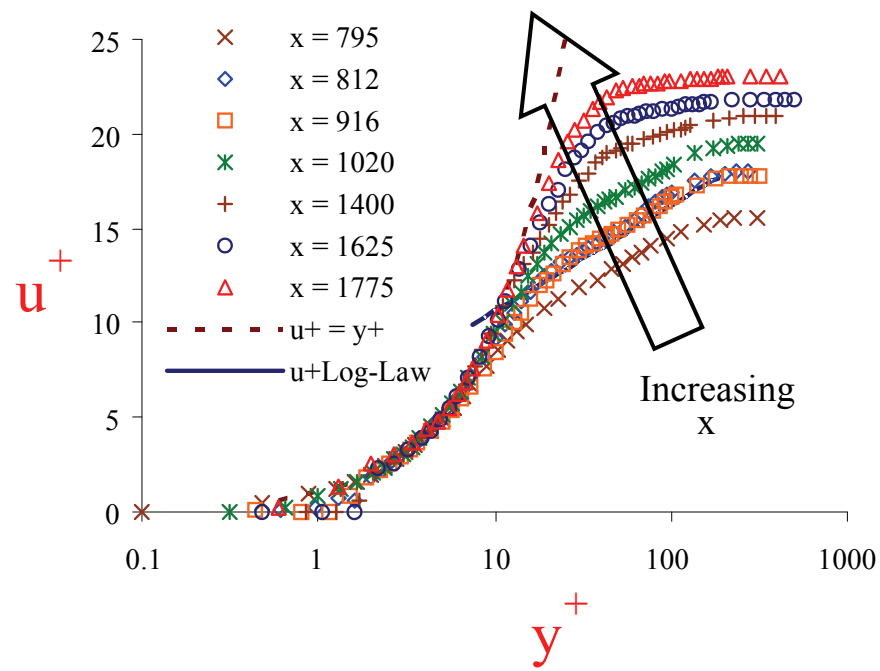
University of Idaho

Typical near-wall LDV measurements downstream of roughness

Immediately downstream



Effect of streamwise pressure gradient



Additional data = $c_f\{x\},\ \delta\{x\},\ \theta\{x\},\ u'\{x,y\},\ v'\{x,y\},\ \overline{uv}\{x,y\}$

for reference smooth plates and for plates upstream and downstream of roughness

University of Idaho

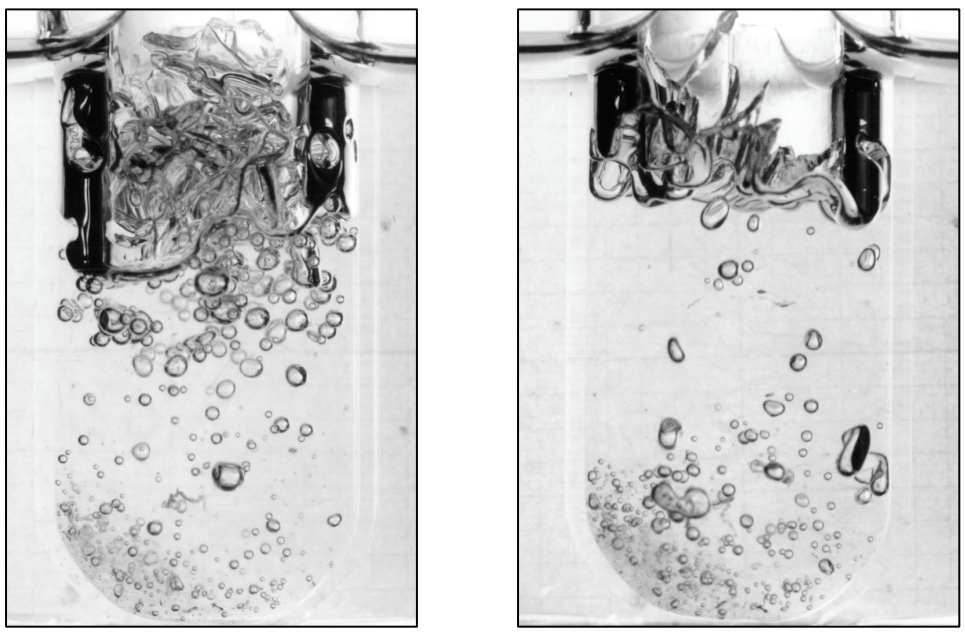
Multiphase flow in complex fracture apertures under a wide range of flow conditions

[P. Meakin, G. E. McCreery and D. M. McEligot, INL]

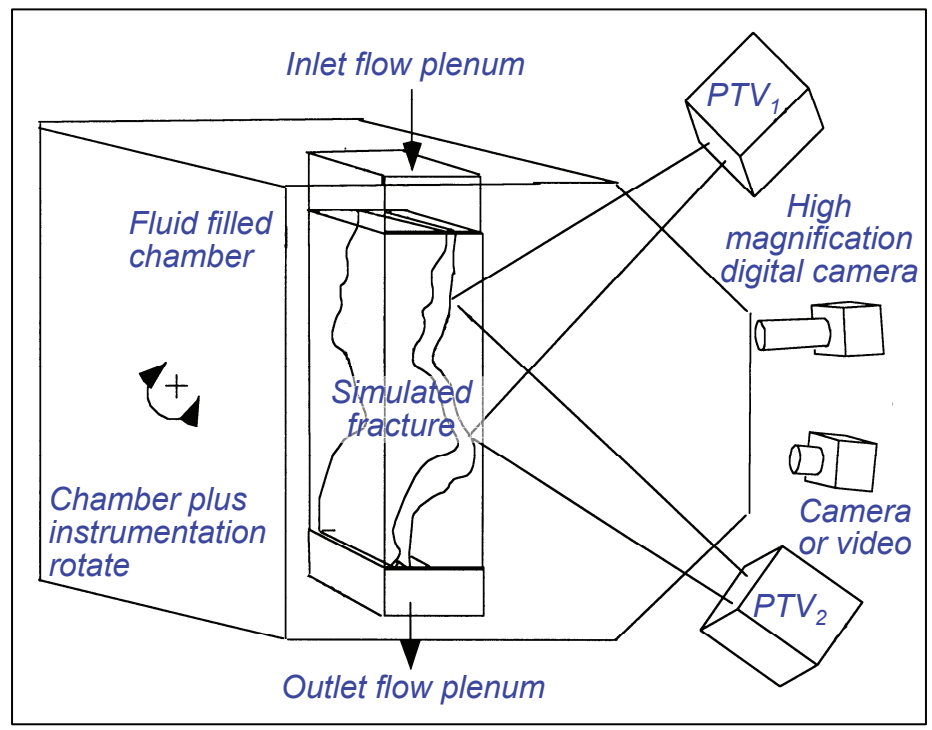
Objective = by coordinating physical and computer modeling, develop new conceptual models to understand how pollutants travel in the vadose (unsaturated gas-liquid) zone

Customer = DoE EM Science program, 2002-2005

Collaboration = Prof. D. Rothman, MIT, Profs. B. Jamtveit and J. Feder, U. Oslo



Small-scale demonstration of transient phase displacement in a porous medium by MIR [McCreery, INEEL, 2001]

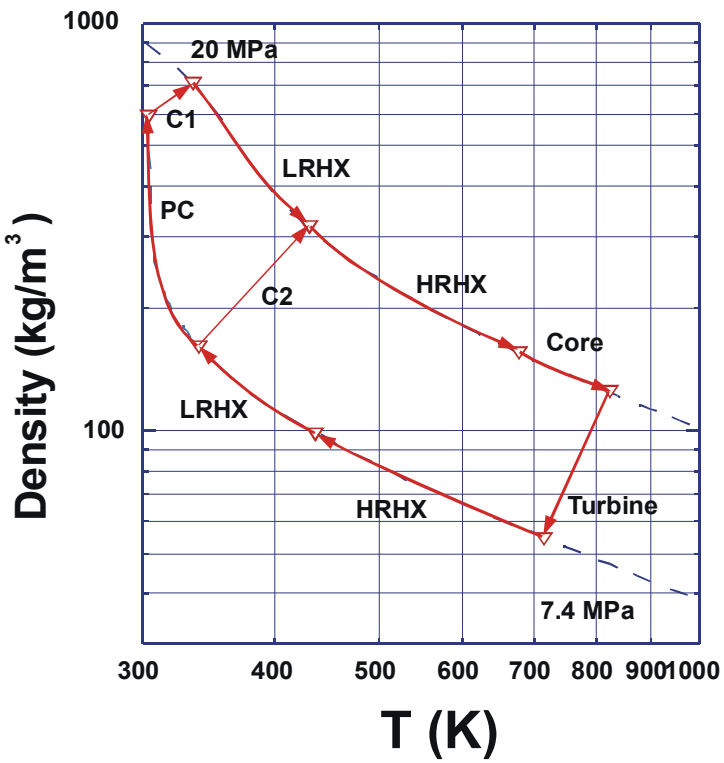


Ref: McCreery, G.E., 2002. Initial simulated fracture apparatus, INEEL memo, November

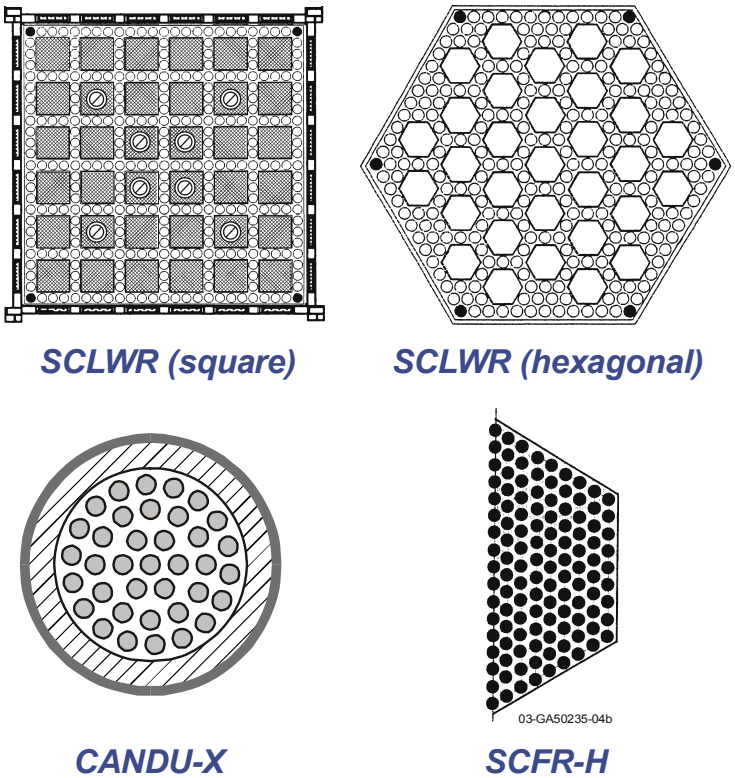
Advanced computational thermal fluid physics and its assessment for light water reactors (LWRs) and supercritical reactors (SCRs)

