Idaho National Engineering and Environmental Laboratory

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

Idaho National Engineering and Environmental Laboratory (INEEL)
Idaho Falls, Idaho 83415-3885

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*

- 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

  ➔ INEEL 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

Topics

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

Contacts:

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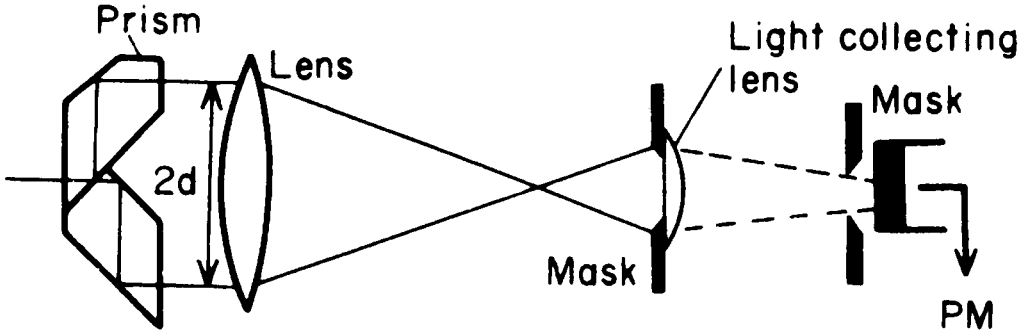
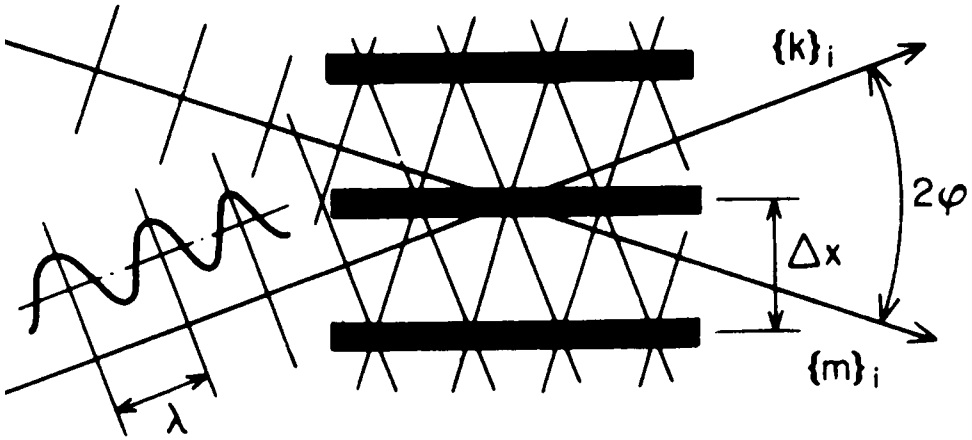
INEEL technical leader = Donald M. McEligot, 208-526-2881 (dm6@inel.gov)

INEEL program manager = Keith G. Condie, 208-526-9383 (kgc@inel.gov)

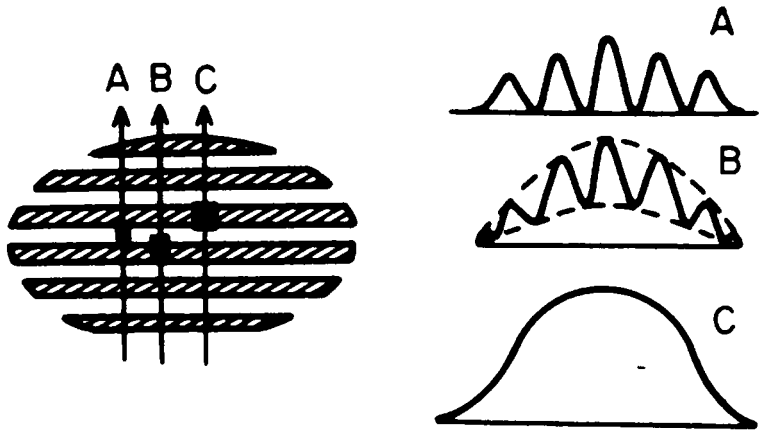
Laser Doppler Velocimetry (LDV)



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



Fringe model [Rudd, 1969]

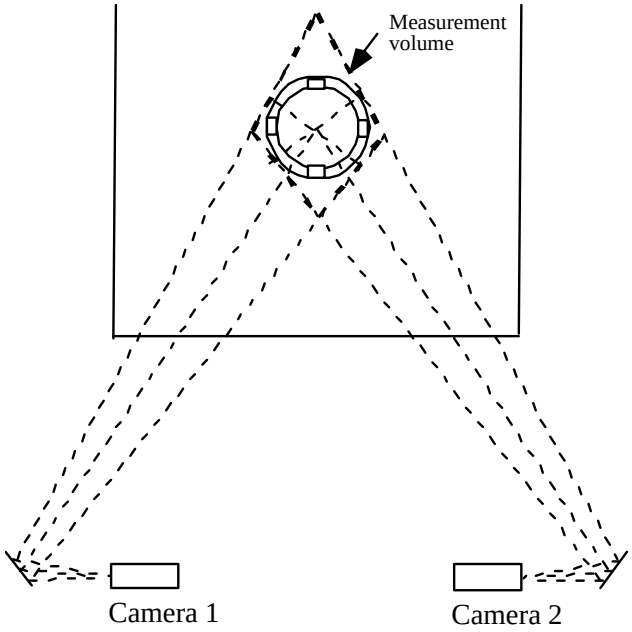


Signal

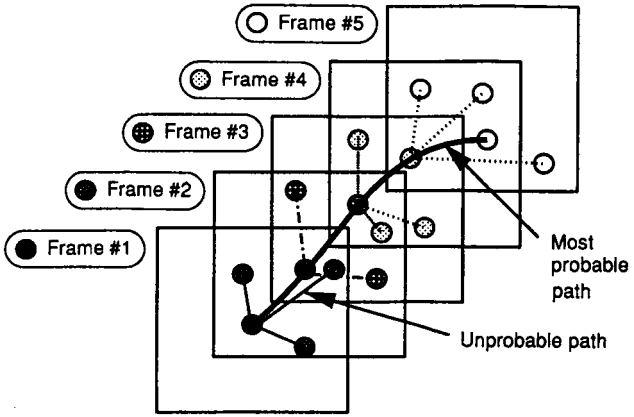
3-D Particle Tracking Velocimetry (PTV)

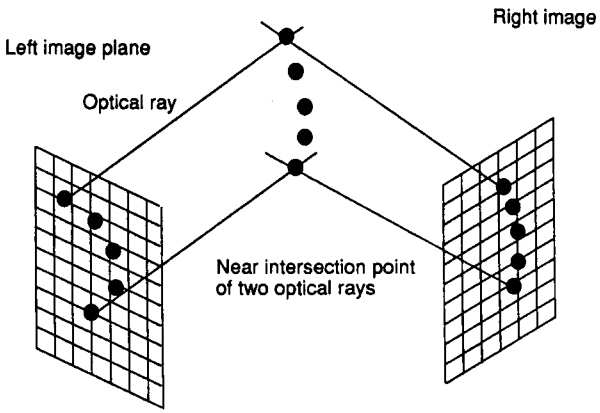
[Guezennec, Brodkey, Trigui and Kent, 1994]

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



PTV in Annulus



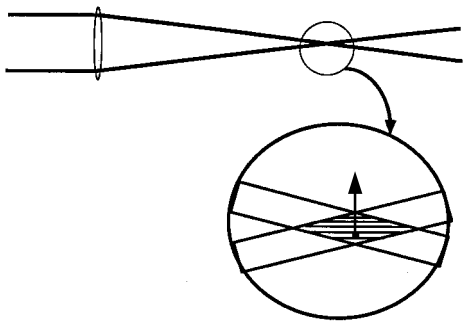


Particle Tracking Technique

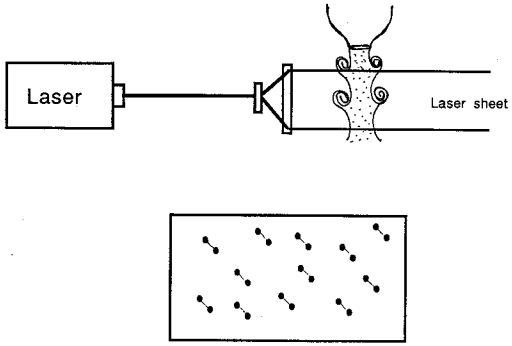
How does refractive-index-matching help?

