Large Matched-Index-of-Refraction (MIR) flow systems for international collaboration in fluid mechanics

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Erlangen-Nürmberg

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Abstract ---- In recent international collaboration, Idaho National Laboratory (INL) and Universität Erlangen (UE) have developed large MIR flow systems which are ideal for joint graduate student education and research. The benefit of the MIR technique is that it permits optical measurements to determine flow characteristics in complex passages and around objects to be obtained without locating a disturbing transducer in the flow field and without distortion of the optical paths. The MIR technique is not new itself; others employed it earlier. The innovation of these MIR systems is their large size relative to previous experiments, yielding improved spatial and temporal resolution. This report will discuss the benefits of the technique, characteristics of the systems and some examples of their applications to complex situations. Typically their experiments have provided new fundamental understanding plus benchmark data for assessment and possible validation of computational thermal fluid dynamic codes.

Topics

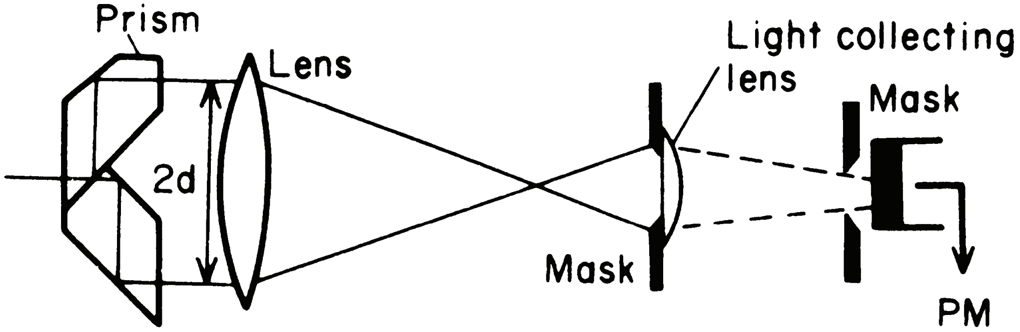
- Benefits of refractive-index-matching for optical flow measurements
- Characteristics and advantages of large MIR flow systems
- Some recent international collaboration
- Potential collaborative interactions
- Concluding remarks

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

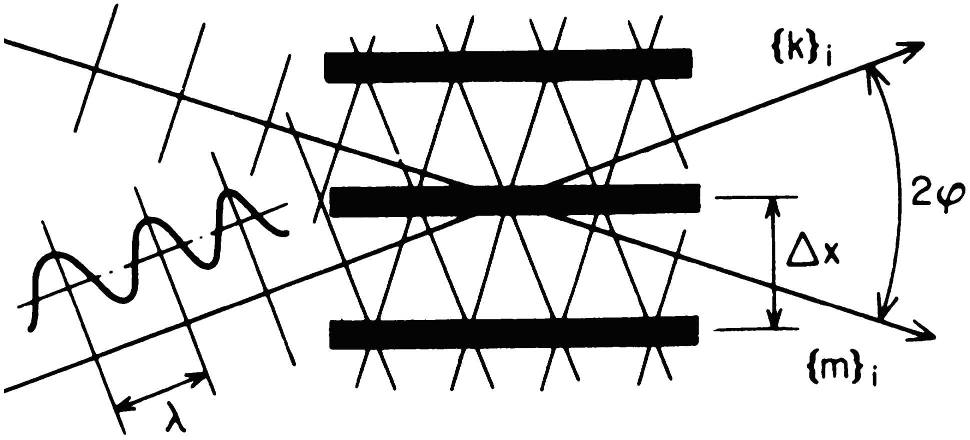
- Extending fundamental knowledge of generic flow processes
- Assessment of proposed CFD codes
- Guidance for improving CFD codes, e.g., turbulence models

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

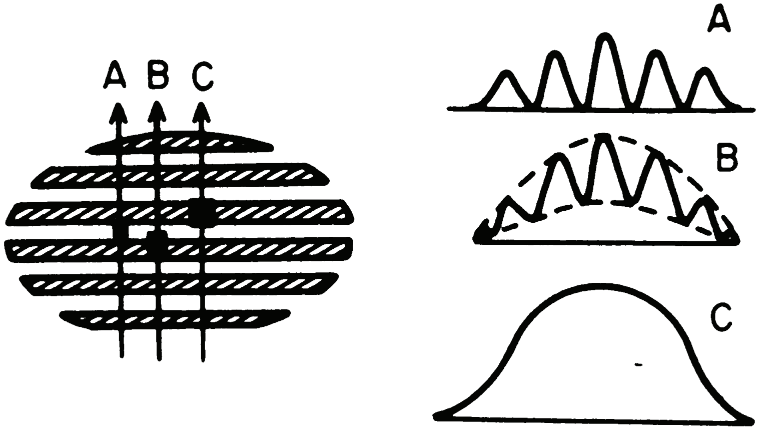
Laser Doppler Velocimetry (LDV)



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



Fringe model [Rudd, 1969]