Objective = develop fundamental knowledge needed for improved predictive techniques in LWR and SCR applications

Funding = DoE US/RoK I-NERI program, 2001-2005

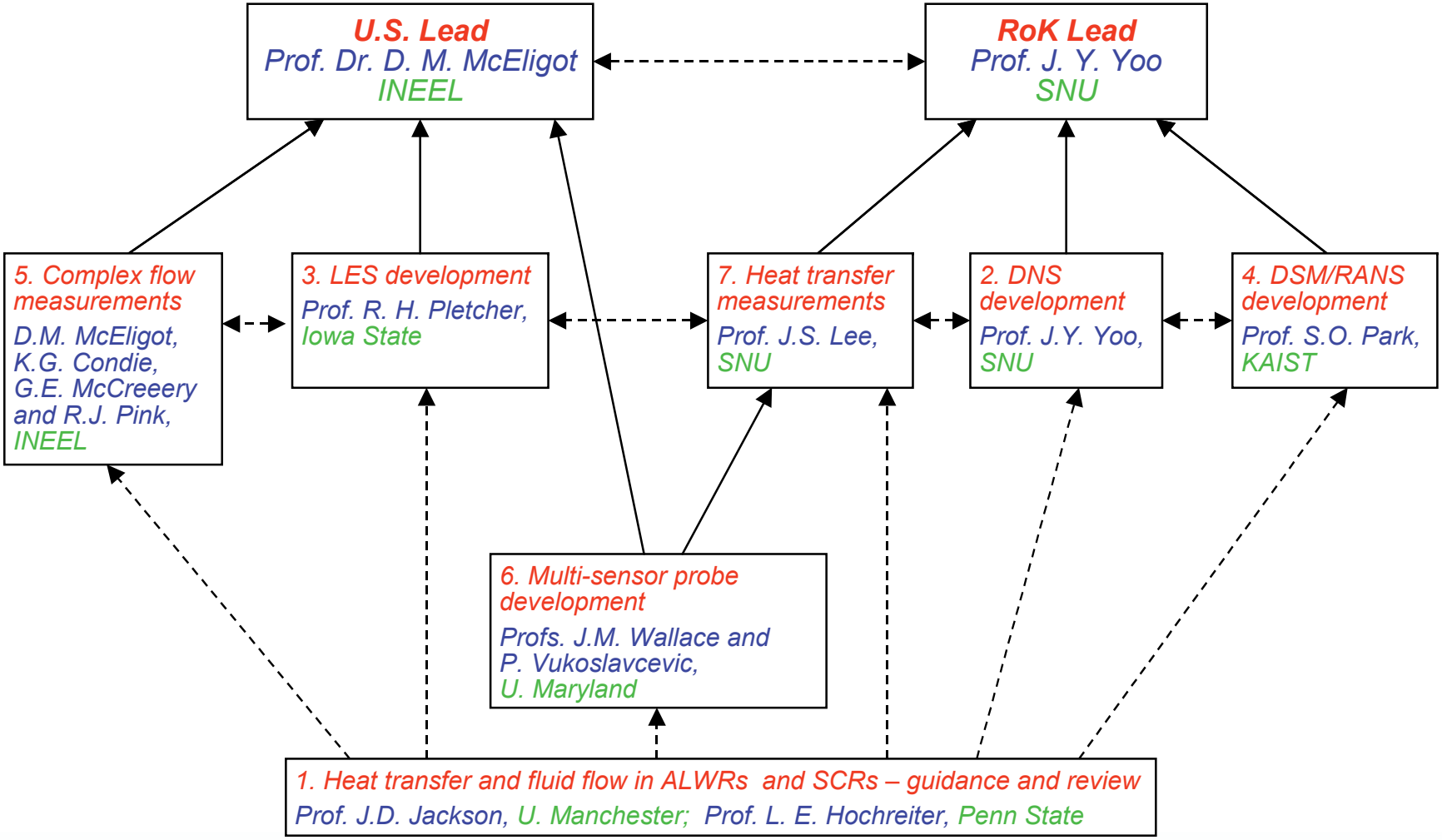


→ Fluid property variation!

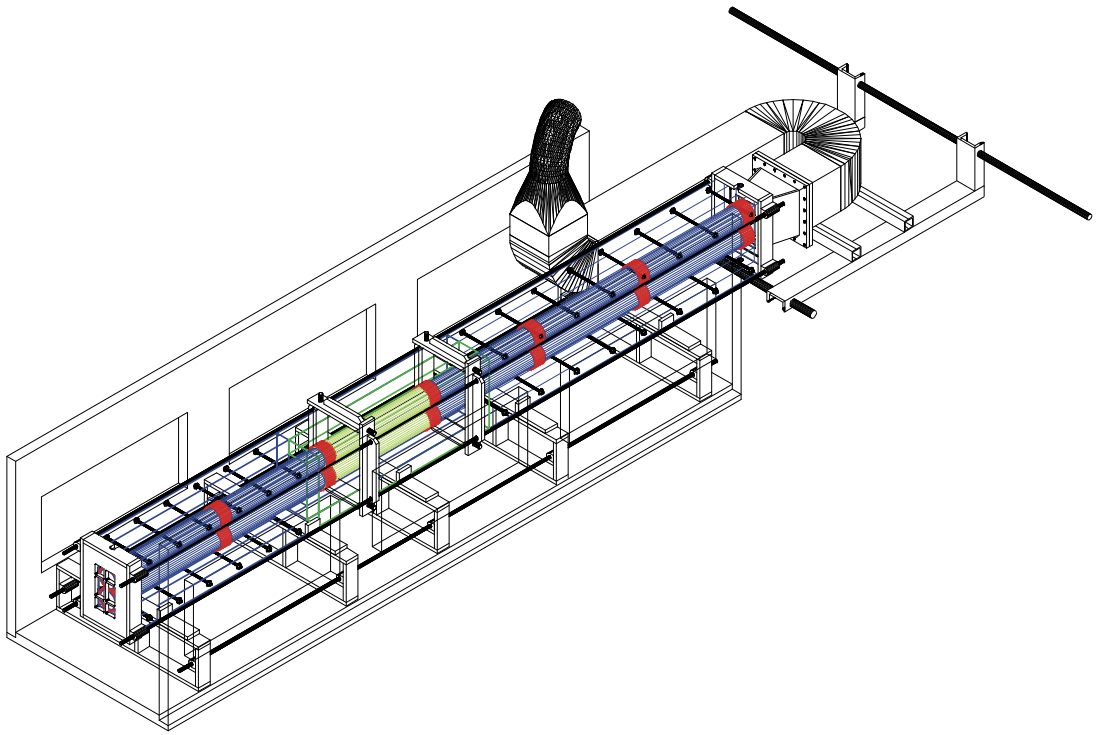


→ Complex geometries!

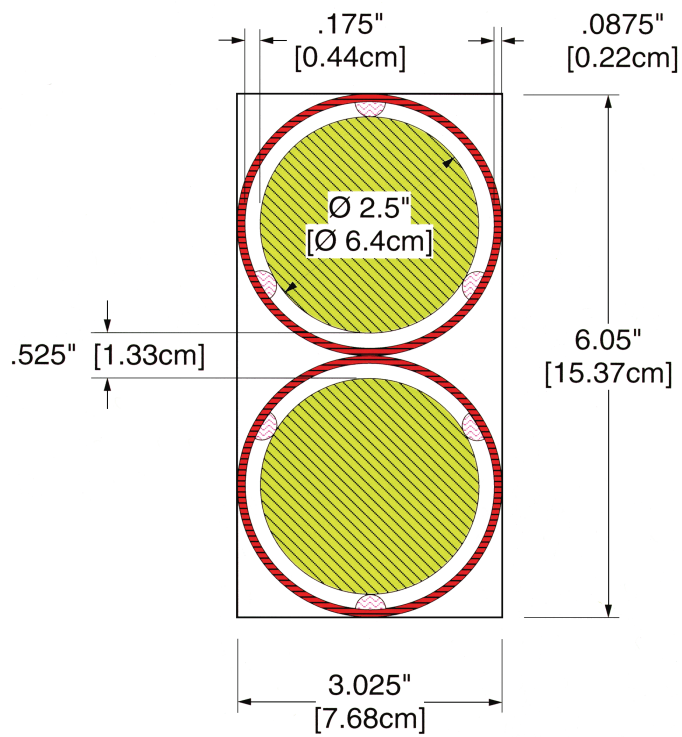
Project tasks



INL role = MIR experiments for assessment of predictive codes for flow through complex reactor geometries

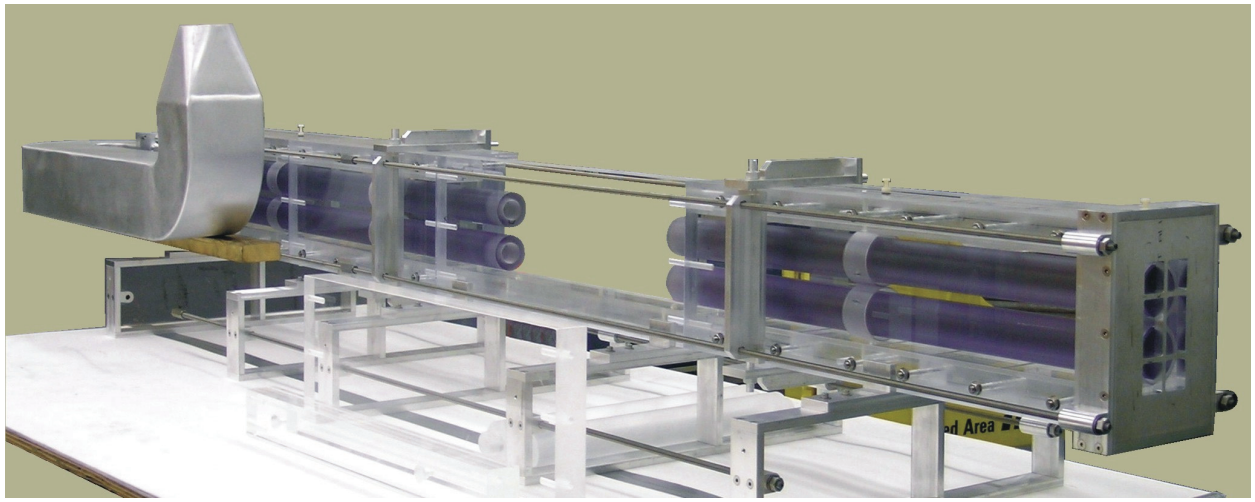


Design of model installation in MIR test section



Model cross section

Model assembled as it should appear in MIR test section with refractive indices matched