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

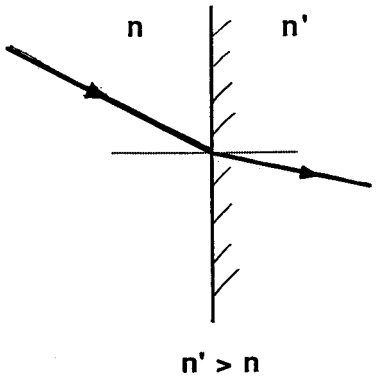
Laser Doppler Velocimetry



Particle Image Velocimetry

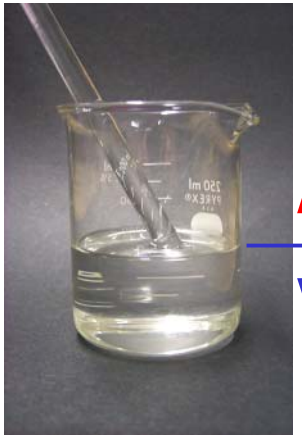


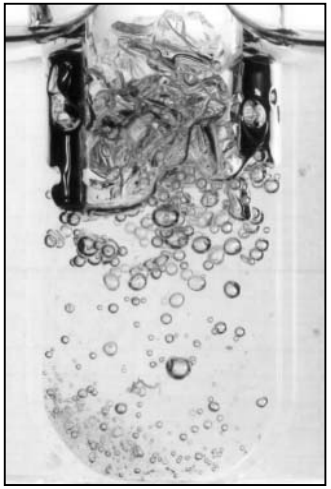
Snell's Law



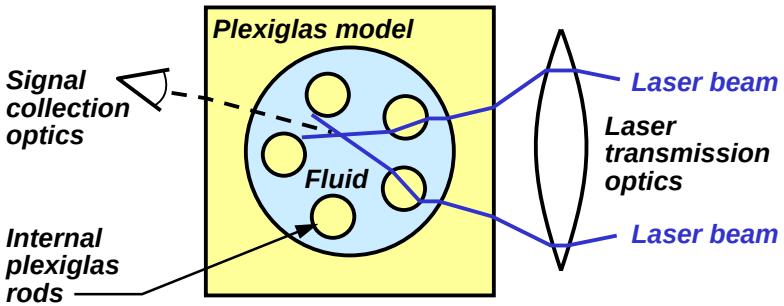
- *Unless the refractive indices are matched, the view may be distorted or impossible even with "transparent" materials and position measurements may be incorrect*