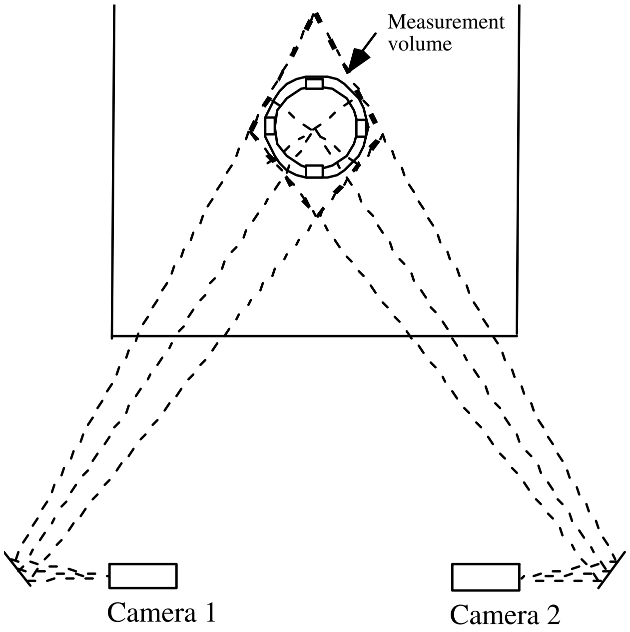


Signal

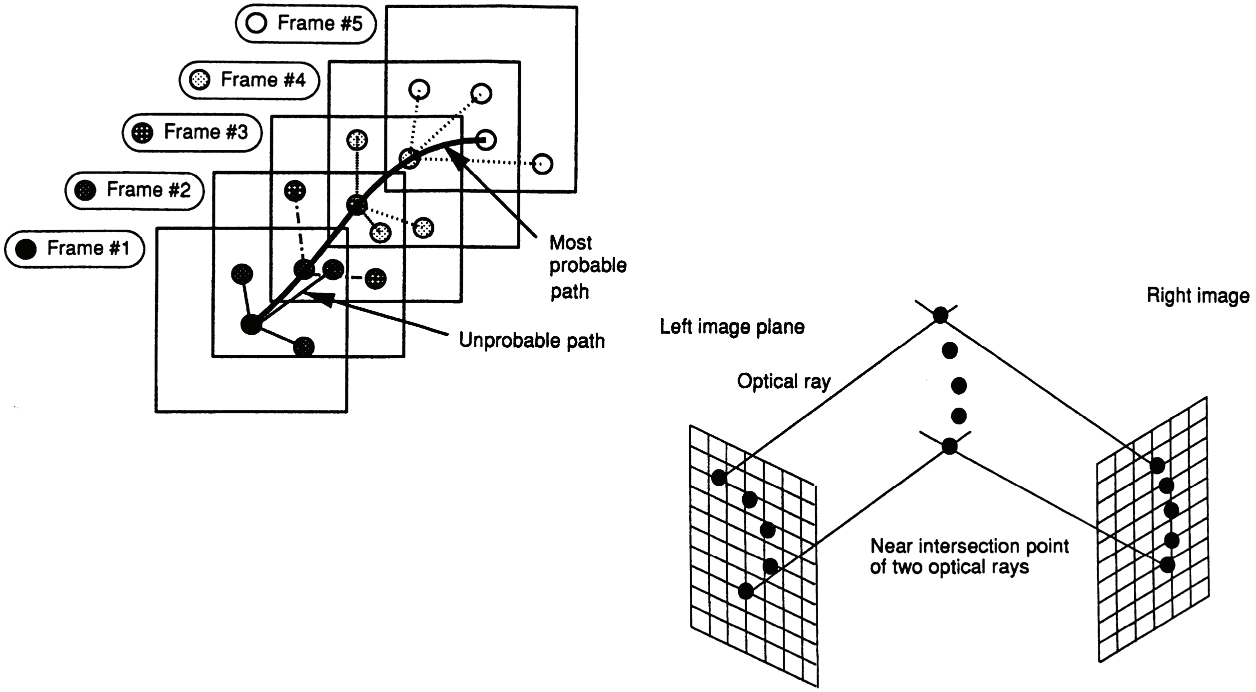
3-D Particle Tracking Velocimetry (PTV)

[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)



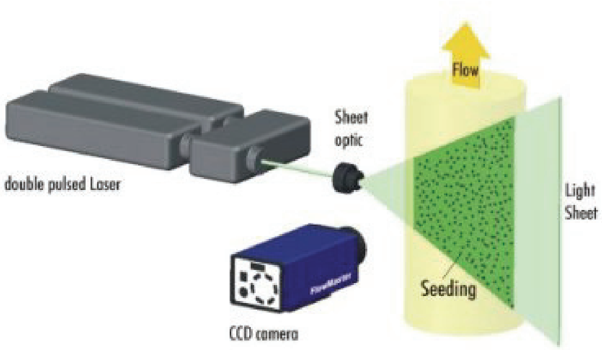
PTV in Annulus



Particle Tracking Technique

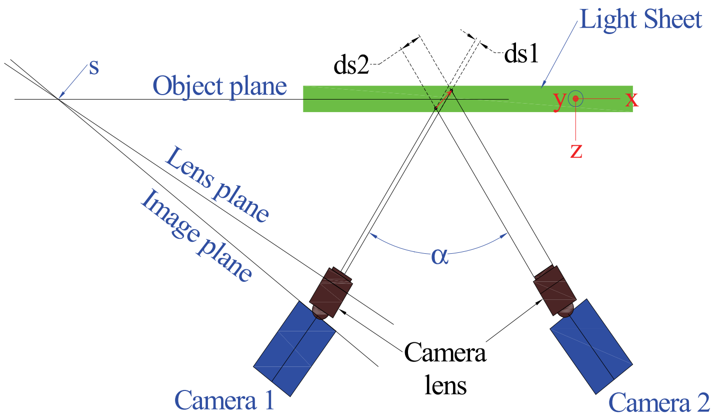
Particle Image Velocimetry

Taking Data



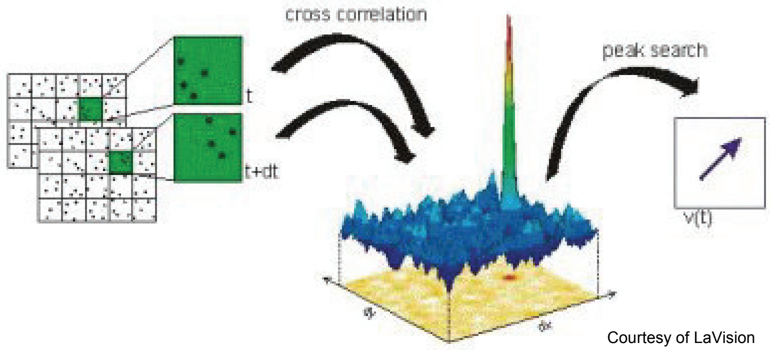
Courtesy of LaVision

2-D PIV uses 1 camera and takes planar images



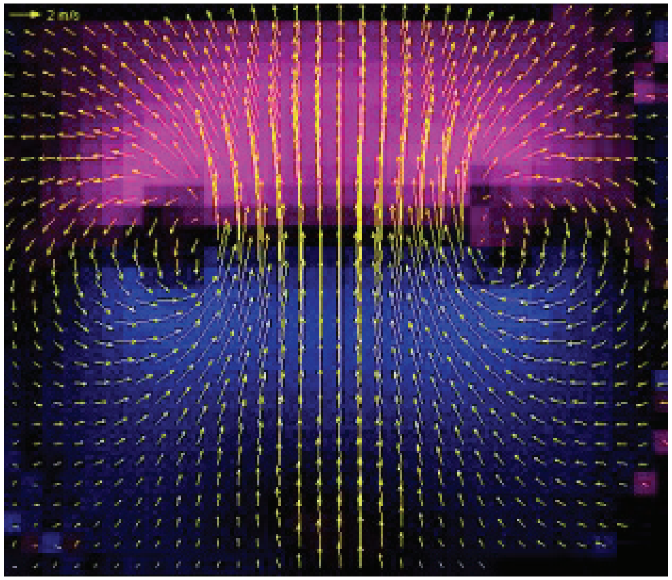
3-D PIV (or stereo) uses 2 cameras to detect particle motion in all 3 axes of motion

Data Processing



Courtesy of LaVision

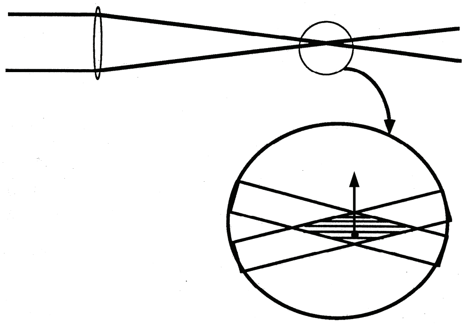
The computer then uses a cross correlation technique to generate vector fields and other useful data



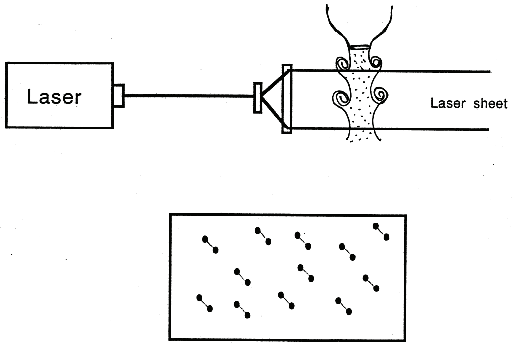
How does refractive-index-matching help?