Some publications:

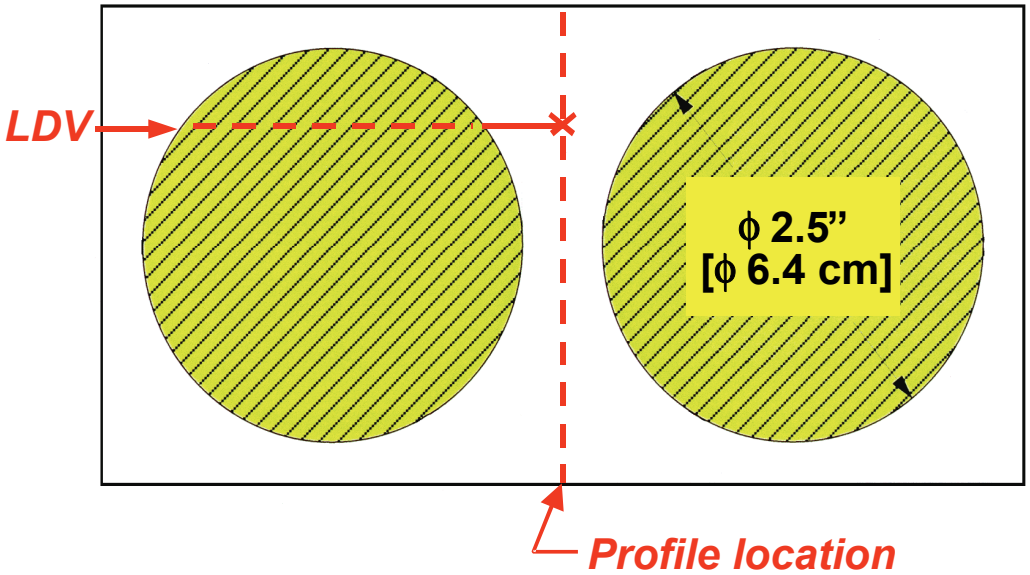
- Petrovic, D., P. Vukoslavcevic and J. M. Wallace, 2003. The accuracy of turbulent velocity component measurements by multi-sensor hot-wire probes: a new approach to an old problem. *Exp. Fluids*, 34, pp. 130-139.
- Xu, X., J. S. Lee, R. H. Pletcher, A. M. Shehata and D. M. McEligot, 2004. Large eddy simulation of turbulent forced gas flows in vertical pipes with high heat transfer rates. *Int. J. Heat Mass Transfer,* 47, pp. 4113-4123.
- He, S., W. S. Kim, P. X. Jiang and J. D. Jackson, 2004. Simulation of mixed convection heat transfer to carbon dioxide at supercritical pressure. *Int. J. Mech. Eng. Sci.,* Proc. I. Mech. E., 218, Part C, Special Issue, pp. 1281-1296.
- Spall, R. E., A. H. Richards and D. M. McEligot, 2004. An assessment of the k-w and v2-f turbulence model for strongly heated internal gas flows. *Numerical Heat Transfer, Part A*, 46, pp. 831-849.
- Bae, J. H., J. Y. Yoo, H. Choi and D. M. McEligot, 2008. Structure of turbulent boundary layers developing in a heated vertical annular pipe at supercritical pressure. *Phys. Fluids* 20, pp. 055108-1 to -20.

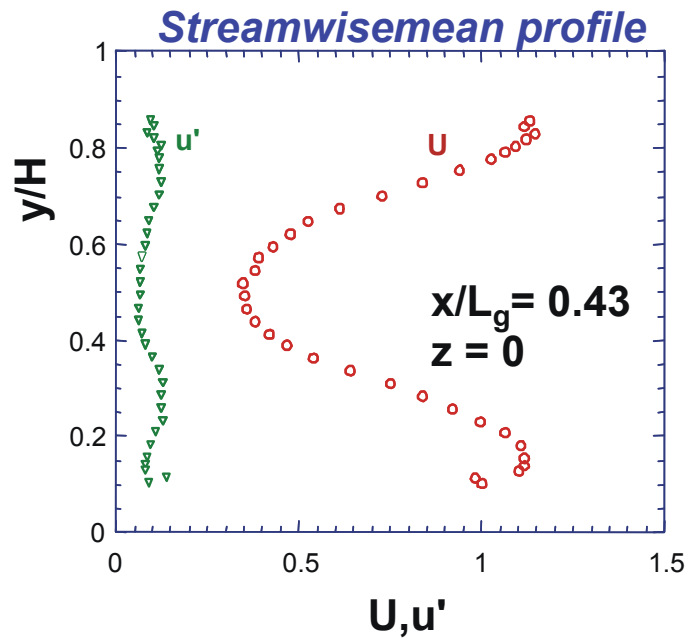
Final report:

McEligot, D. M. et al., 2005. INEEL/EXT-05-00001, October. Availiable from OSTI

LDV measurements in MIR flow system

Data on centerplane between rods

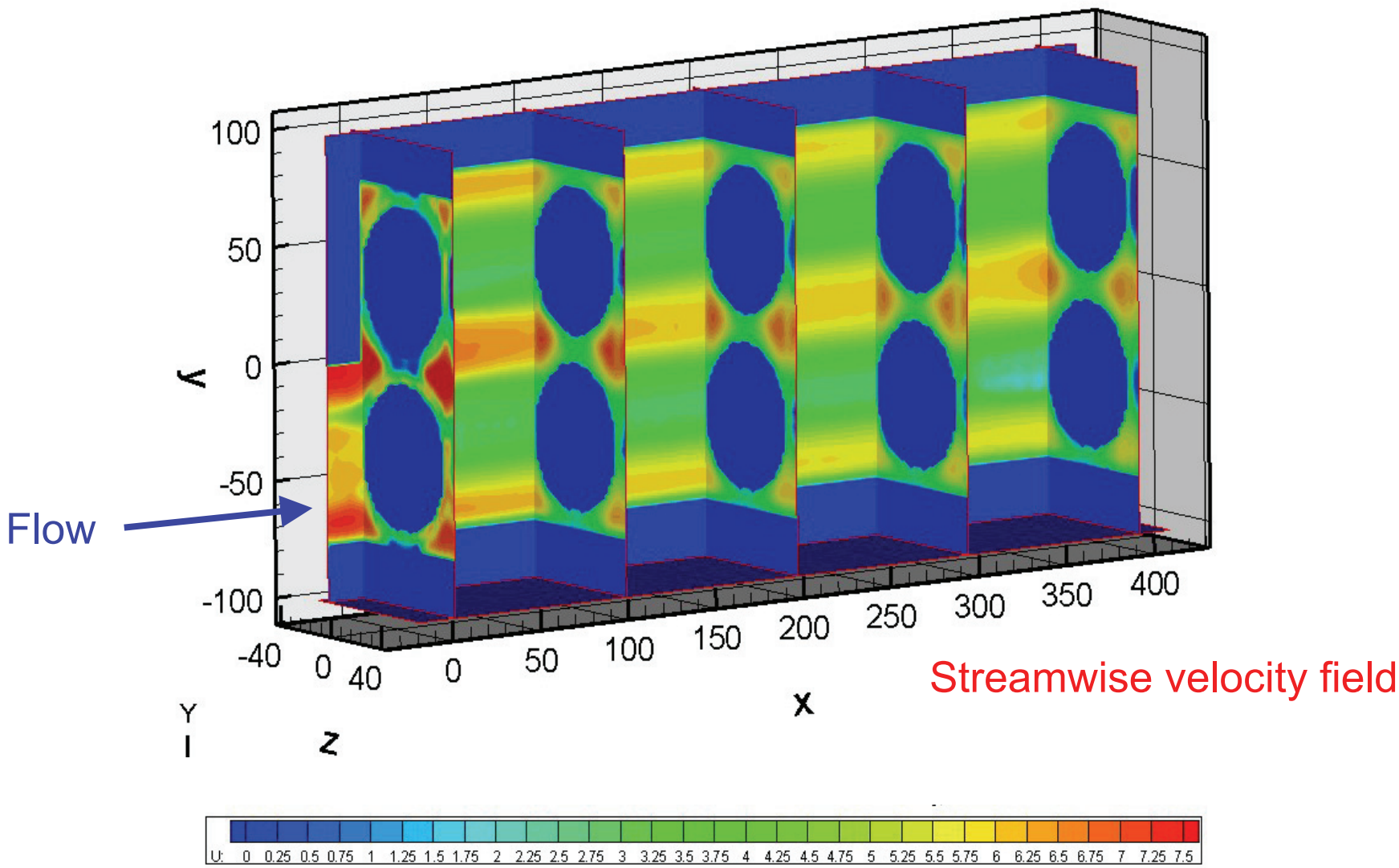




Matching of the refractive indices of the fluid and rod allows undistorted access to the profile plane

PIV data from INL MIR flow system

(Idealized coolant channels in US/Korea I-NERI project [2005])



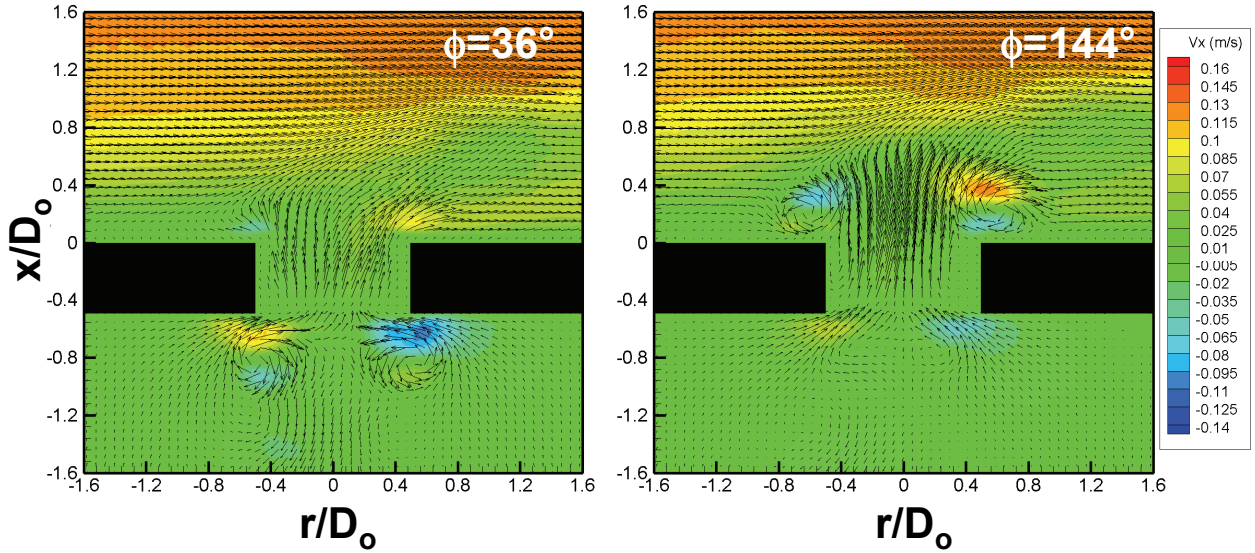
Streamwise velocity field

http://www.efdl.usu.edu

Interaction of synthetic jet with a boundary layer

Objective = Obtain improved fundamental understanding of the interaction between a synthetic jet and a cross flow