Example of application of refractive-index-matching





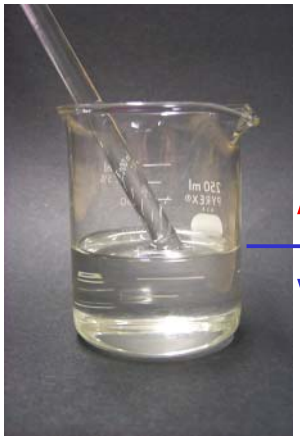
Refractive index not matched

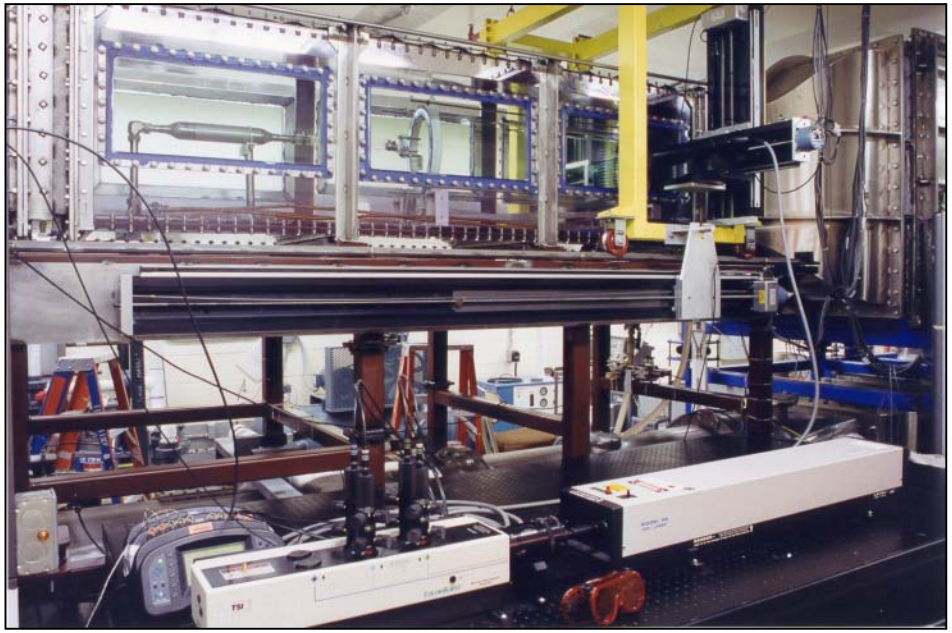


Benefits of INEEL MIR flow system

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

Example of application of refractive-index-matching

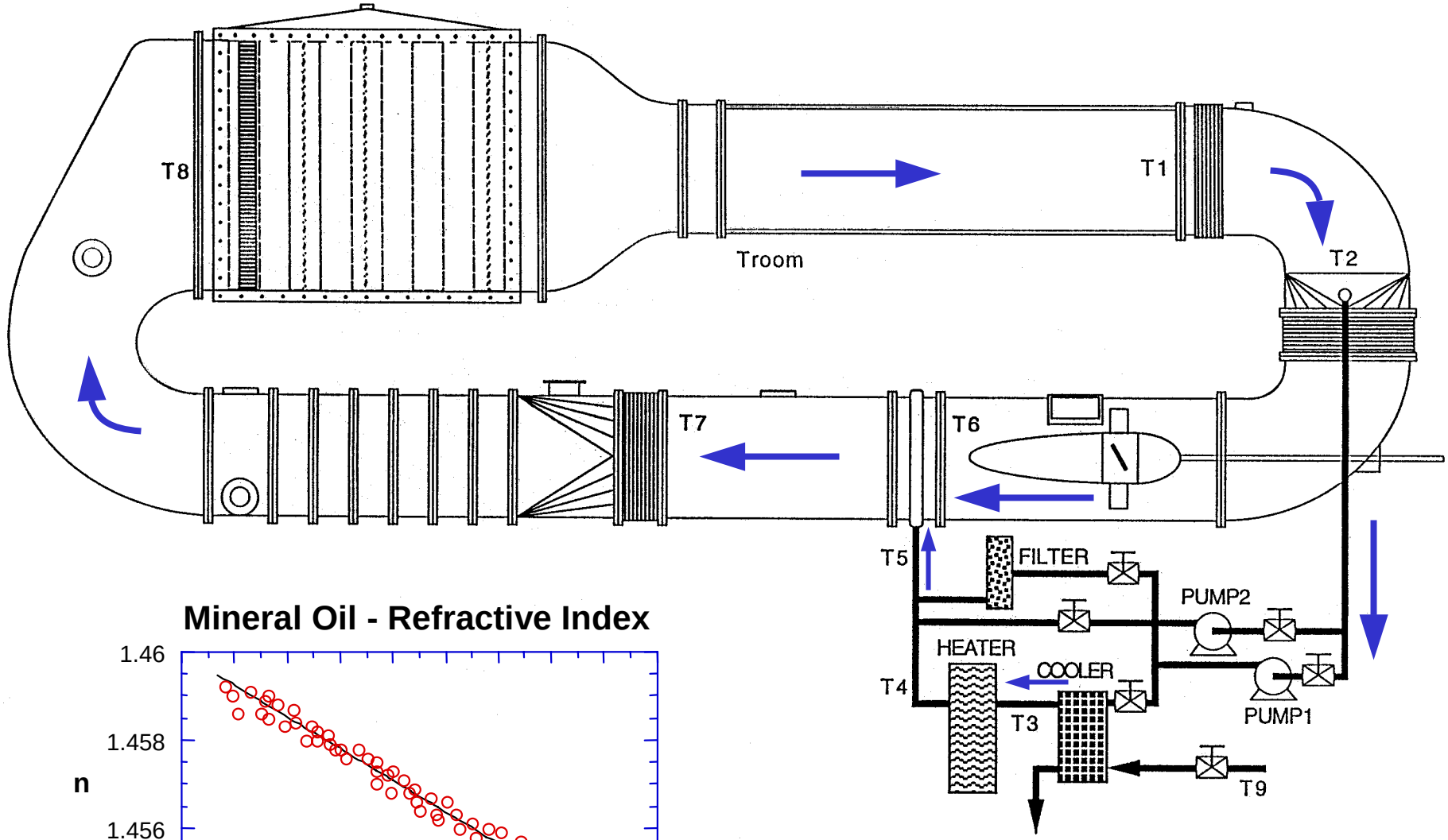




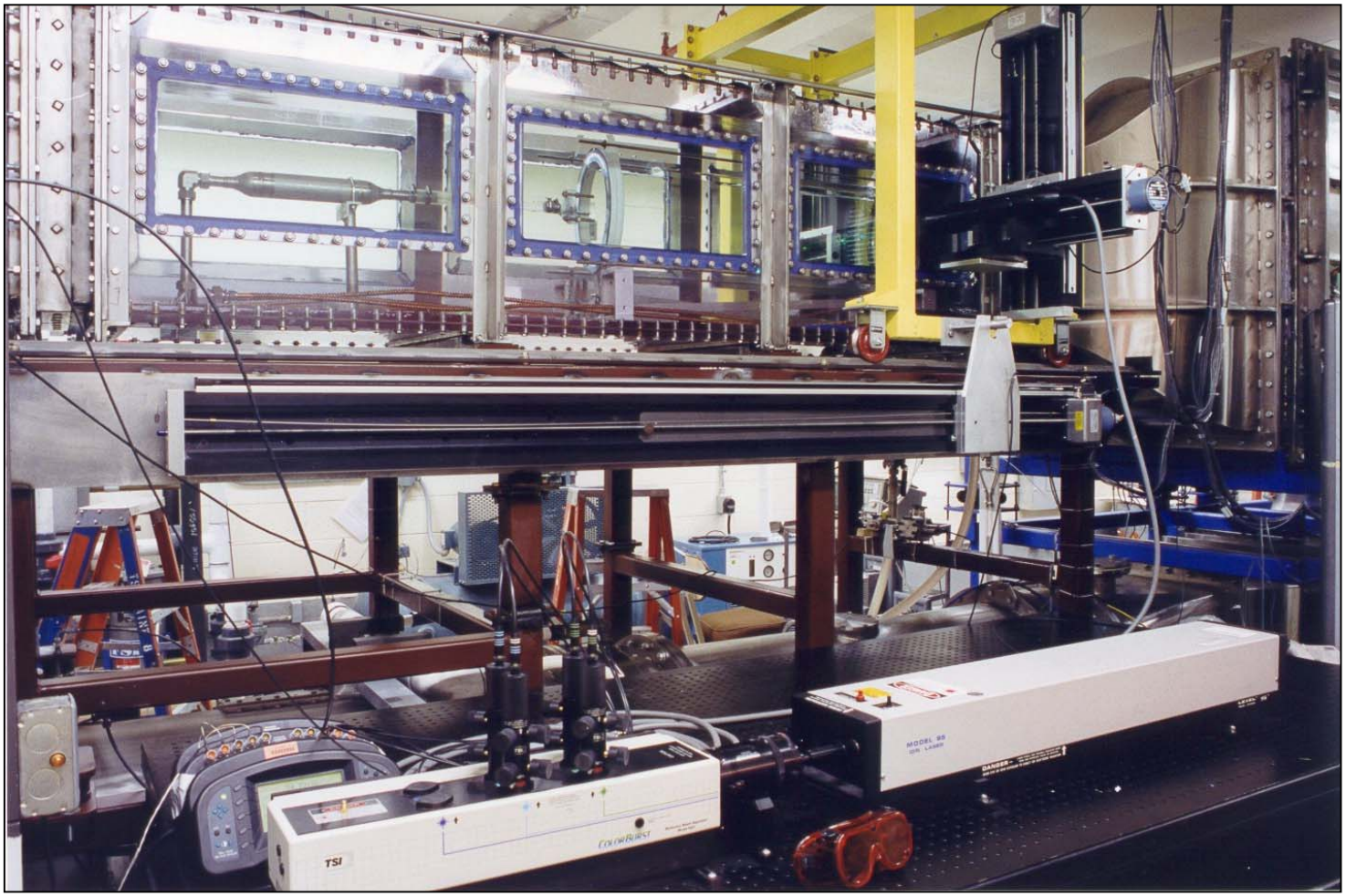
Apparatus to study fluid physics phenomena in idealized SNF canister for EM Science project

- **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 INEEL MIR Flow System



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

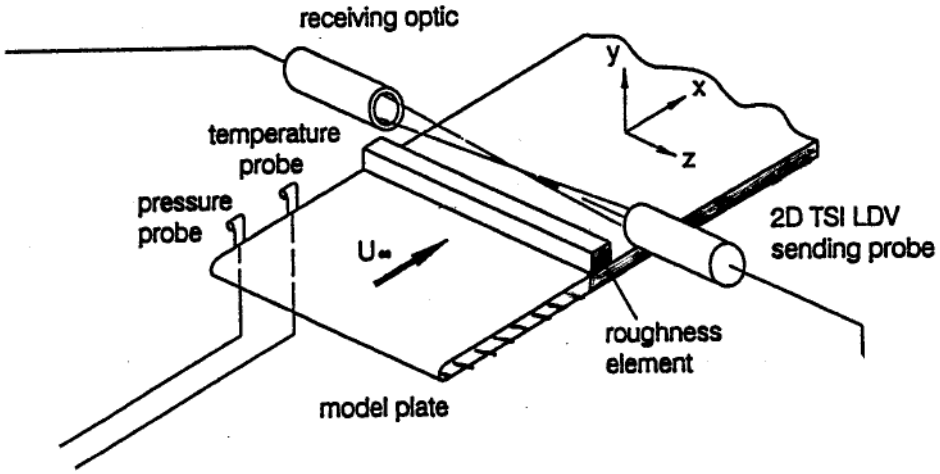


Recent and current collaboration

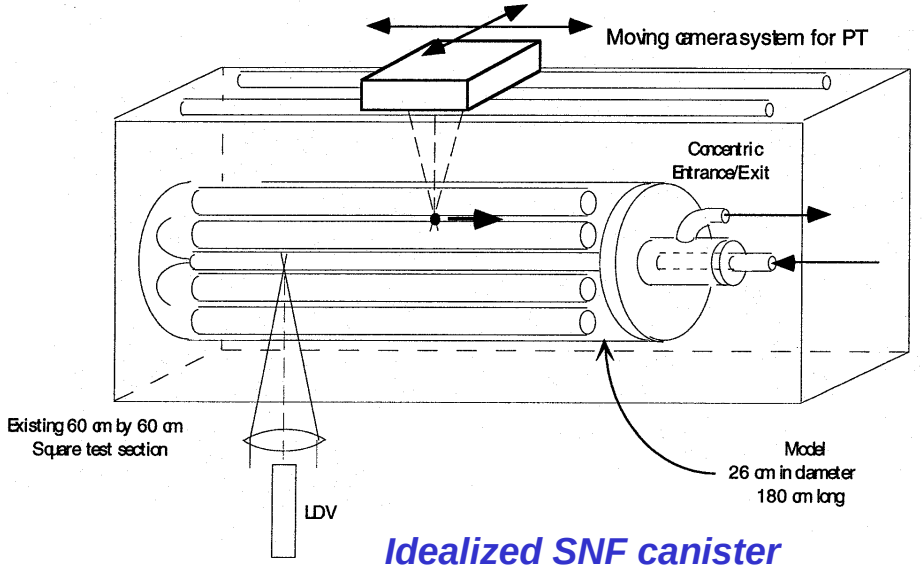
Prof. F. Durst, Uni. Erlangen, Germany	Structure of transitional flow*
DoE EM Science program	Fundamental flow in SNF canisters*
DoE NERI program	Fundamental thermal fluid physics of advanced reactors*
Bechtel R&D	Flows around buildings
Prof. R. S. Budwig, U. Idaho	Basic measurements of transitional 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*