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

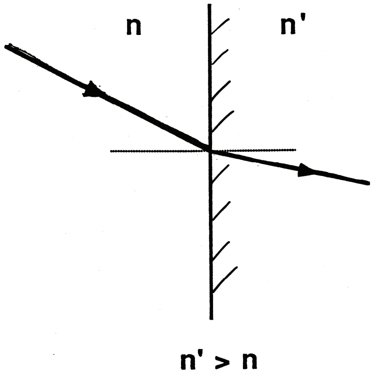
Laser Doppler Velocimetry



Particle Image Velocimetry

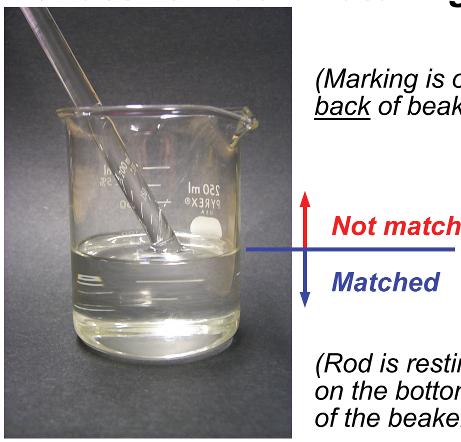


Snell's Law



- 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



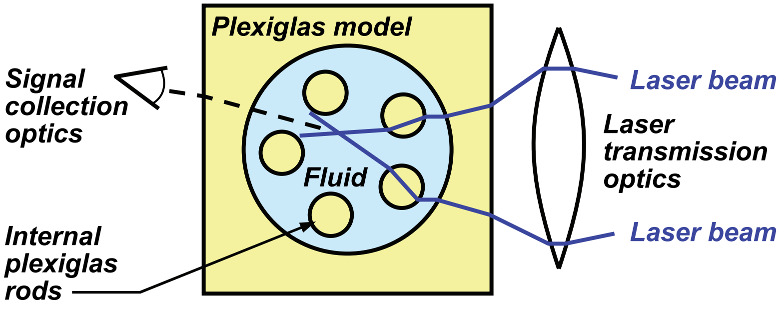
(Marking is on *<u>back</u> of beaker)*

Not matched

Matched

(Rod is resting on the bottom of the beaker)

Refractive index not matched



Plexiglas model

Signal collection optics

Fluid

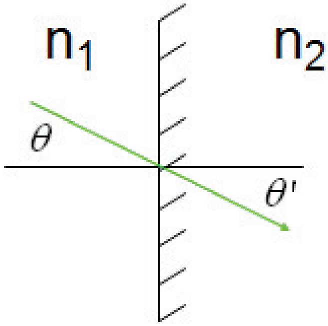
Internal plexiglas rods

Laser beam

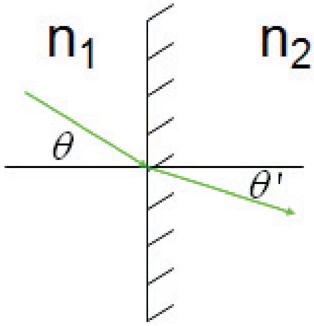
Laser transmission optics

Laser beam

Refractive-Index-Matching



$n_1 = n_2$

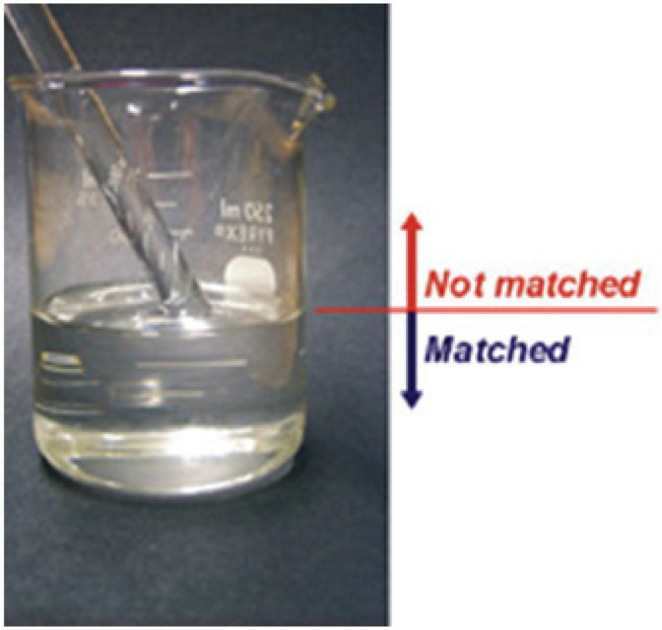


$n_1 > n_2$

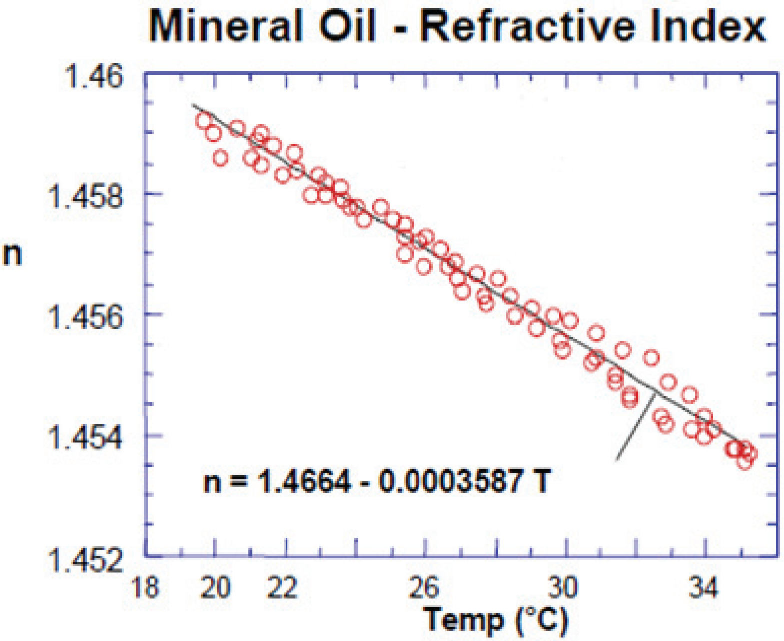
Snell's Law describes the relationship between angles of incidence and angles of refraction, when referring to light of other waves passing through a boundary between two different isotropic media

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

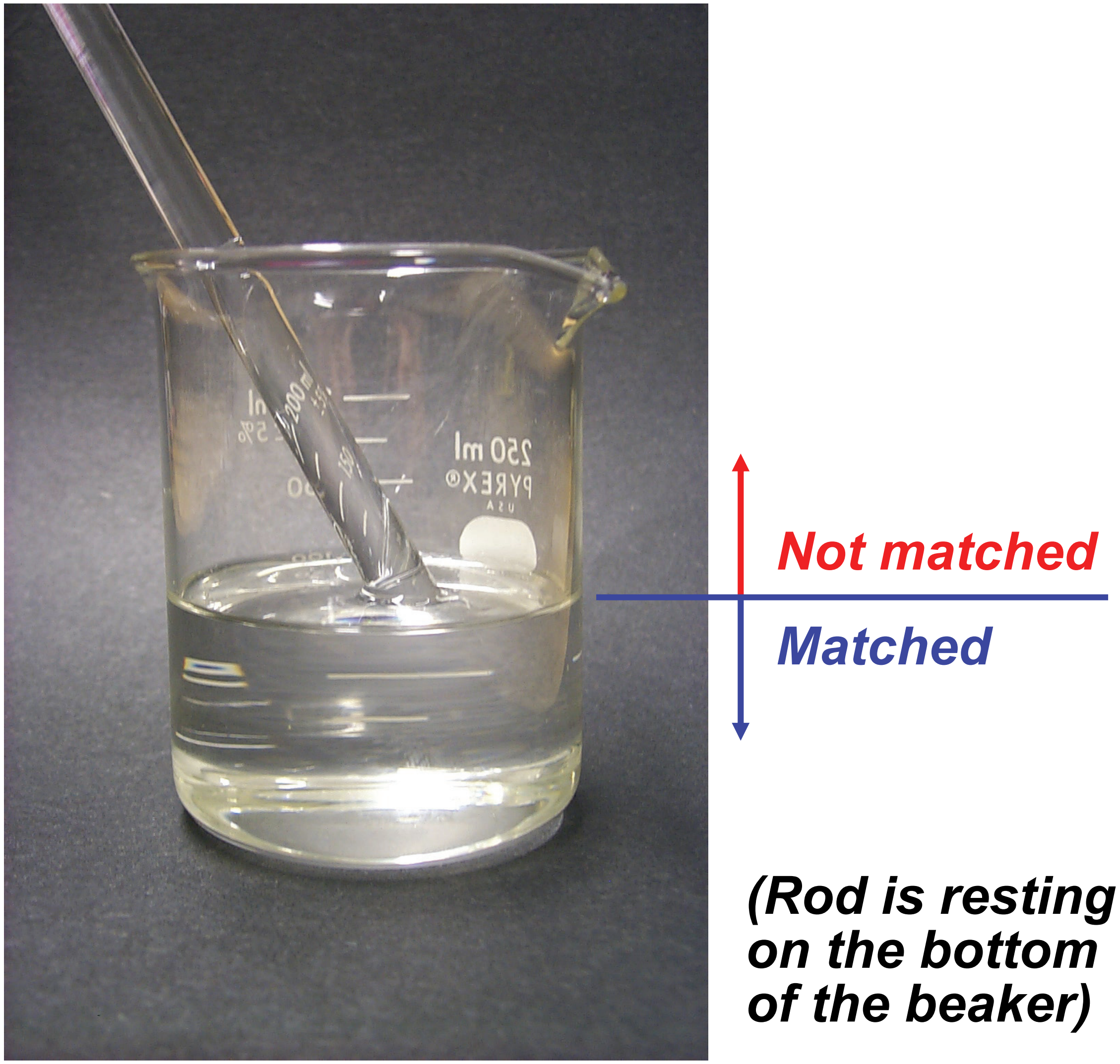
The index of refraction is temperature and wavelength dependent