User = U. Wyoming for AFOSR/D-EPSCoR project, 2003-4

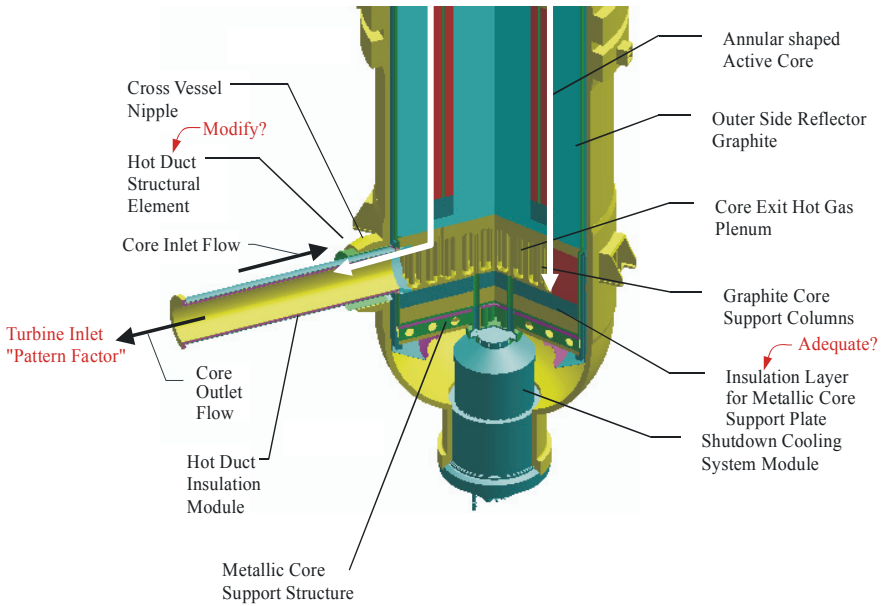


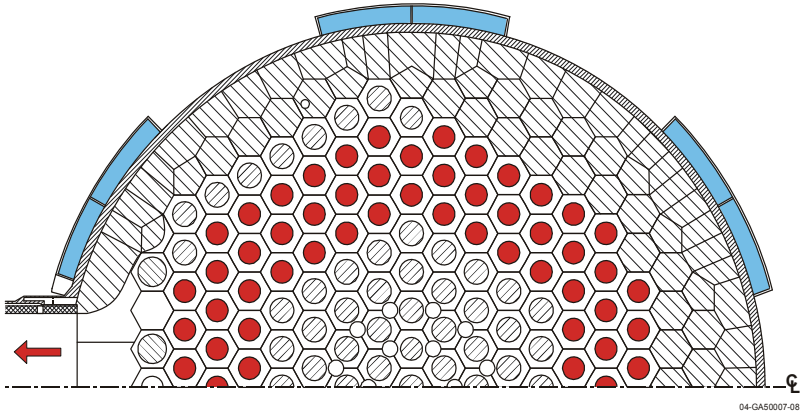
Shuster, J.M., R.J. Pink, D.M. McEligot and D.R. Smith, 2005. The interaction of a circular synthetic jet with a cross-flow boundary layer. AIAA Fluid Dynamics Conference, June.

Complex flow features in the lower plenum of an NGNP concept

Objective: Provide benchmark data for assessment and improvement of codes proposed for NGNP designs and safety studies

Customer = DoE NE NGNP program, 2004-2007

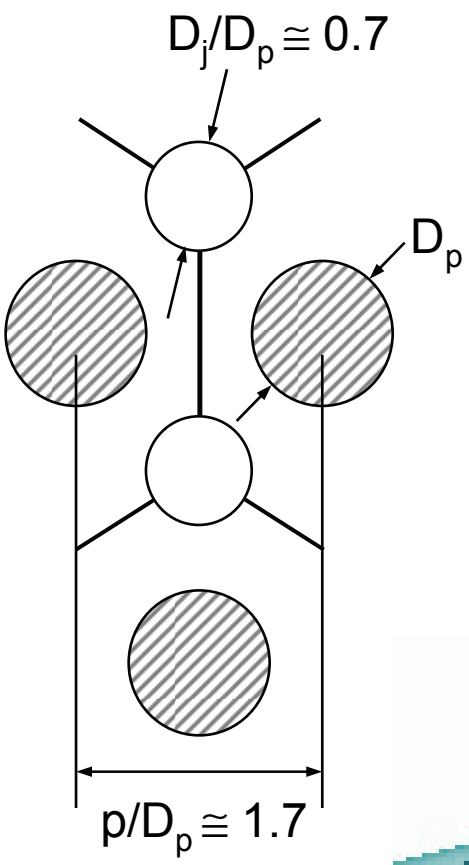




Plan view of lower plenum for prismatic NGNP concept

McEligot, D.M., and G.E. McCreery, 2004. Scaling studies and conceptual experiment designs for NGNP CFD assessment. INEEL/EXT-04-02502, November.

Preliminary scaling studies -- lower plenum ("hot streaking")

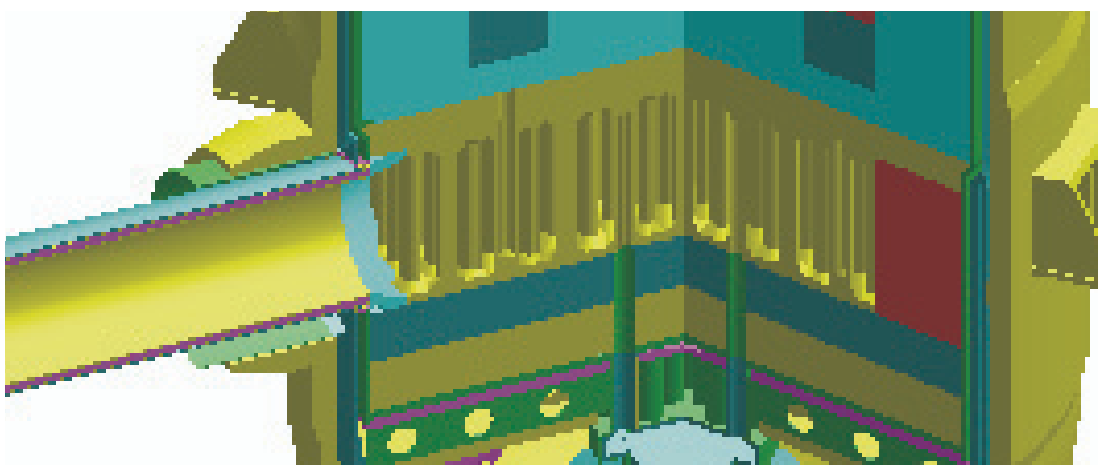


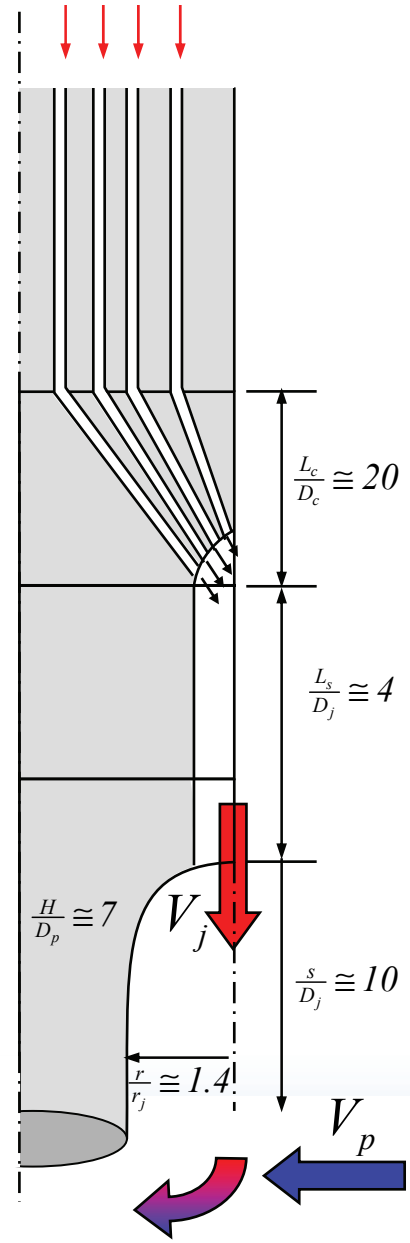
One typical concept

Desired: T (or C), $\vec{V}$, $\vec{v}'$ as fns{x,y,z}, Nu for surfaces, f or L, Str

Parameters: Geometry, Re_p, Re_j, V_j/V_p, Ri or a buoyancy parameter and T_j/T_p for heated jets

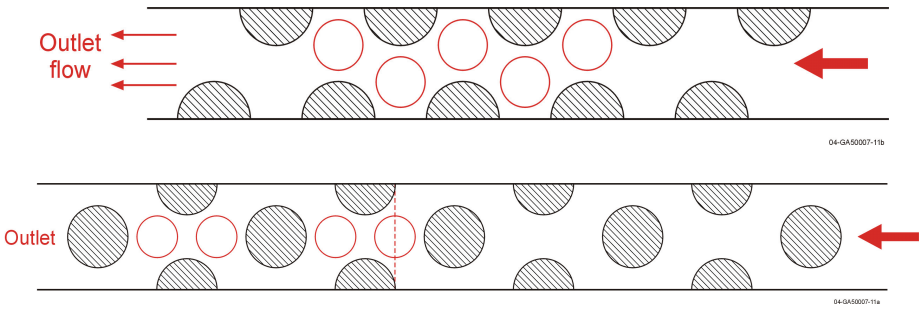
Conditions: Normal, reduced power, transients