* Basic research -- addressing science issues

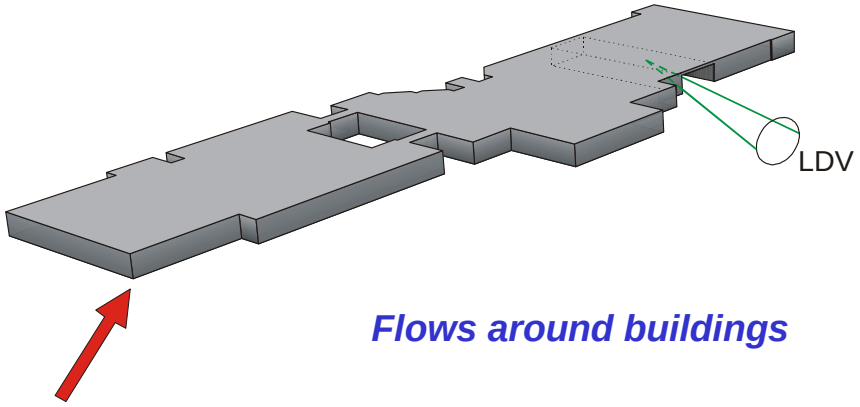
Recent and Current Experiments



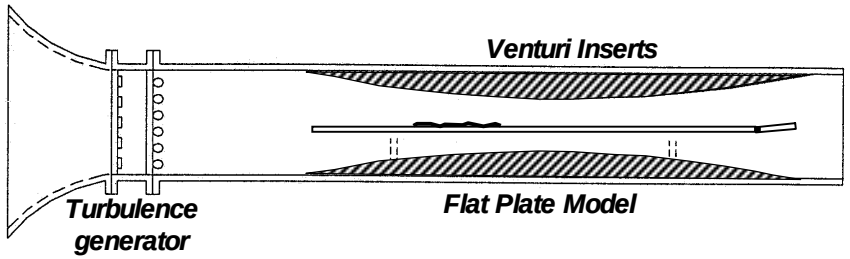
Boundary layer transition



Idealized SNF canister

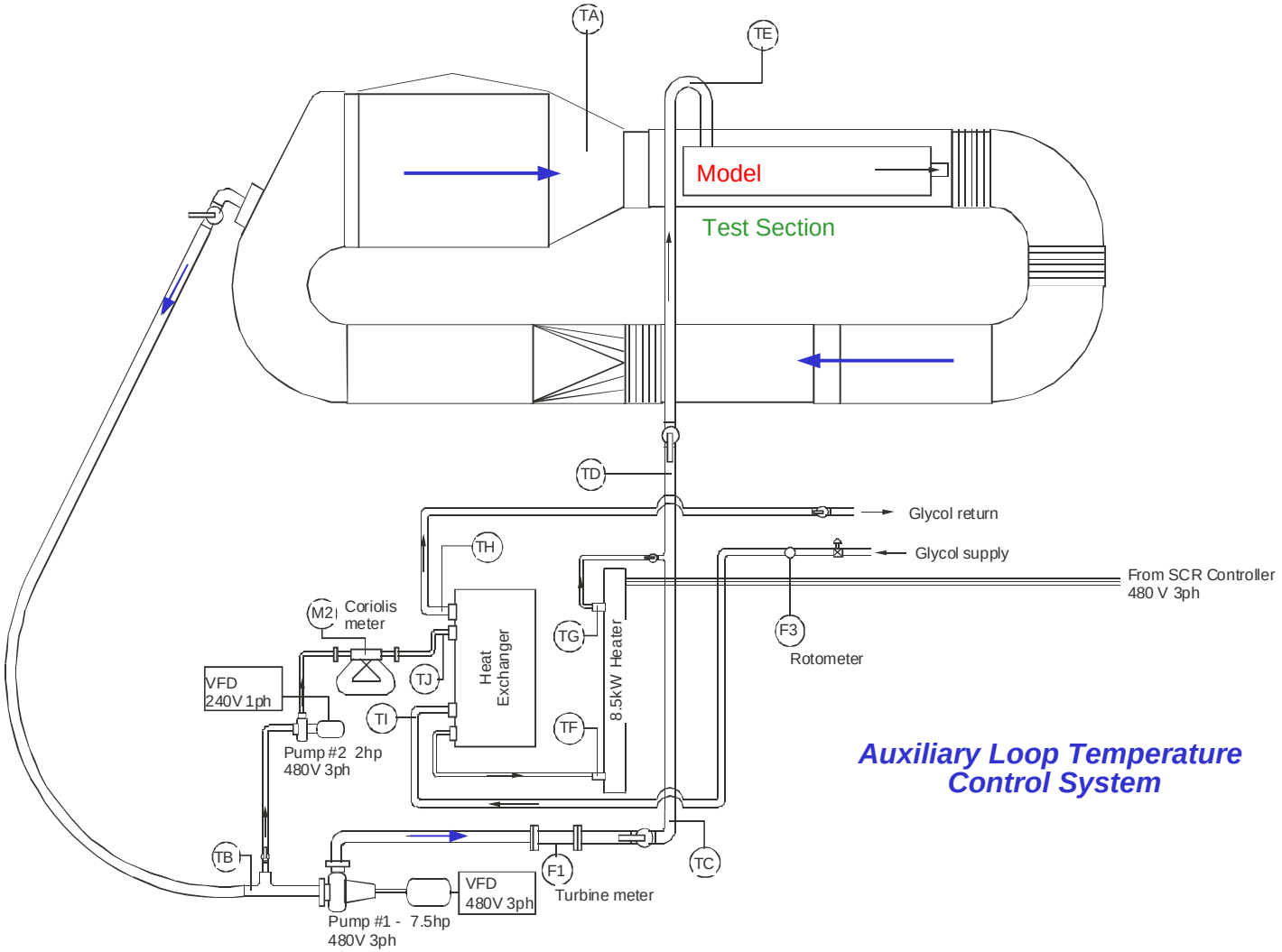


Flows around buildings



Realistic rough surfaces in turbomachinery

Schematic diagram of typical internal flow experiment



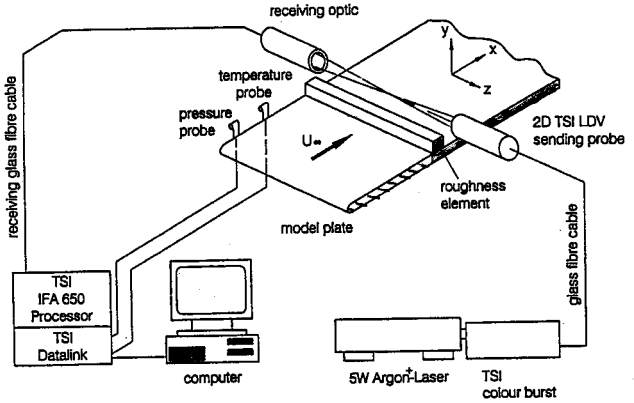
Auxiliary Loop Temperature Control System

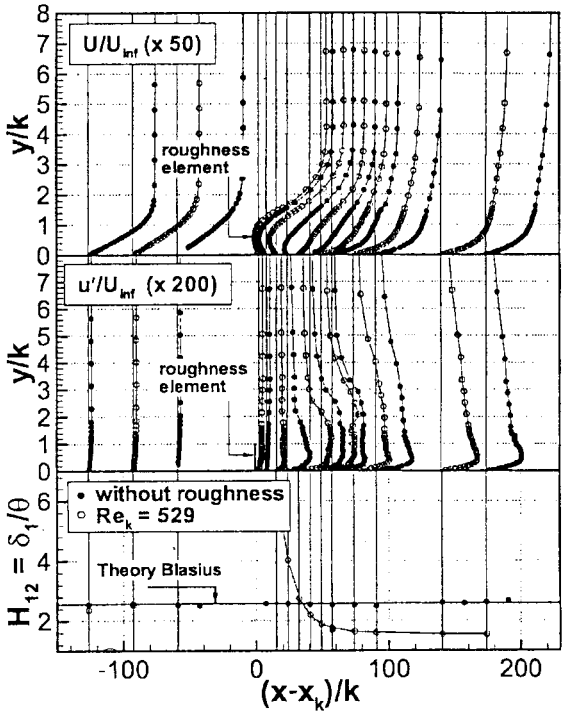
Temperatures of main flow and flow through the model are controlled independently to match the refractive indices of the fluid and transparent model

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.

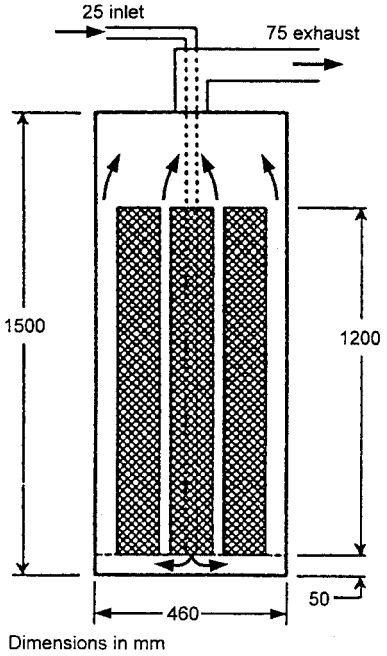
Stoots, C., S. Becker, K. Condie, F. Durst and D. M. McEligot, 2001. A large-scale matched index-of-refraction flow facility for LDA studies around complex geometries. ***Exp. Fluids***, 30, pp 391-398.

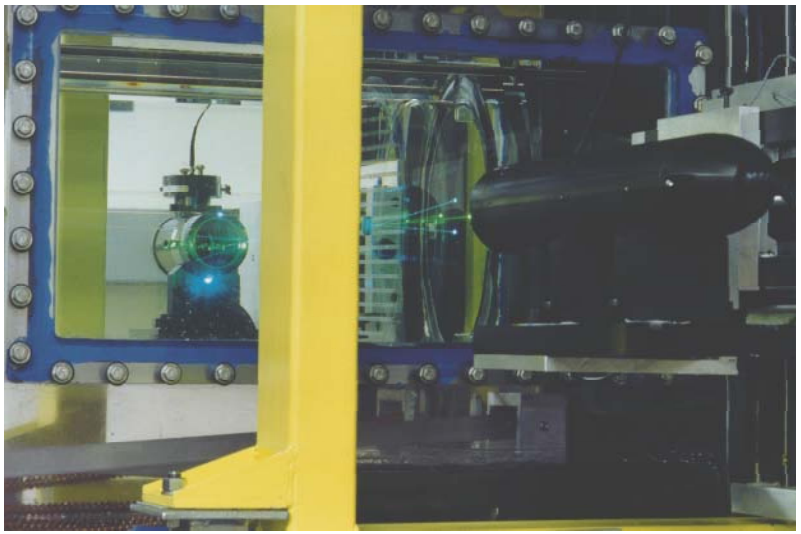
Measurements of fundamental fluid physics of SNF storage canisters

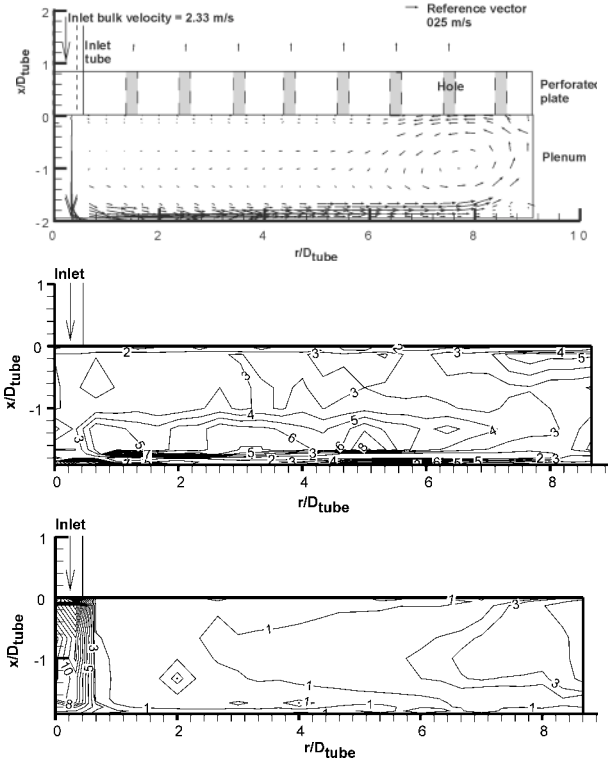
Objective = obtain fundamental measurements of generic flow phenomena occurring during drying applications