A quartz rod in mineral oil illustrates a matched index of refraction, making the rod "invisible" when submerged



Example of application of refractive-index-matching



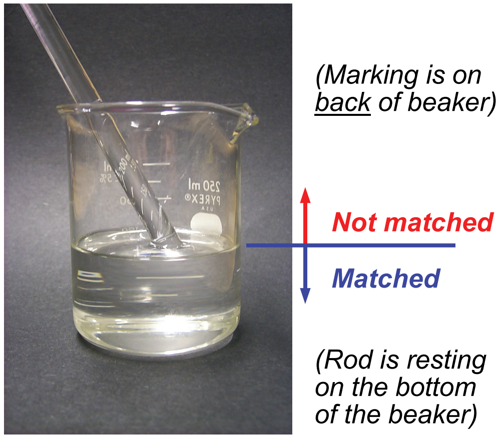
(Marking is on __back__ of beaker)

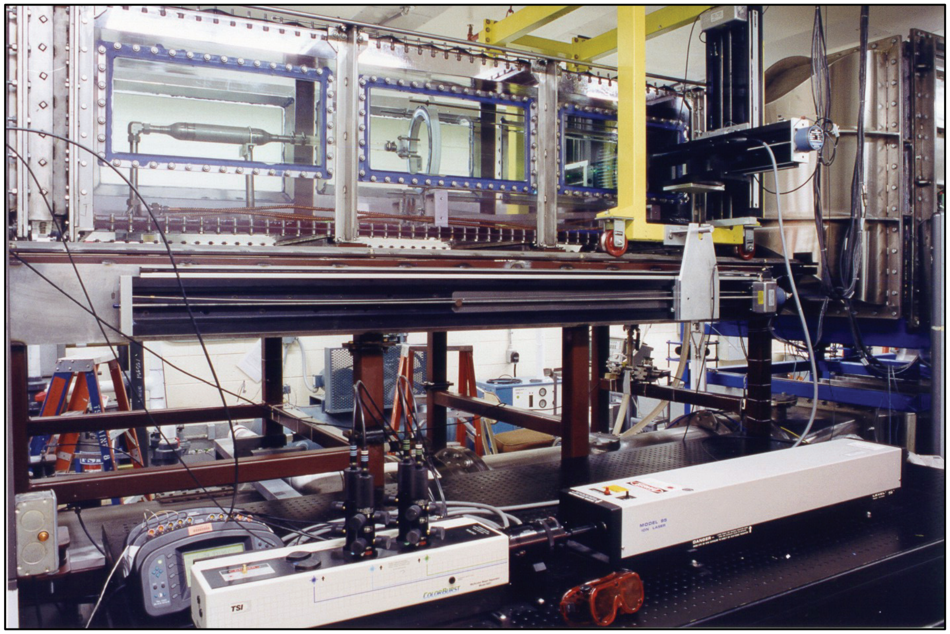
(Rod is resting on the bottom of the beaker)