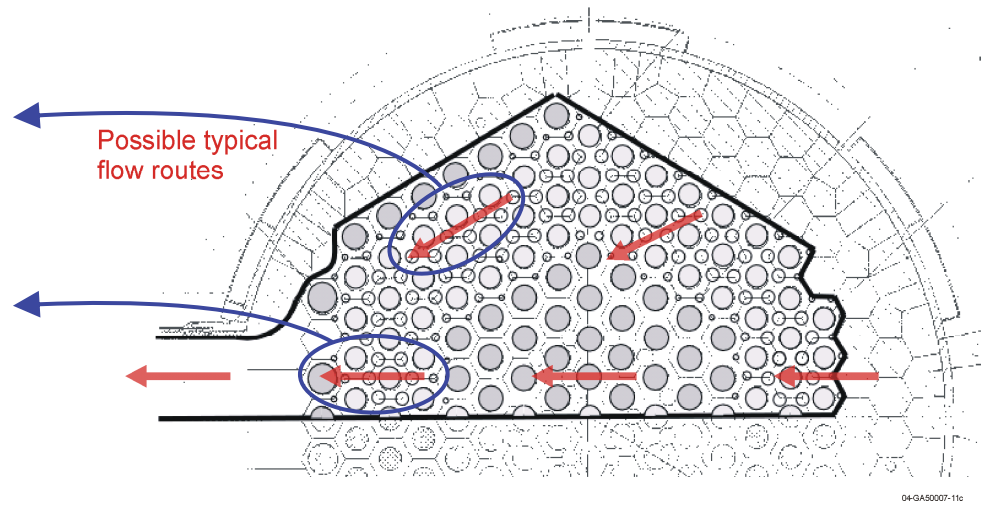


Potential experiment concepts for lower plenum flows

Purpose: assessment of momentum equation solution, scalar mixing and turbulence models for typical plenum geometry in limiting case of negligible buoyancy and constant properties



Conceptual model designs (plan view)



Possible flow paths in NGNP lower plenum

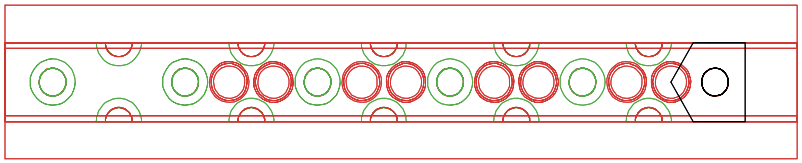
Measurements

Flow visualization

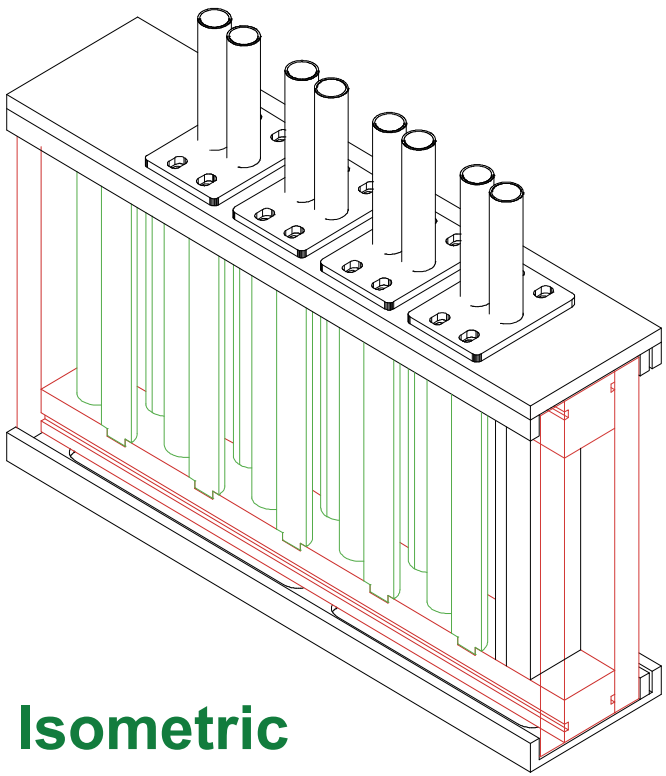
Particle imaging velocimeter – flow patterns, mean velocities, mixing of passive scalars

Laser Doppler velocimeter – time-resolved mean velocity components and turbulence quantities in flows

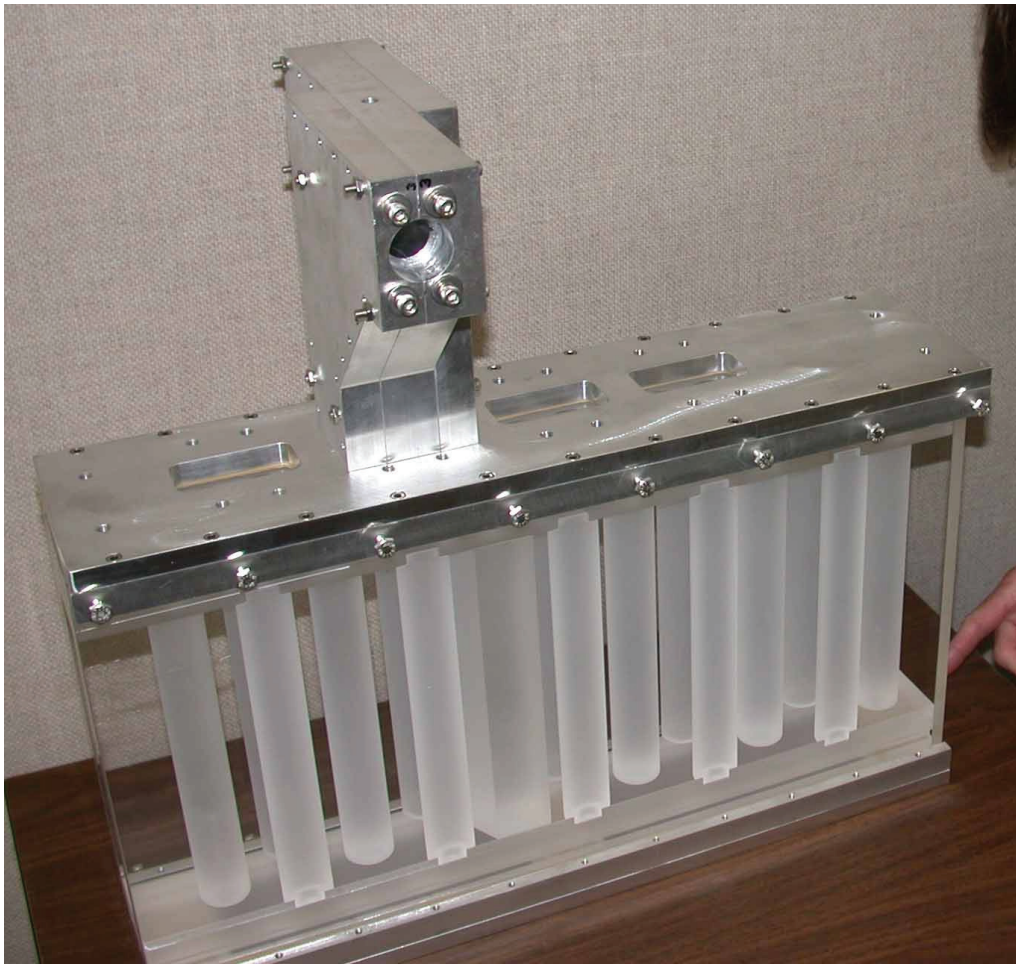
Initial INL lower plenum MIR experiment, ~1/7th scale