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





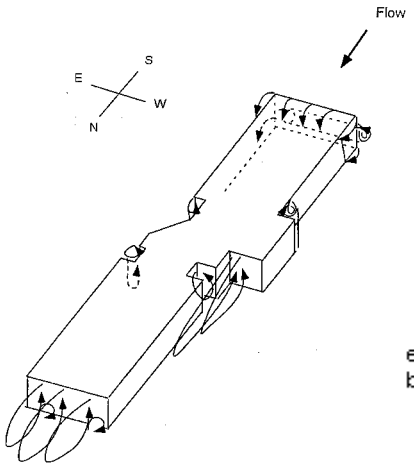


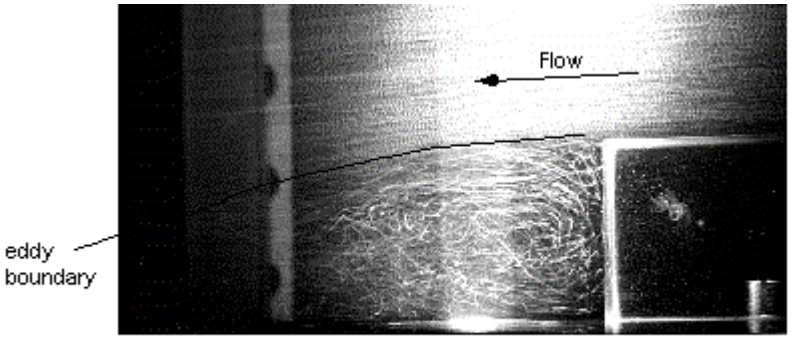
Ref: McCreery, G. E., K. G. Condie, R. C. Clarksean and D. M. McEligot, 2002. Convective processes in spent nuclear fuel canisters. ***Heat Transfer 2002*** (Proc., 12th International Heat Transfer Conf., Grenoble) Vol. 4, pp 663-668.

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

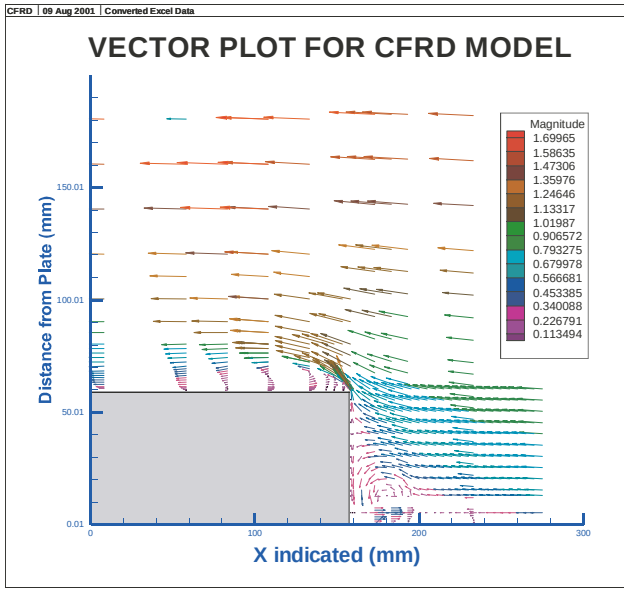
Objective = obtain measurements to assess CFD models for simulation of flow around buildings, particularly separated flow regions

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





Trailing eddy downstream of model



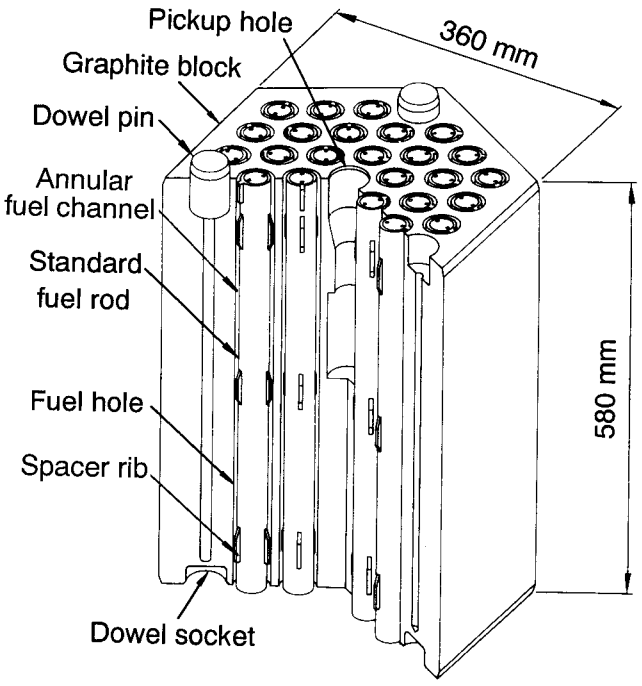
Products:

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

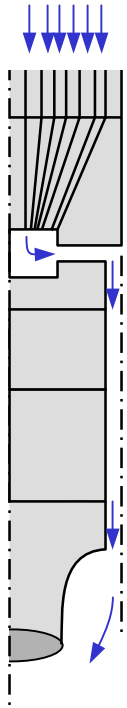
Fundamental thermal fluid physics of high temperature flows in advanced reactor systems

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

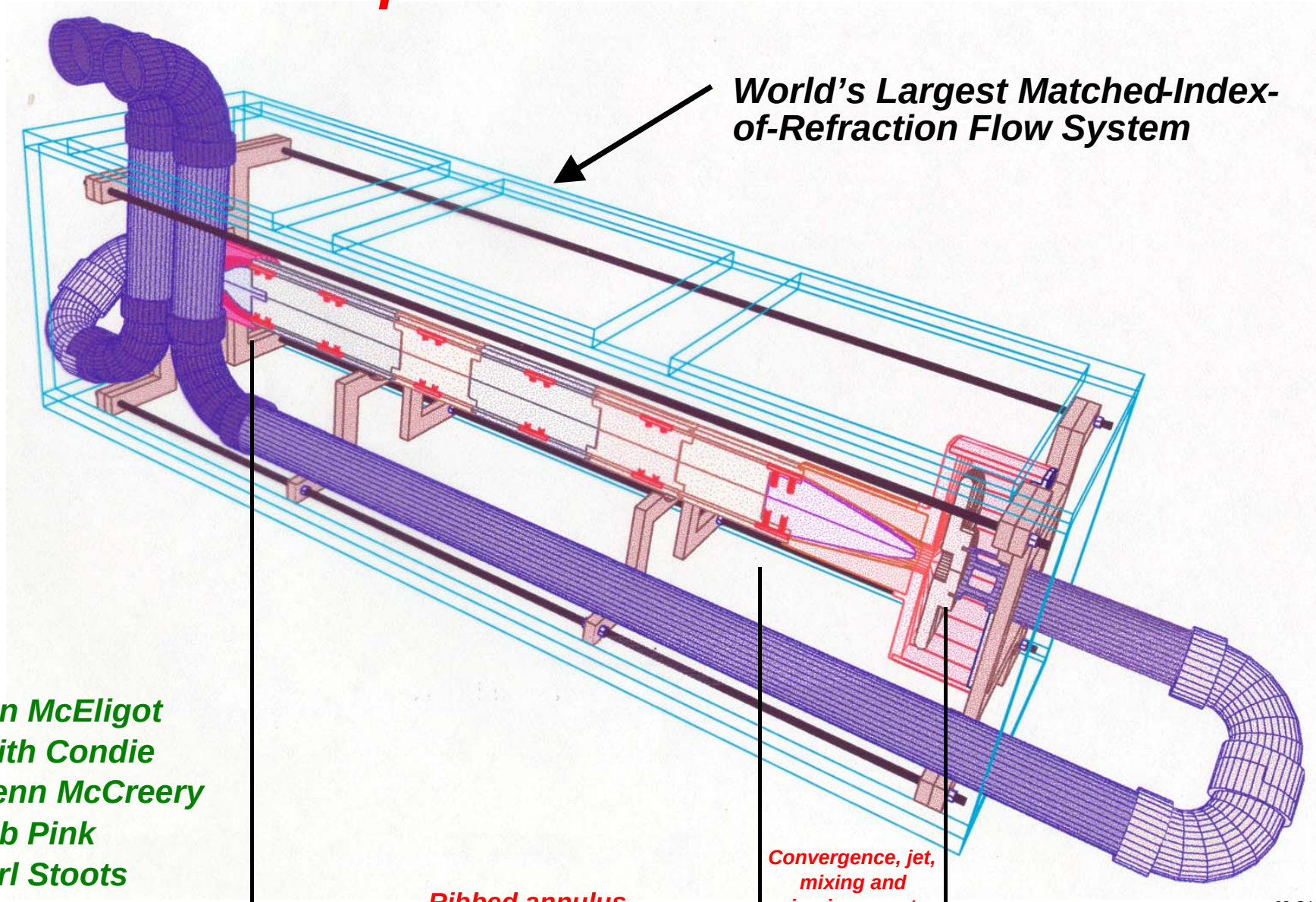
Emphases =

- ***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 / INEEL
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

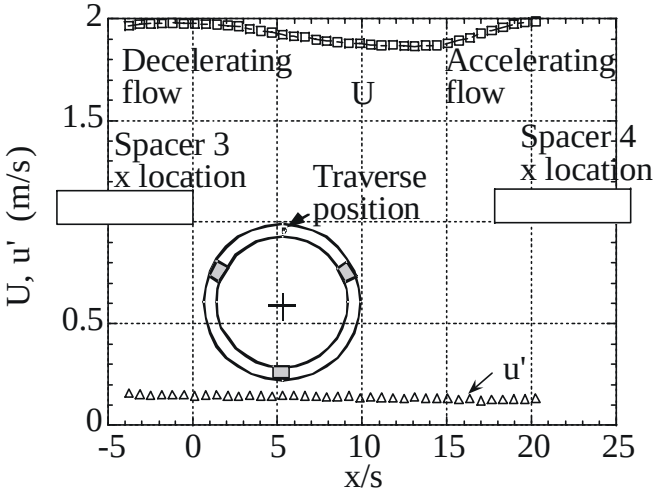
INEEL – Experiment for Assessment of Computer Codes for Complex Reactor Flow Phenomena