Benefits of large MIR flow systems

- 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

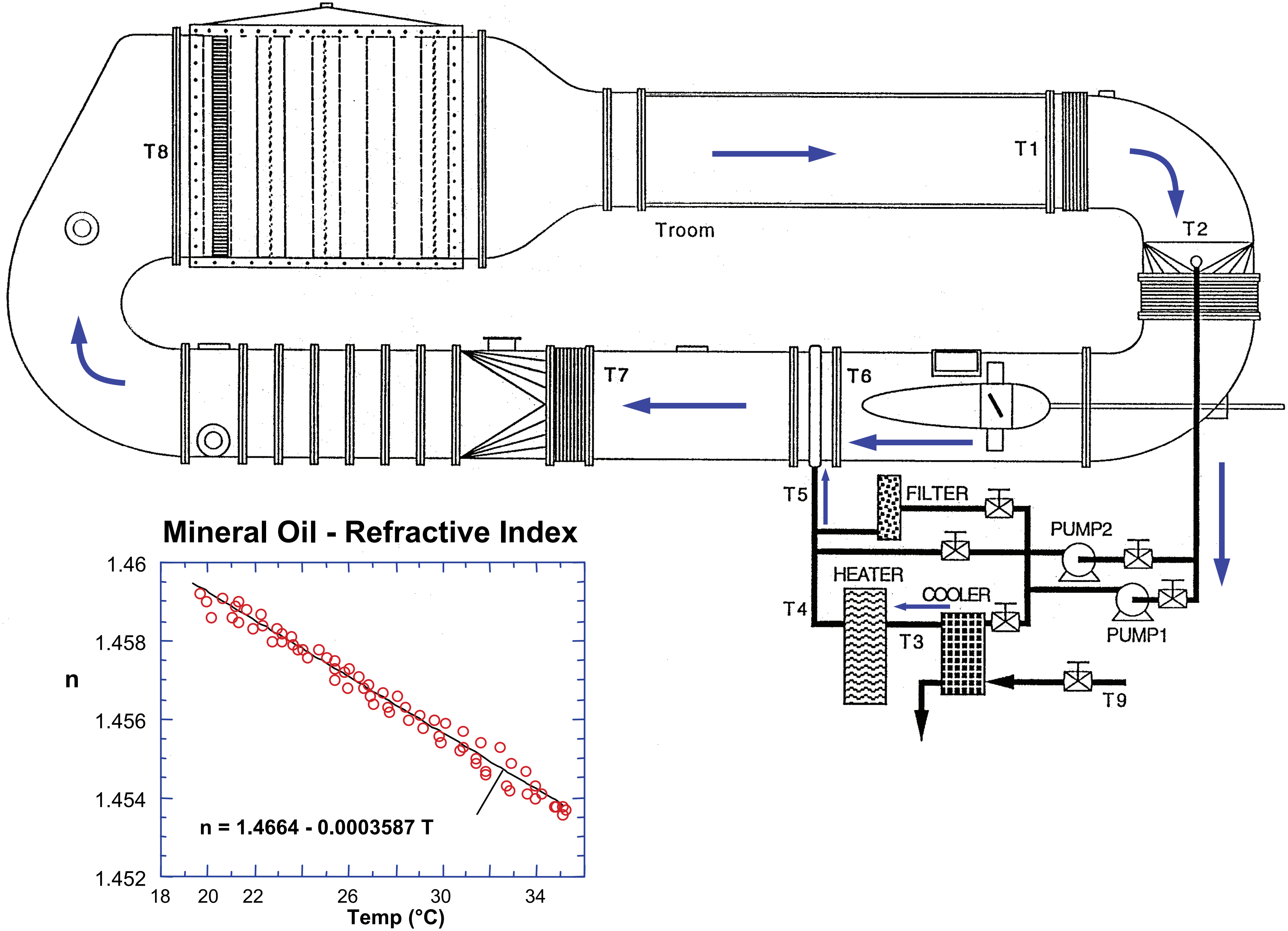




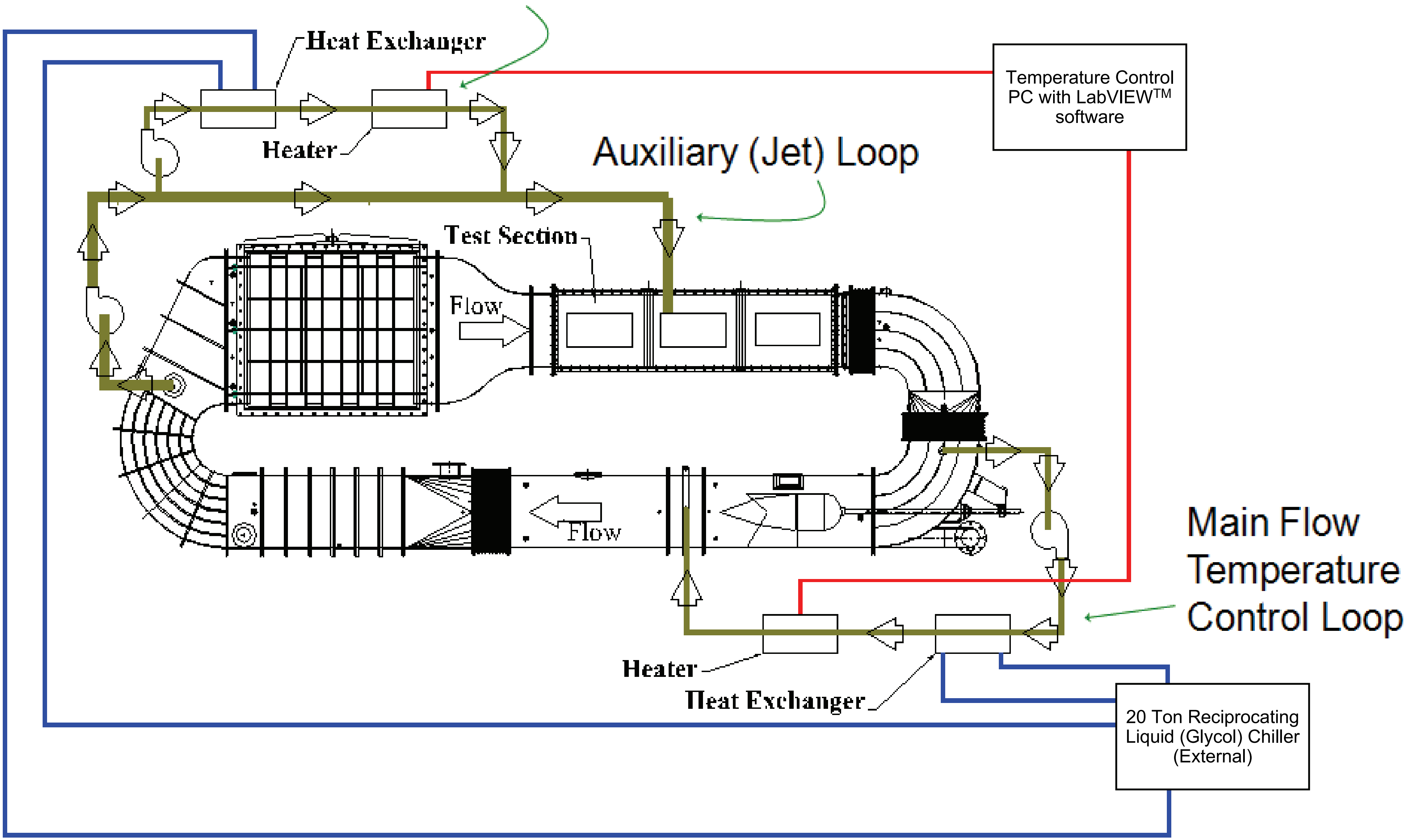
Apparatus to study fluid physics phenomena in idealized SNF canister for EM Science project

- **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 Facility Temperature Control



Auxiliary Loop Temperature Control

Auxiliary (Jet) Loop

Main Flow Temperature Control Loop

Temperature Control PC with LabVIEW^{TM} software

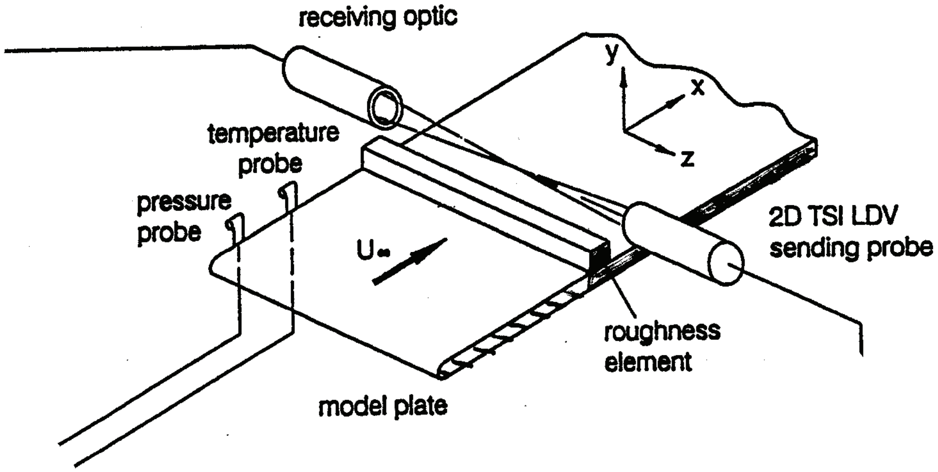
20 Ton Reciprocating Liquid (Glycol) Chiller (External)