Plan view



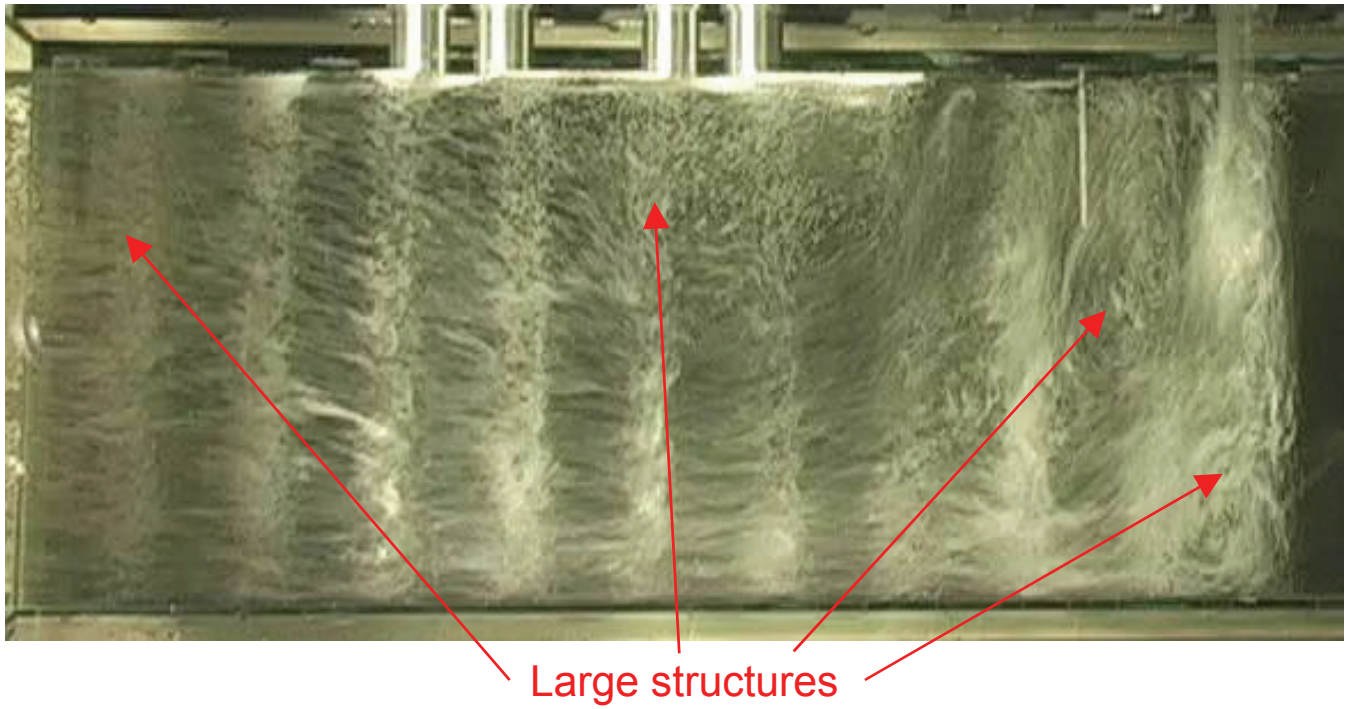
Isometric



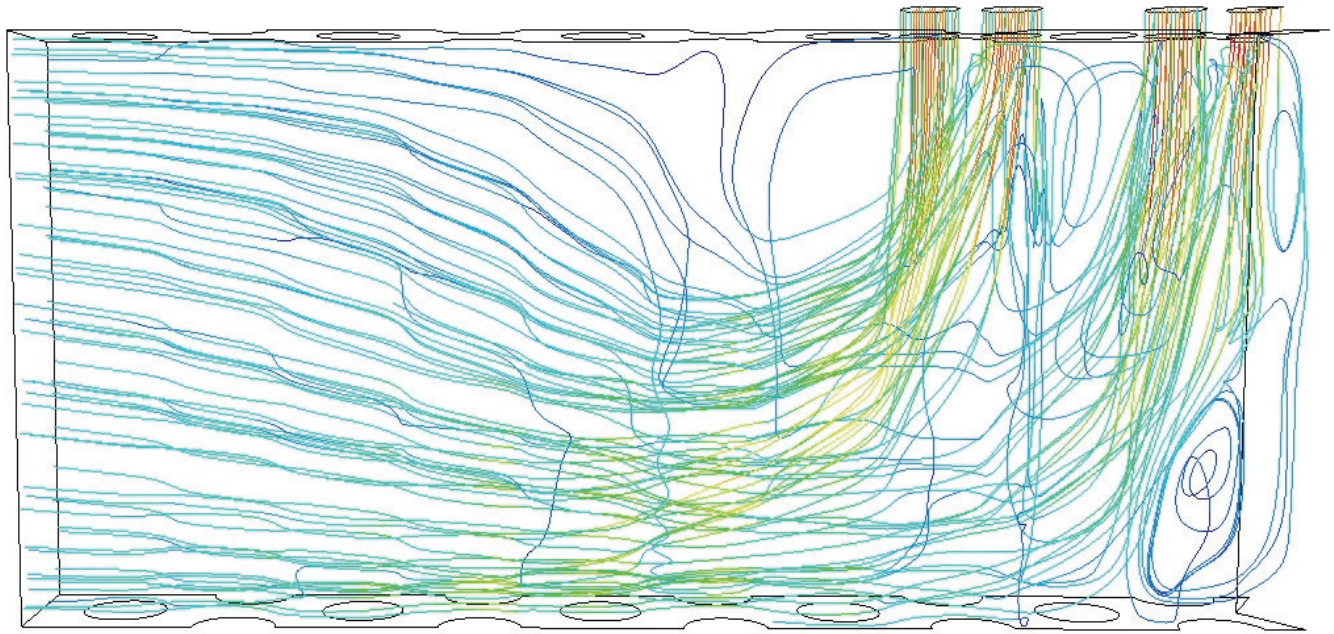
Quartz and aluminum model

General flow patterns

Flow visualization by D. Christensen and R. C. Johnson [INL/EXT-06-15161]

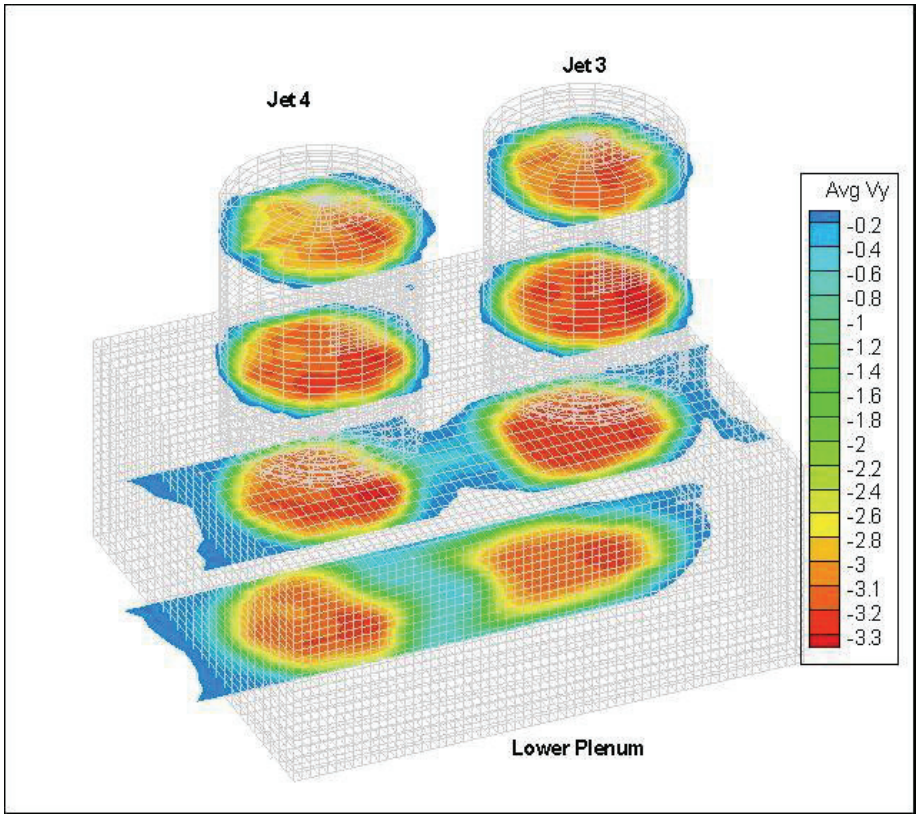


CFD predictions by R. W. Johnson [ICONE17-75604, 2009]

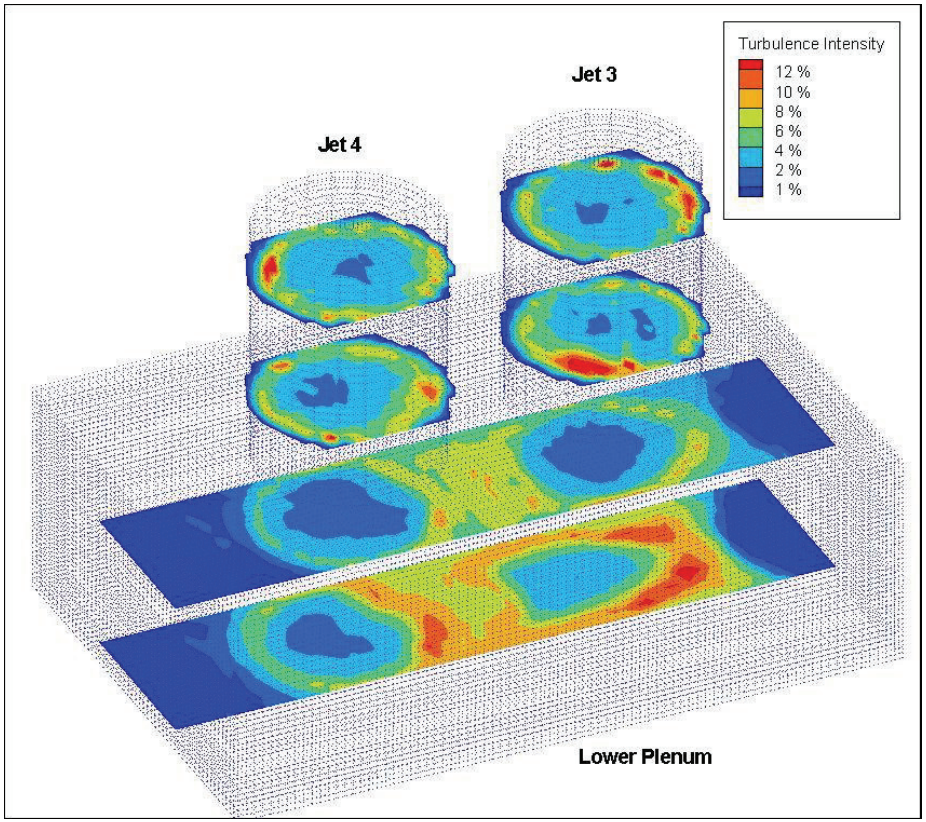


3-D PIV measurements of inlet jet flows

Vertical mean velocity

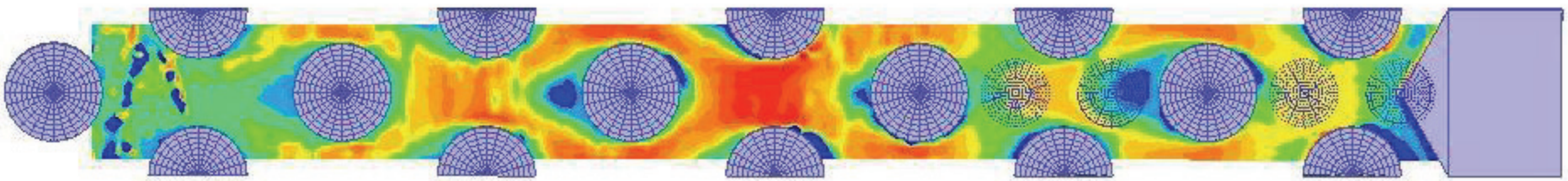


Turbulence intensities

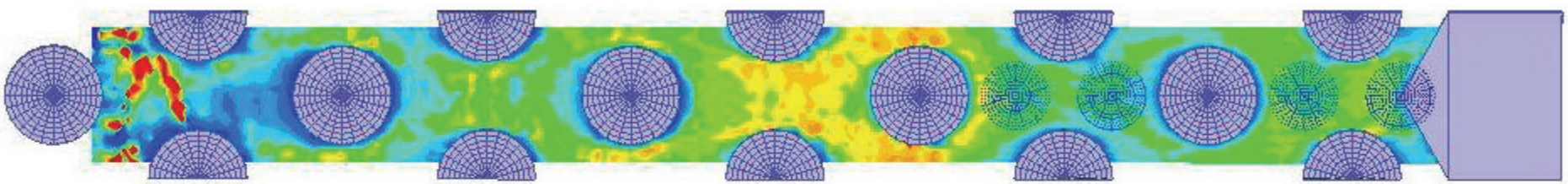


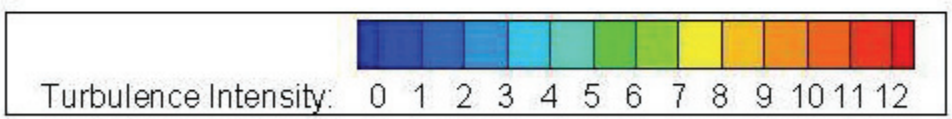
3-D PIV measurements at a low plane in model