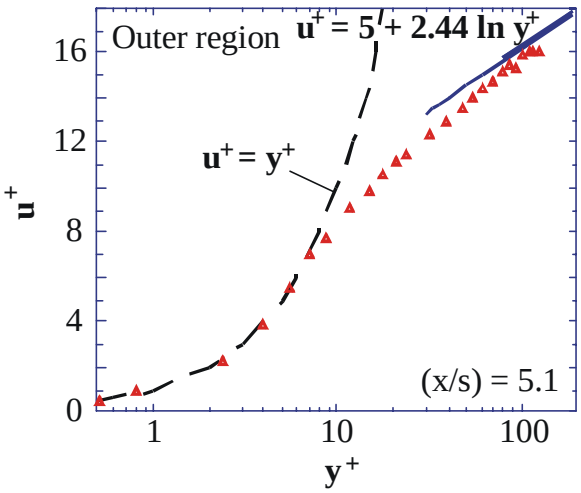
Don McEligot
Keith Condie
Glenn McCreery
Bob Pink
Carl Stoots

Streamwise mean velocity measurements by LDV

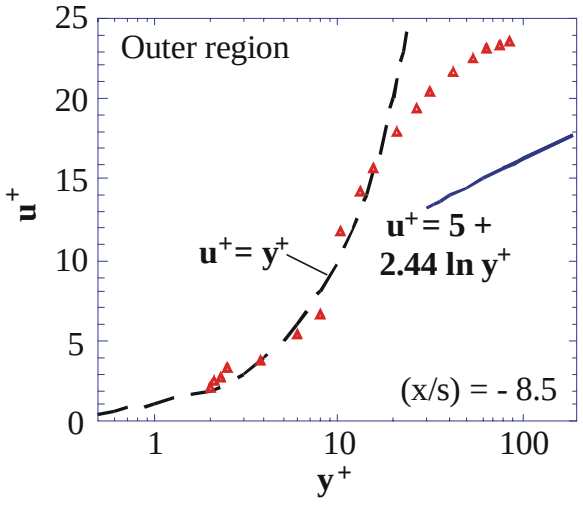
Axial profiles



Decelerating region

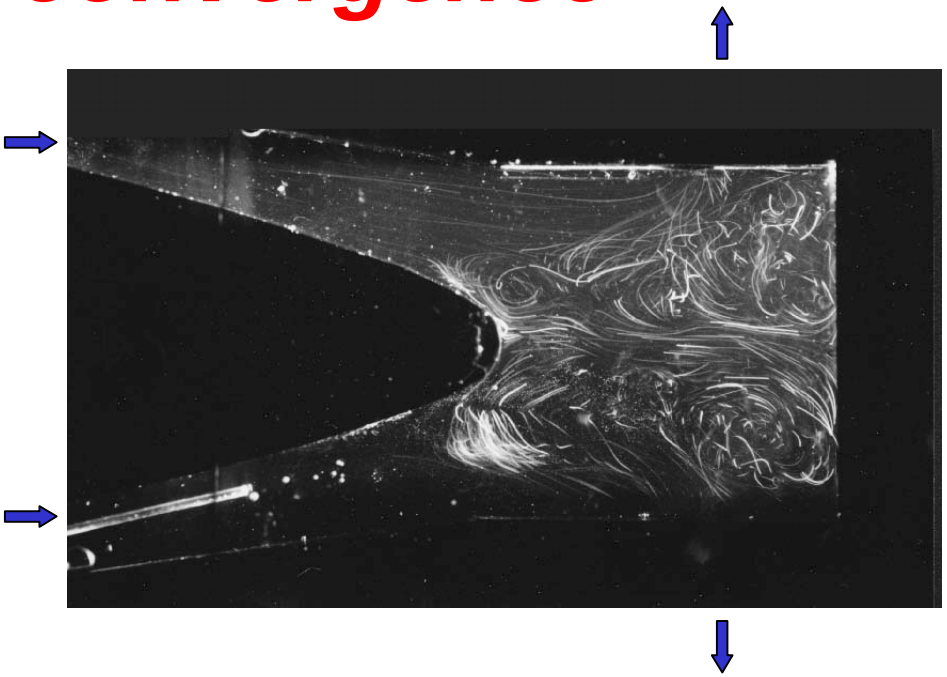


Accelerating region

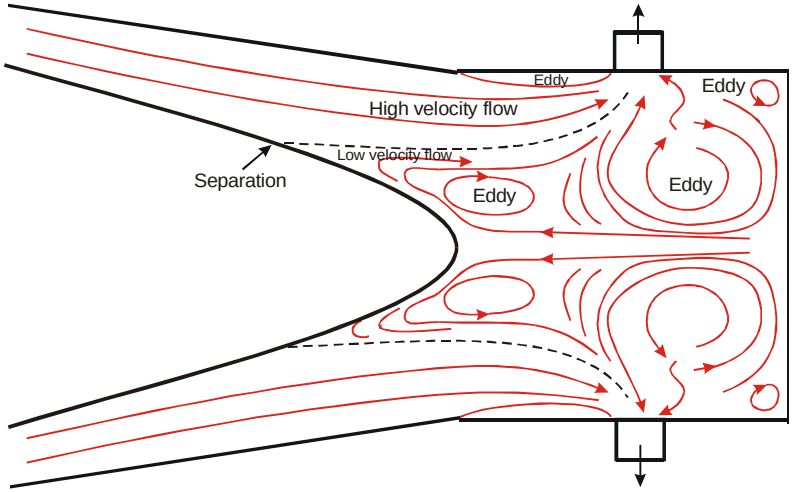


Ref: McCreery, G. E., R. J. Pink, K. G. Condie, 2003. Fluid dynamics of ribbed annuli. NuReth-10 paper J00203, Seoul, October.

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

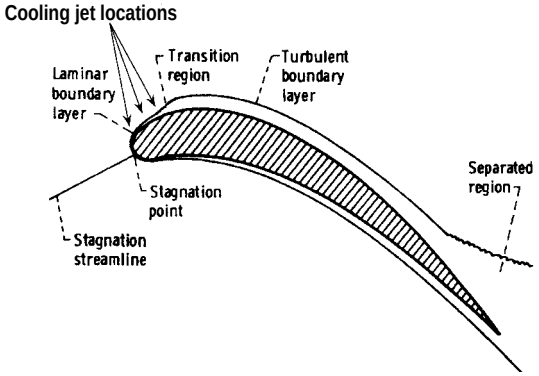
Related to this NERI project

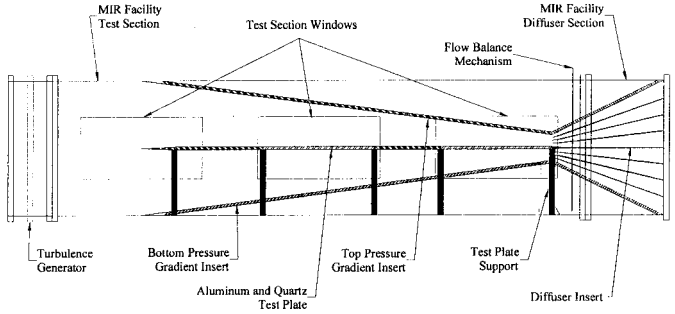
- 31 publications and presentations on other topics

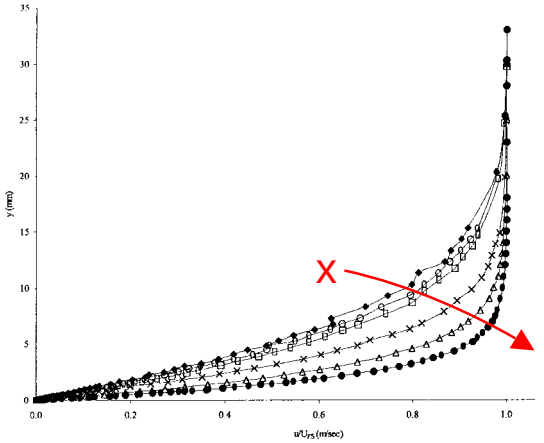
Boundary layers on turbine blades with rough surfaces

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. Distributed roughness, III. Realistic roughness