The large Matched-Index-of-Refraction flow system at Uni. Erlangen

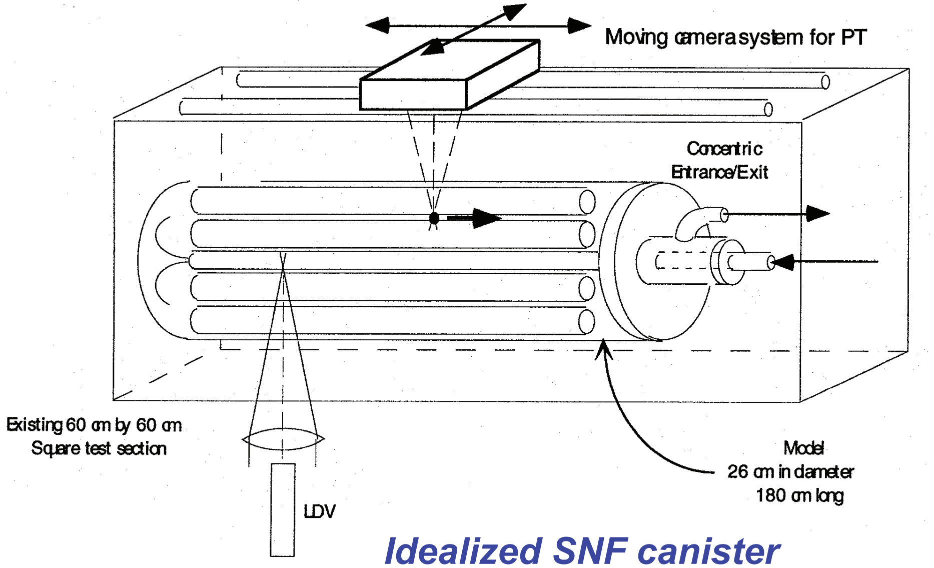
Technical specifications of the Matched-Index-of-Refraction flow systems

	INL	**Uni. Erlangen**
Cross section of test section (m^2)	0.62 x 0.62	0.6 x 0.45
Length of test section (m)	2.4	2.52
Contraction ratio	4:1	6:1
Fluid / oil	Drakeoel 5 (PENRECO)	Odina 913 (SHELL)
LDA index matching temperature (C)	23.75	28.7
Refractive index	1.4579	1.4585
Kinematic viscosity (m^2/s)	13.9 x 10^{-6}	11.2 x 10^{-6}
Temperature control	External	Internal
Maximum inlet velocity (m/s)	1.9	5
Inlet turbulence intensity (%)	0.5 - 1	0.15

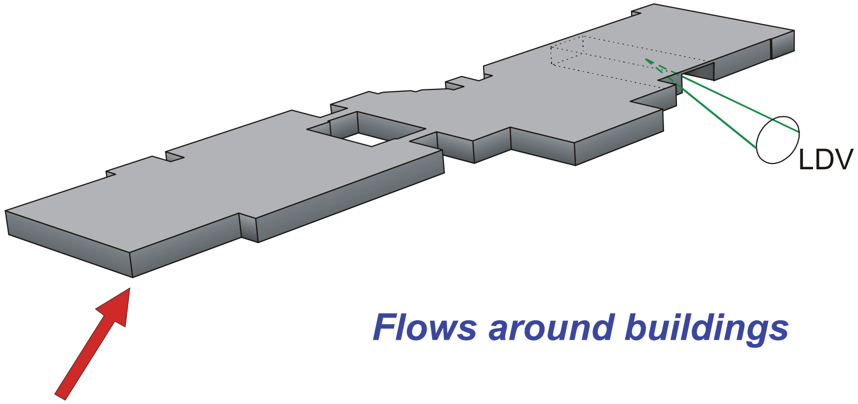
Typical recent experiments -- external and internal flows



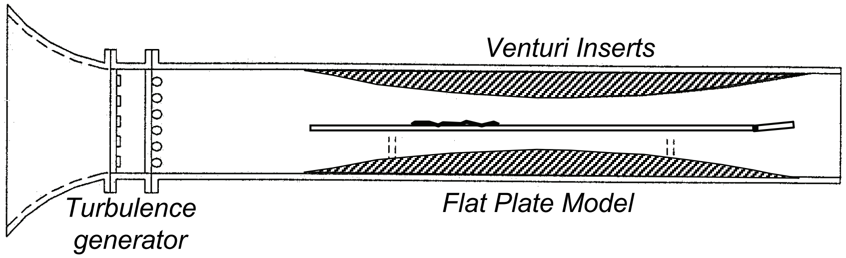
Boundary layer transition



Idealized SNF canister



Flows around buildings



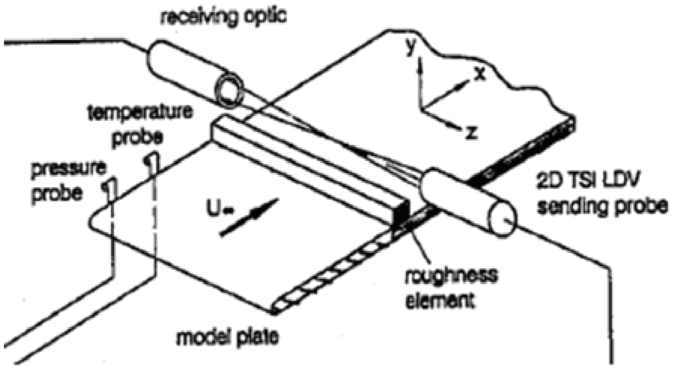
Realistic rough surfaces in turbomachinery

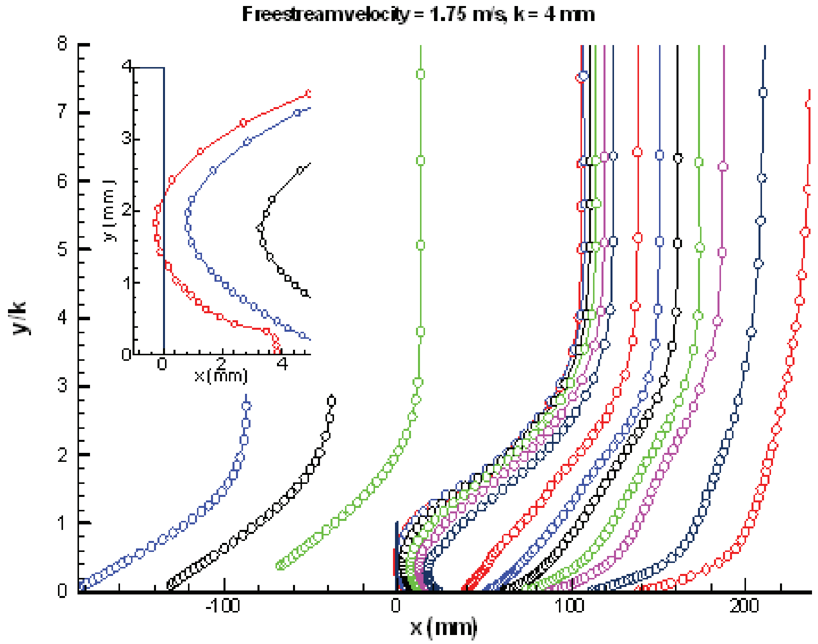
Some recent international collaboration

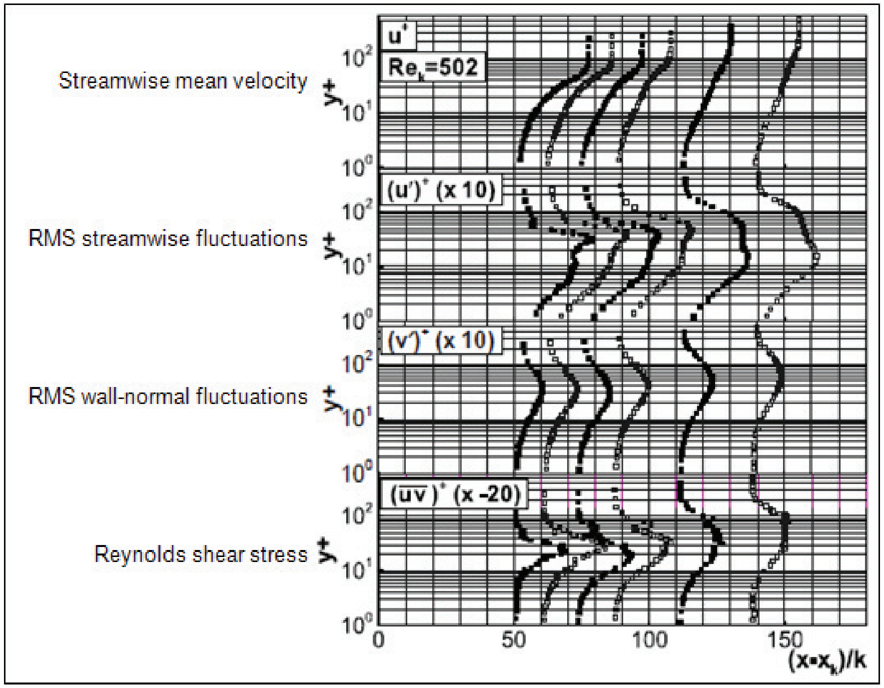
Germany, US	Structure of transitional flows
Japan, Montenegro, UK, US	Coolant flows in advanced GCRs
Germany, US	Suction in transitional boundary layers
Korea, Montenegro, UK, US	Coolant flows in SCWRs
France, US	Flows in the lower plena of GCRs
Germany, Ireland, Sweden, UK, US	Entropy generation in transitioning flows
Korea, US	Bypass flows in prismatic GCRs