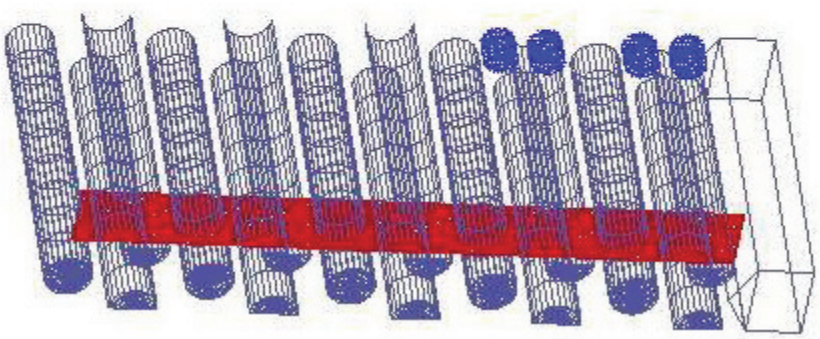
Streamwise mean velocity, U



Turbulence intensity (%)



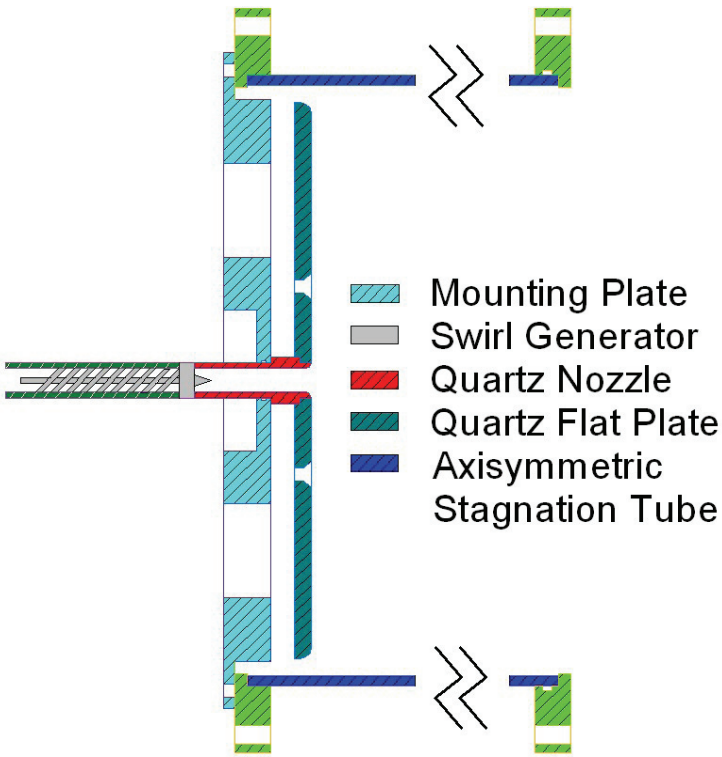




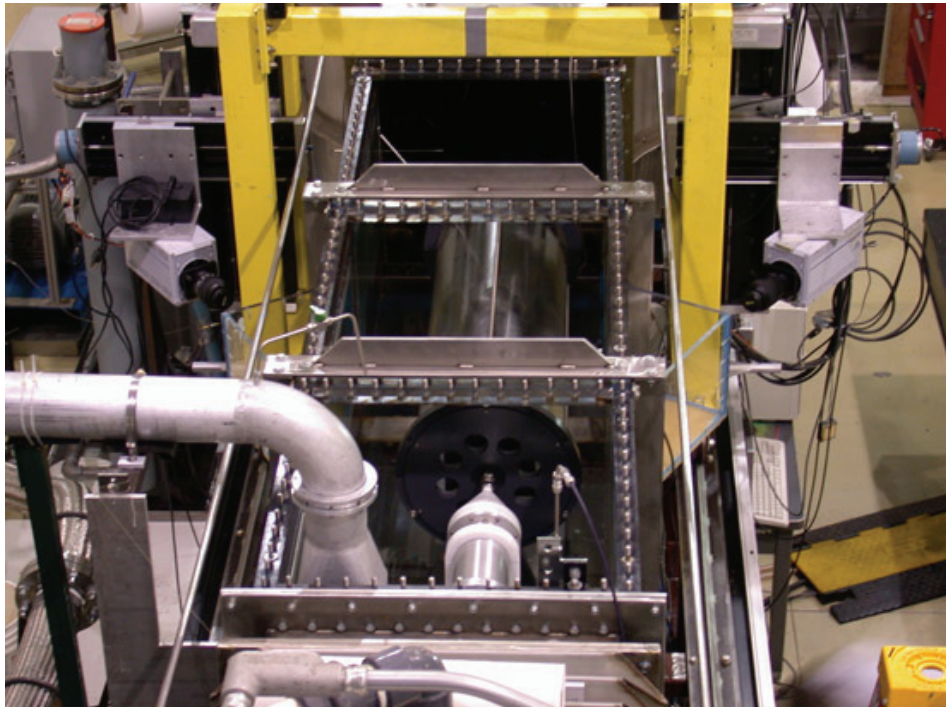
Flow in non-symmetric swirling jets

Objective(s) = validation and enhancement of CFD and HT predictive capabilities for Gen IV reactor systems

User = Utah State U. for DoE U-NERI program, 2006-9



Jet model

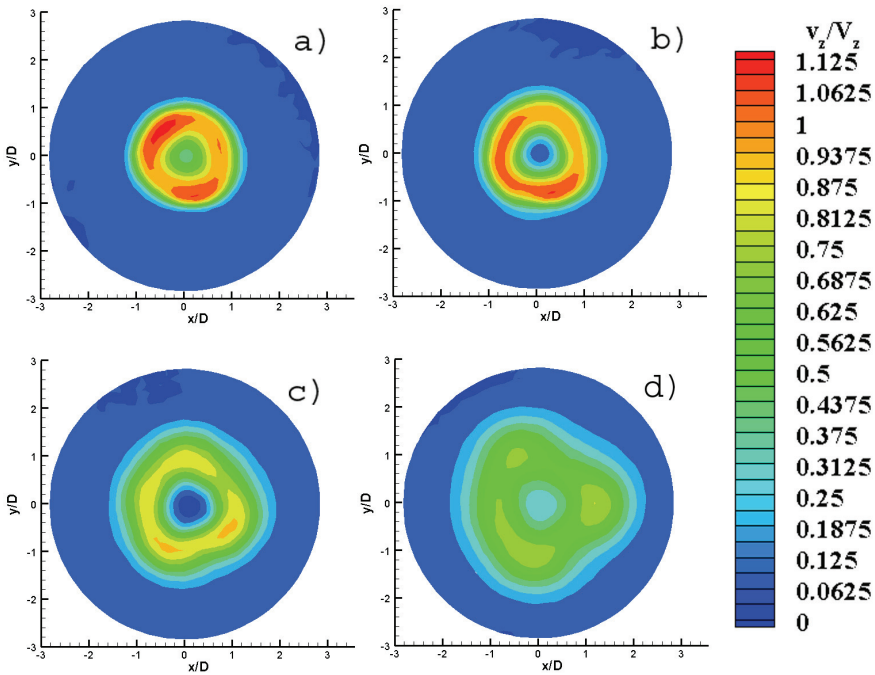


Installation

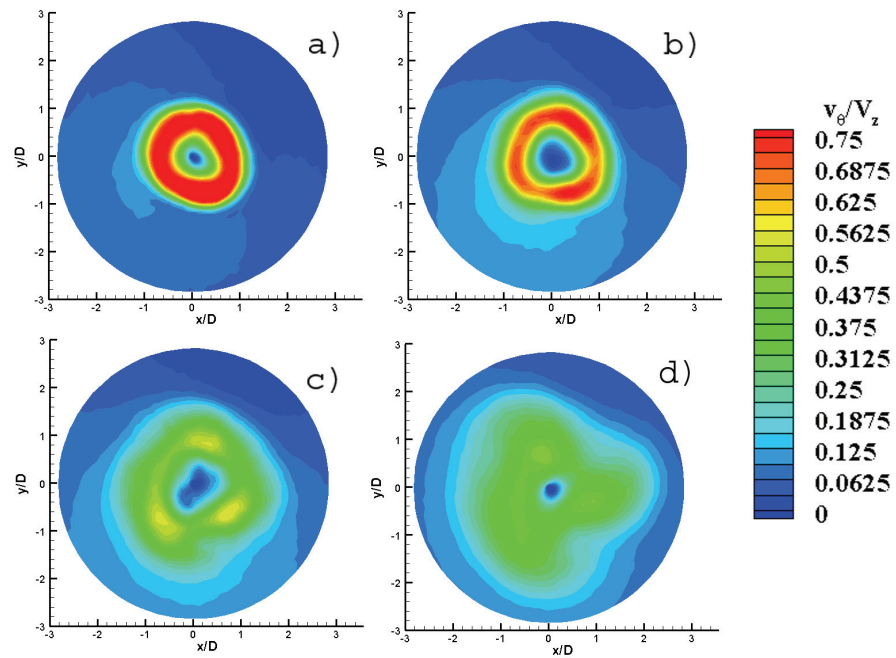
Downstream development measured by PIV

Re = 3650, Ro = 0.63 at x = 0.25 D, 0.5 D, 1 D and 1.5 D

Axial velocity



Circumferential velocity



Wilson, Smith, Spall and McIlroy [ASME paper FEDSM2009-78386]

Idaho National Laboratory

Potential Interactions with INL

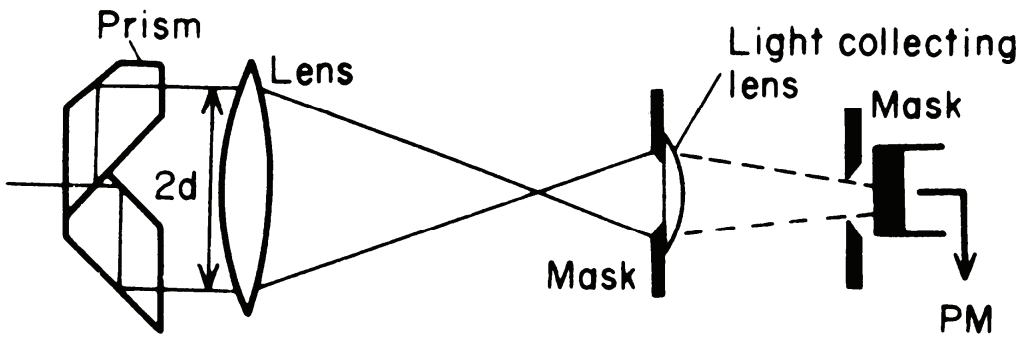
- Collaborative faculty projects in INL mission areas
- Faculty collaborative research proposals
- Faculty sabbatical leaves
- Doctoral dissertations
- Training students -- participation in ongoing experiments
- Training post doctoral associates
- Fluid mechanics conferences and workshops on topical areas
- Modification of facility to expand capabilities of interest
- Advisory committees