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

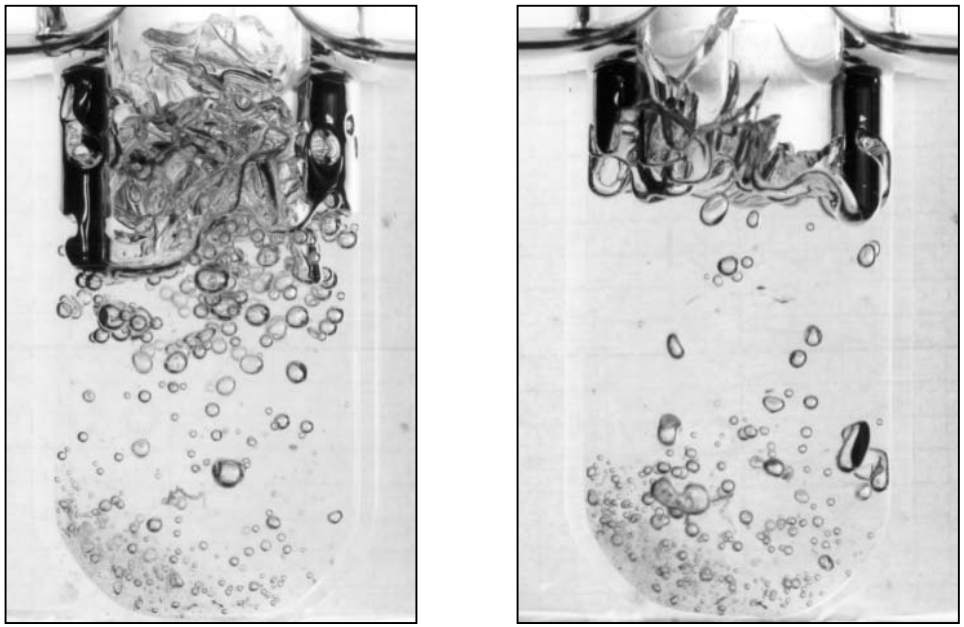
Multiphase flow in complex fracture apertures under a wide range of flow conditions

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

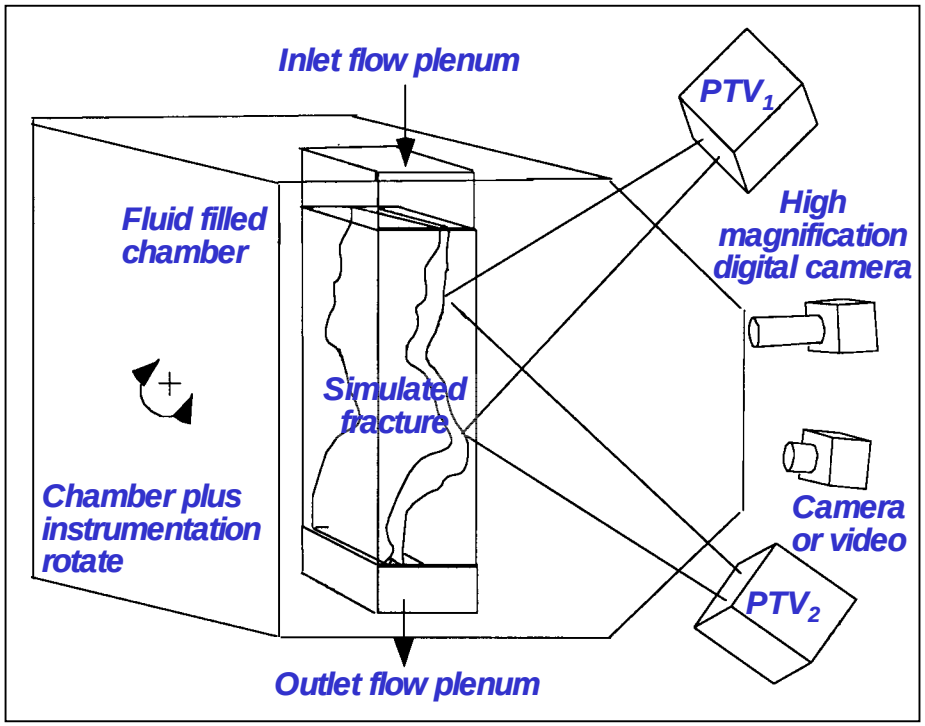
Objective = by coordinating physical and computer modeling, develop new conceptual models to understand how pollutants travel in the vadose (unsaturated gas-liquid) zone

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]

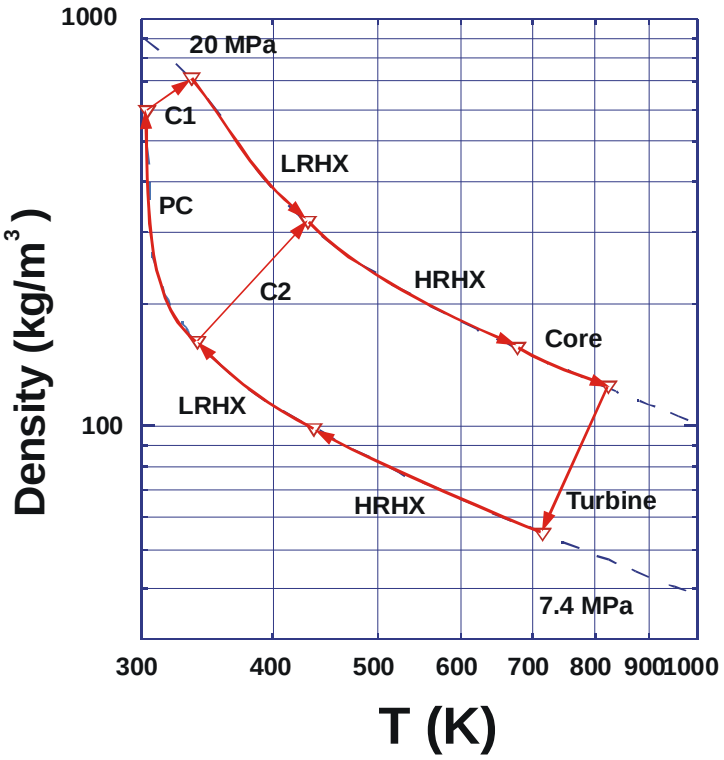


Ref: McCreery, G.E., 2002. Initial simulated fracture apparatus, INEEL memo, November

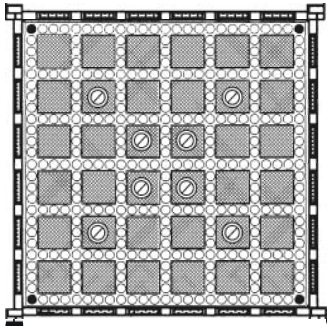
Advanced computational thermal fluid physics and its assessment for light water reactors (LWRs) and supercritical reactors (SCRs)

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

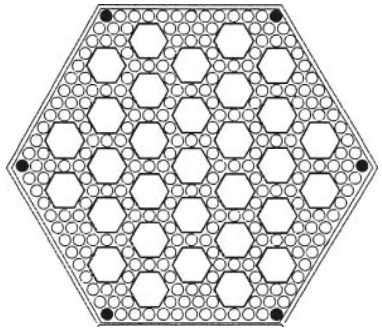
Funding = DoE US/RoK I-NERI program, 2001-2005



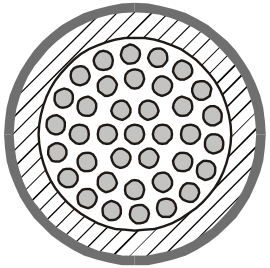
→ ***Fluid property variation!***



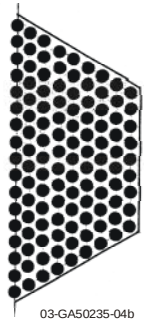
SCLWR (square)



SCLWR (hexagonal)