Transition in boundary layers induced by a square rib – S. Becker and F. Durst, Uni. Erlangen, Germany and K. G. Condie and D. M. McEligot, INL, US

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



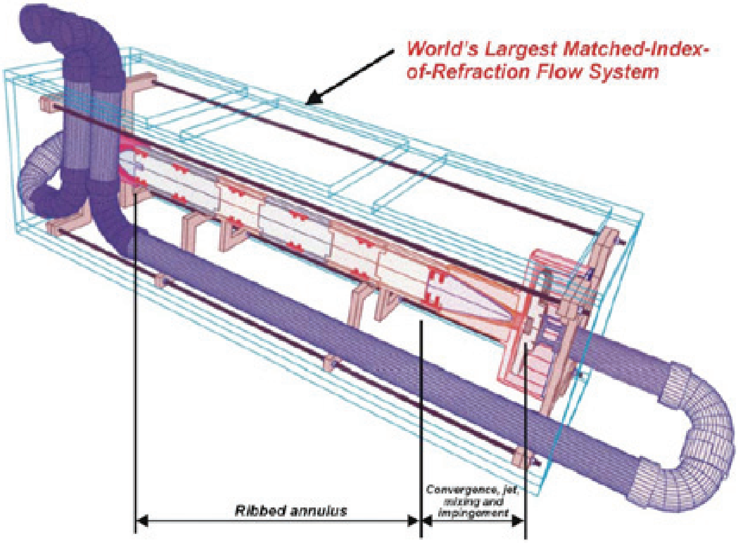




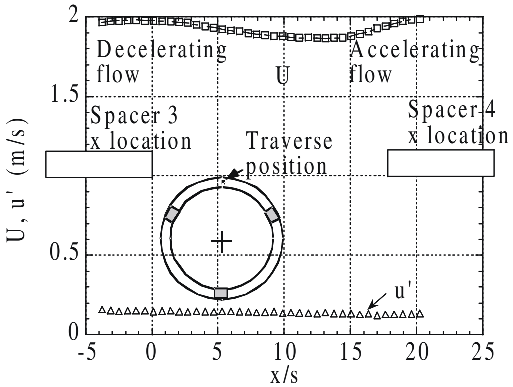
Becker et al., 2002, "LDA-Measurements of Transitional Flows Induced by a Square Rib," J. Fluids Eng., **124**, pp. 108-117

Coolant flows in advanced gas-cooled reactors (GCRs) – T. Kunugi, Kyoto U., and S.-i. Satake, Toyama U., Japan, J. D. Jackson, U. Manchester, UK, P. Vukoslavcevic, U. Montenegro, R. H. Pletcher, Iowa State, J. M. Wallace, U. Maryland, A. Shenoy and G. Baccaglini, General Atomics and K. G. Condie, G. E. McCreery, R. J. Pink and D. M. McEligot, INL, US

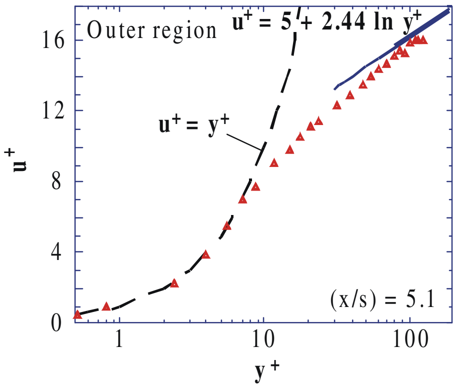
Objective = provide fundamental knowledge necessary for development of improved predictive methods for application to advanced GCRs