Concluding Remarks

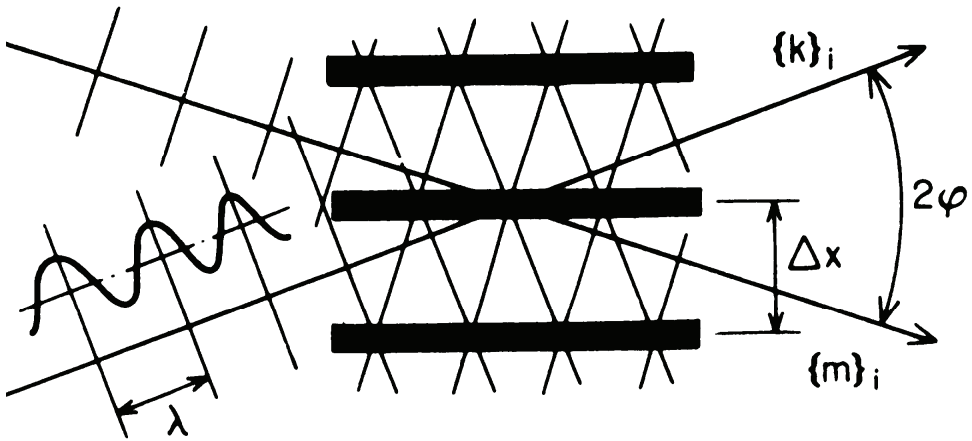
- The large MIR system is a versatile, useful tool for examining flows in complicated situations
- Results are being published and presented in engineering science venues
- Teaming is a normal mode of operation for INL
- The MIR system can provide valuable information for the development of basic knowledge in (various areas)
- The MIR system as an INL User Facility is valuable for collaboration with
  - Fluid dynamicists and convective thermal scientists from
  - Universities, industry and other laboratories

Idaho National Laboratory

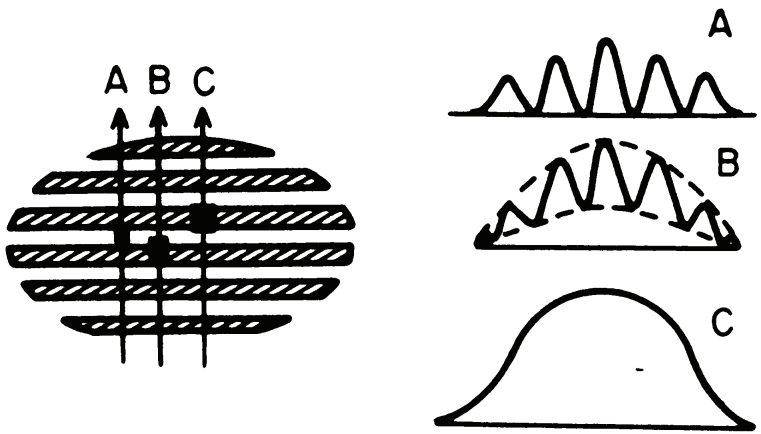
Laser Doppler Velocimetry (LDV)



Prism-system with fixed beam separation [Durst and Whitelaw, 1971]



Fringe model [Rudd, 1969]

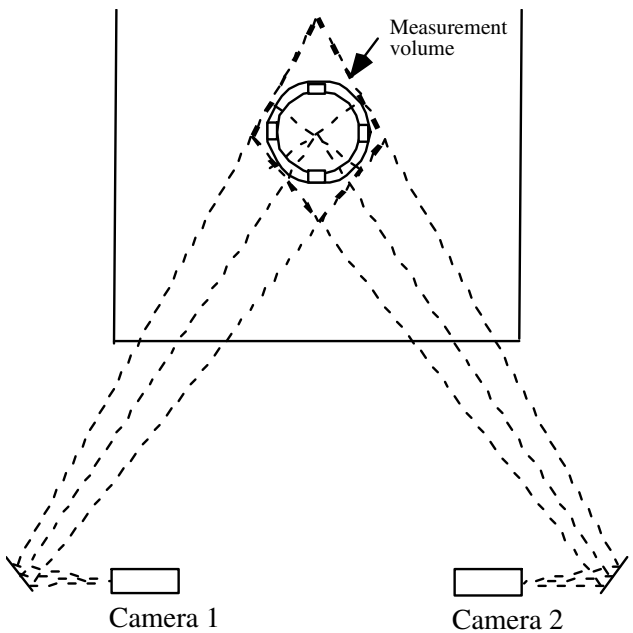


Signal

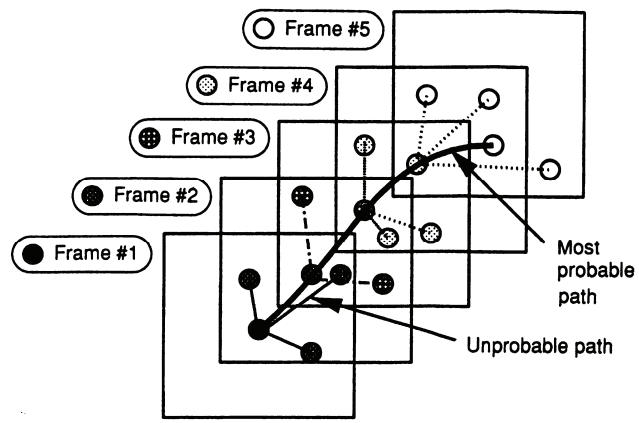
3-D Particle Tracking Velocimetry (PTV)

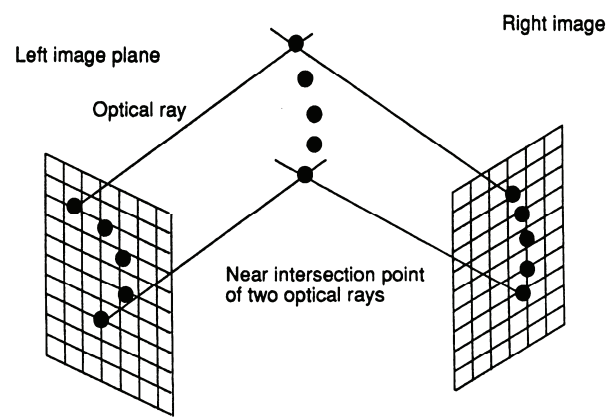
[Guezennec, Brodkey, Trigui and Kent, 1994]

- **Characterize global velocity field in apparatus**
- **Map path lines of particles**
- **Deduce mixing of passive scalars (e.g., colloidal particles)**



PTV in Annulus

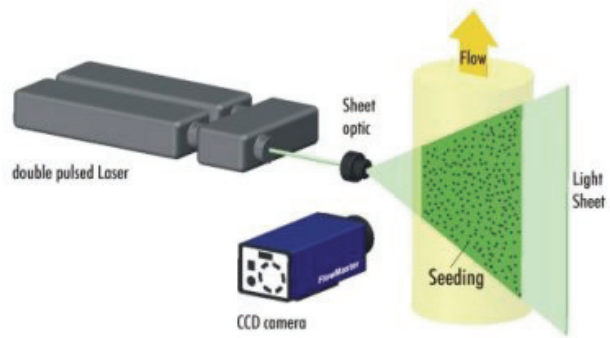




Particle Tracking Technique

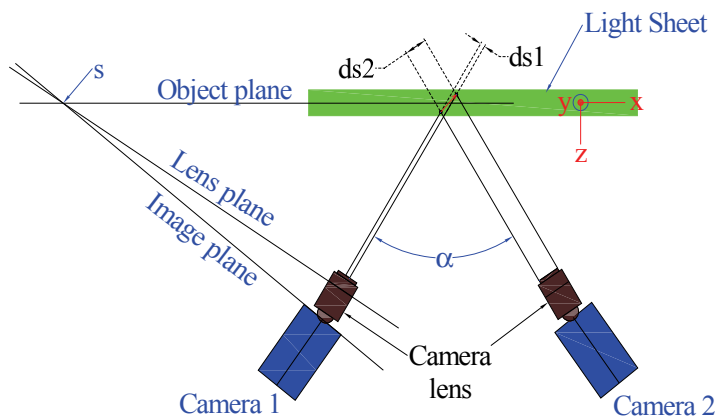
Particle Image Velocimetry

Taking Data



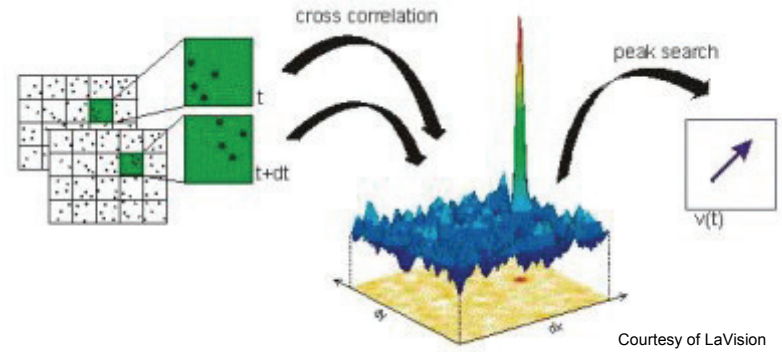
Courtesy of LaVision

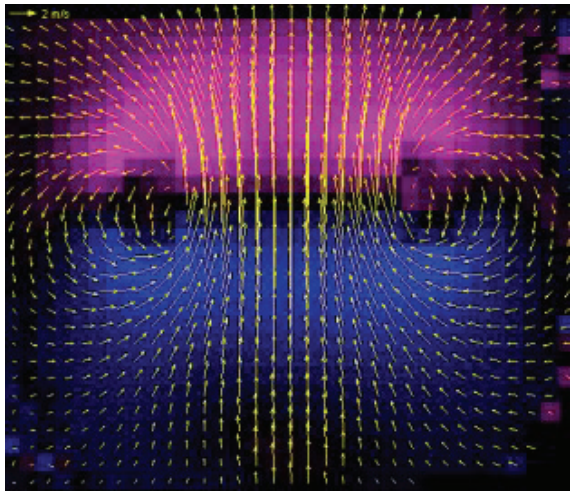
2-D PIV uses 1 camera and takes planar images



3-D PIV (or stereo) uses 2 cameras to detect particle motion in all 3 axes of motion

Data Processing



Courtesy of LaVision

The computer then uses a cross correlation technique to generate vector fields and other useful data