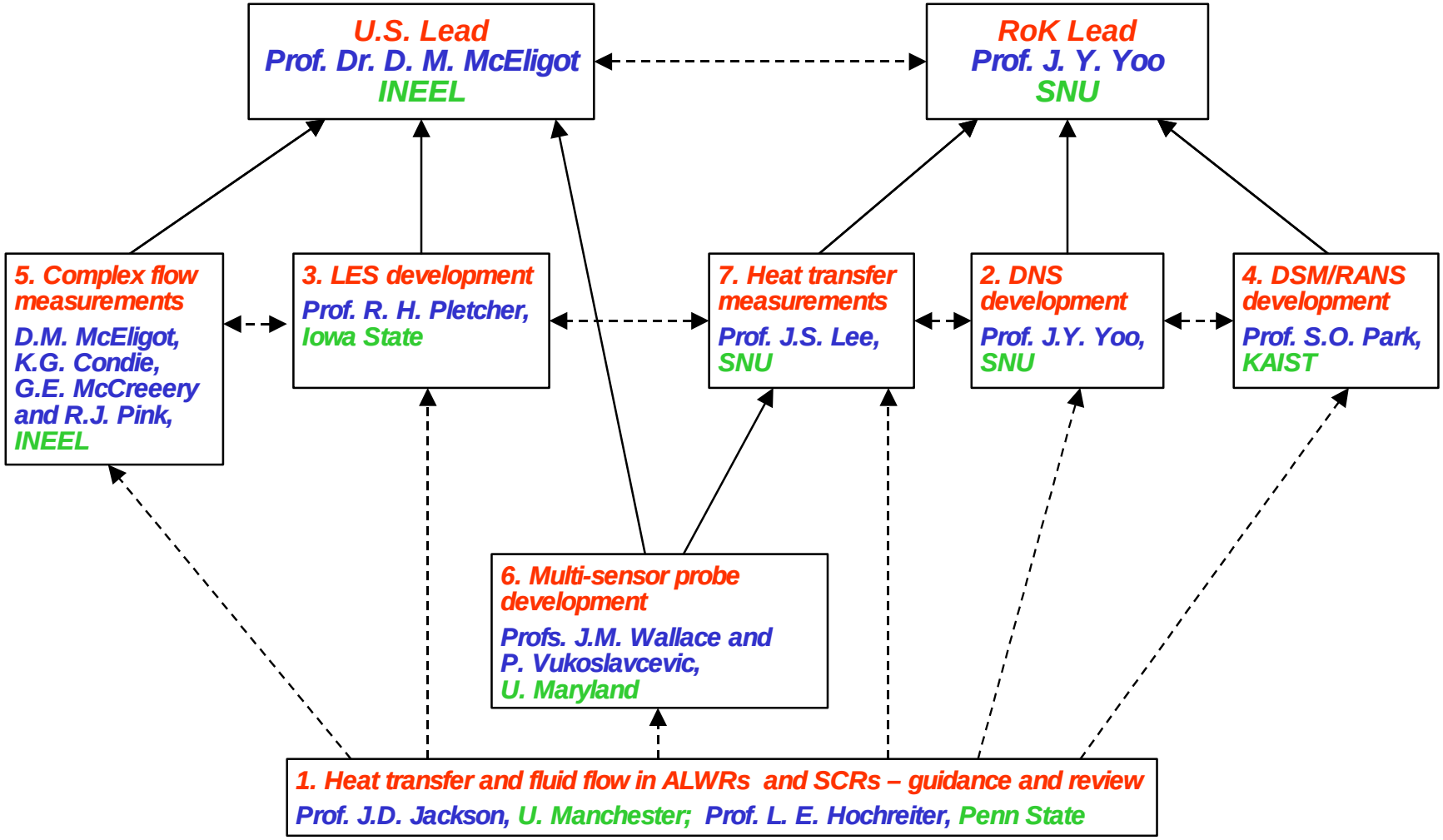
CANDU-X



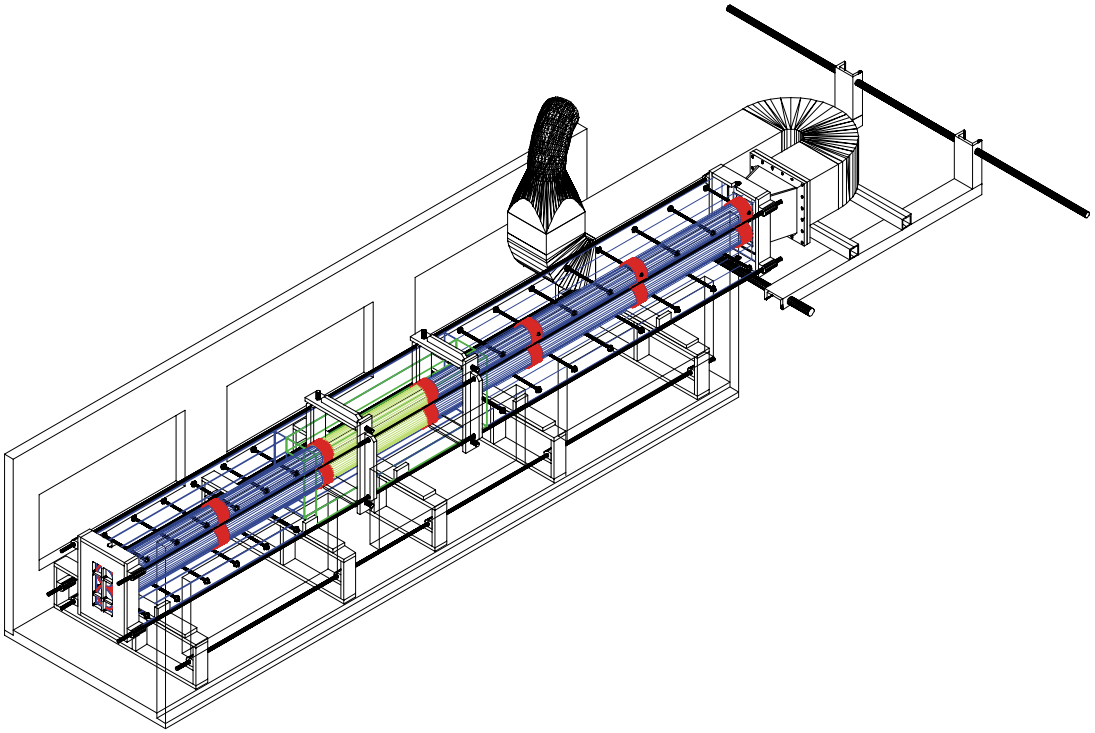
SCFR-H

→ ***Complex geometries!***

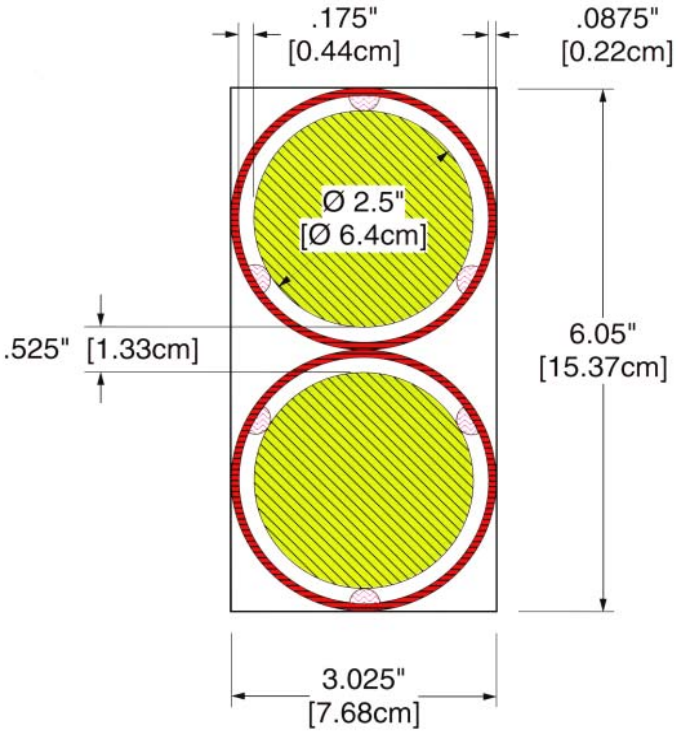
Project tasks



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

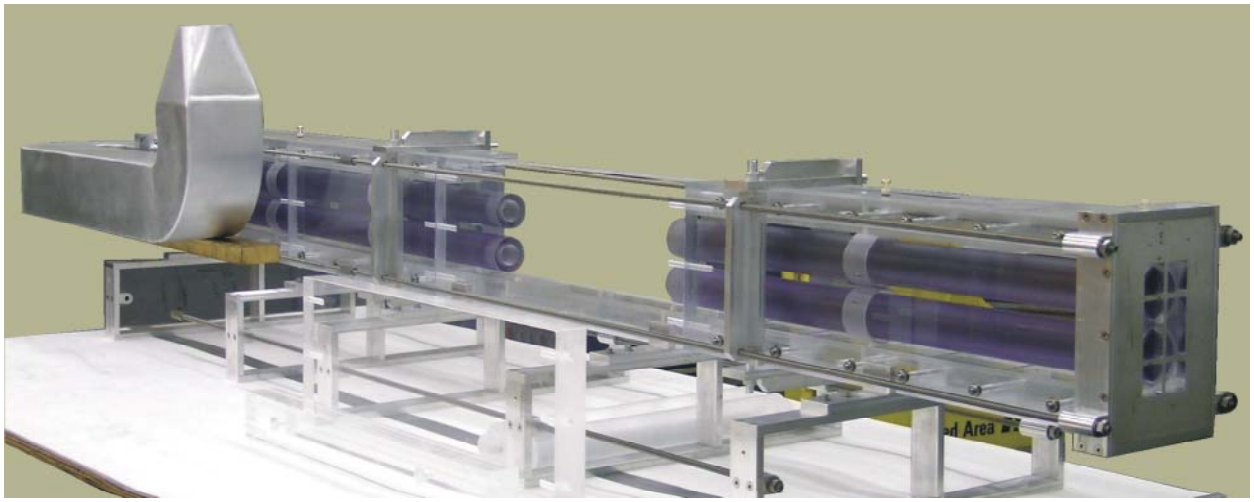


Design of model installation in MIR test section



Model cross section

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



Some publications:

Bae, J. H., J. Y. Yoo and H. Choi, 2003. Direct numerical simulation of heat transfer to CO_2 at supercritical pressure in a vertical tube. NuReTH-10, Seoul, 5-9 October.

Jackson, J. D., K. O. J. Evans Lutterodt and R. Weinberg, 2003. Experimental studies of buoyancy-influenced convective heat transfer in heated vertical tubes at pressures just above and just below the thermodynamic critical value. Paper 1177, GENES4/ANP2003, Kyoto, 15-19 September.

Moro, J. P., P. V. Vukoslavcevic and V. Blet, 2003. A method to calibrate a hot-wire X-probe for applications in low-speed, variable temperature flow. ***Meas. Sci. Technol***., 14, pp. 1054-1062.

You, J., J. Y. Yoo and H. Choi, 2003. Direct numerical simulation of heated vertical air flows in fully developed turbulent mixed convection. ***Int J. Heat Mass Transfer***, 46, No. 9 (April), pp. 1613-1627.

Annual technical report:

McEligot, D. M. et al., 2002. INEEL/EXT-2002-1386, 10 December.

Potential Interactions with INEEL

- Collaborative faculty projects in INEEL 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 INEEL*
- *The MIR system can provide valuable information for the development of basic knowledge in _____*
- *The MIR system as an INEEL User Facility is valuable for collaboration with*
  - *Fluid dynamicists and convective thermal scientists from*
  - *Universities, industry and other laboratories*