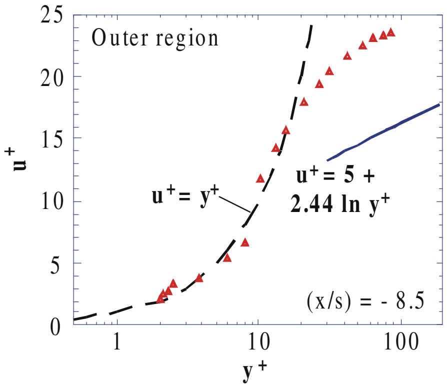
Axial profiles



Decelerating region

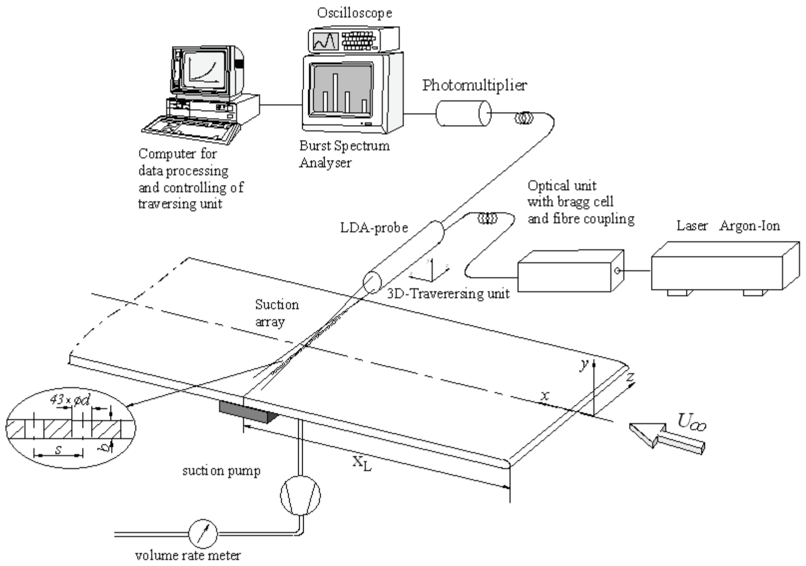


Accelerating region

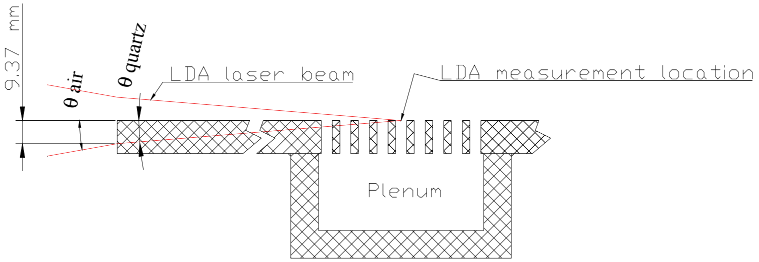


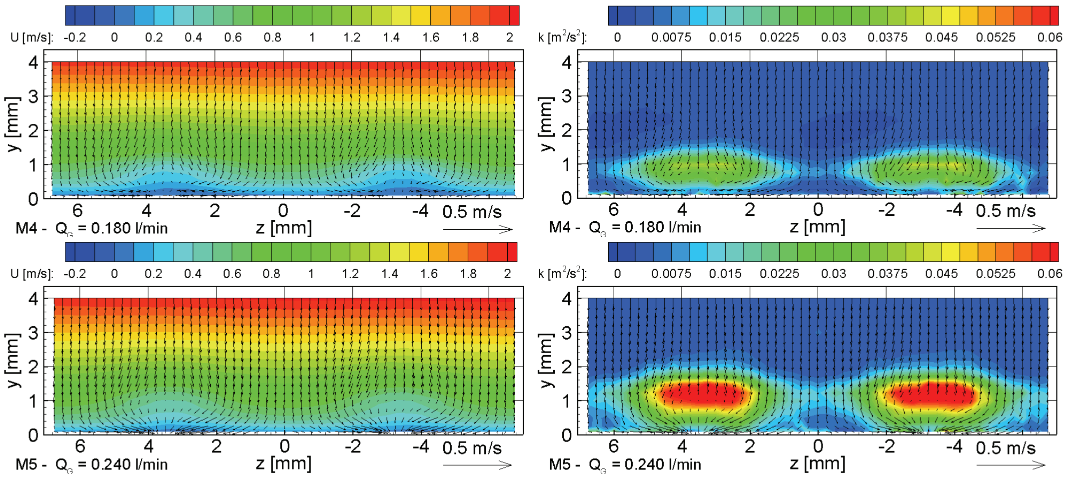
Ref: McCreery, G. E., R. J. Pink, K. G. Condie, 2003. Fluid dynamics of ribbed annuli. NuReth-10 paper J00203, Seoul, October.

Suction in a transitional boundary layer – S. Becker and J. Jovanovic, Uni. Erlangen, Germany and C. M. Stoots, INL, US



Aim = understand the critical parameters affecting stabilization via suction through holes

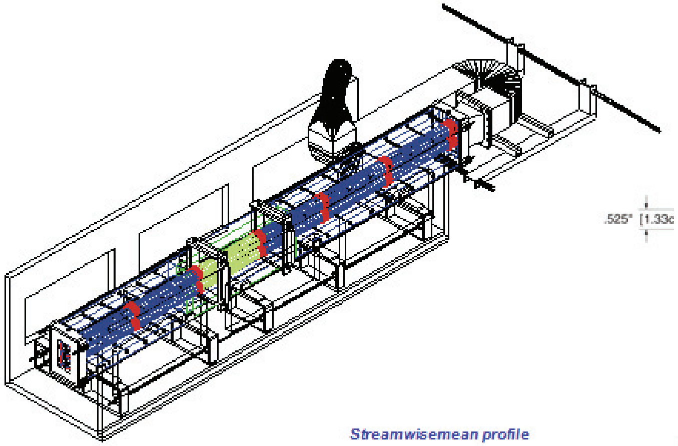


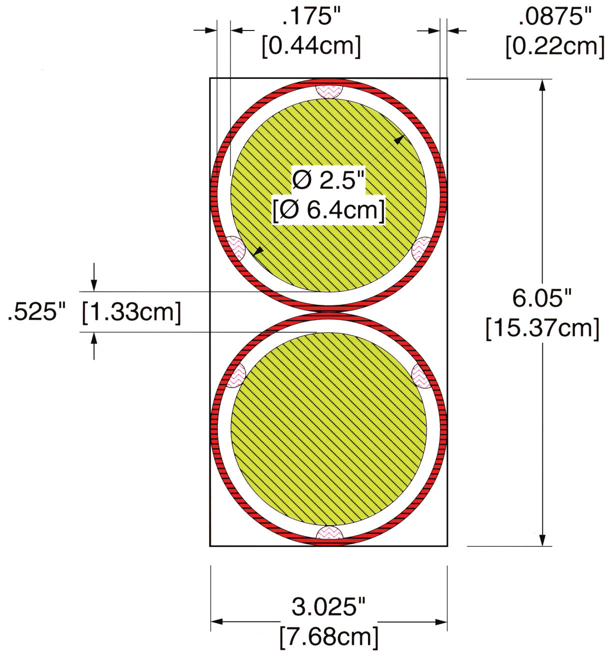


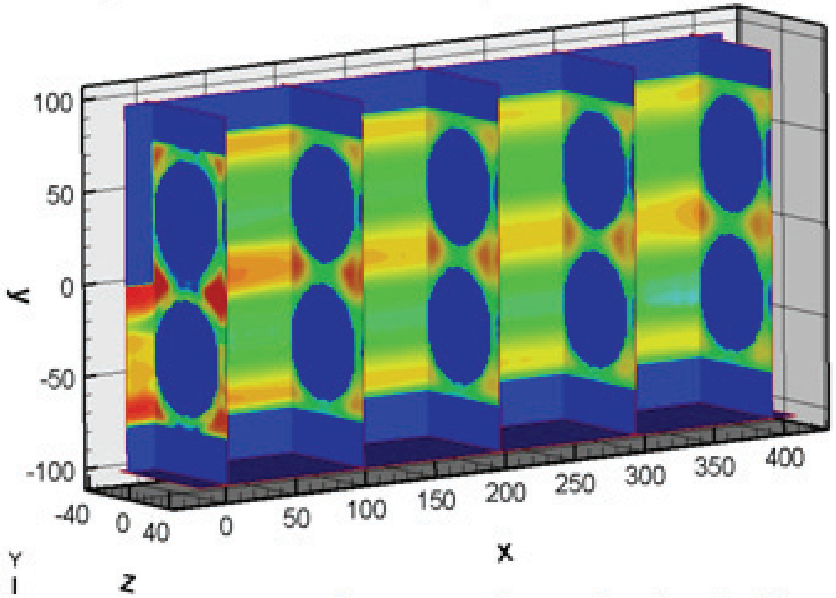
Velocity and TKE fields 1D behind holes

Coolant flows in supercritical water reactors – J. Y. Yoo and J. S. Lee, SNU, S. O. Park, KAIST, Korea, J. D. Jackson, U. Manchester, UK, P. Vukoslavcevic, U. Montenegro, L. E. Hochreiter, Penn. State, R. H. Pletcher, Iowa State, B. L. Smith, Utah State, J. M. Wallace, U. Maryland and K. G. Condie, G. E. McCreery, D. M. McEligot, H. M. McIlroy and R.. J. Pink, INL, US

Objective = develop fundamental knowledge needed for improved predictive methods in SCWR applications







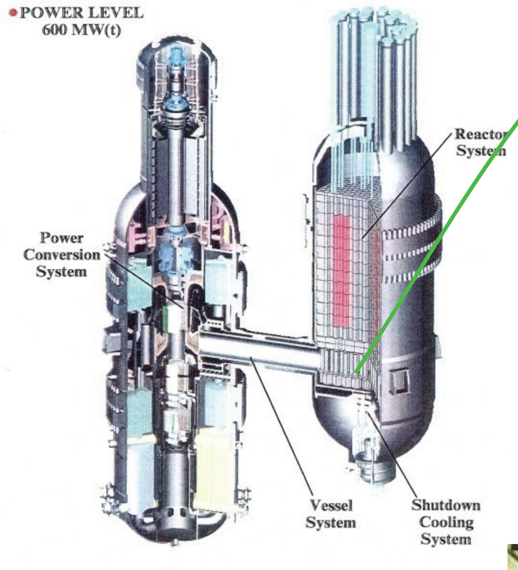
Streamwise velocity field

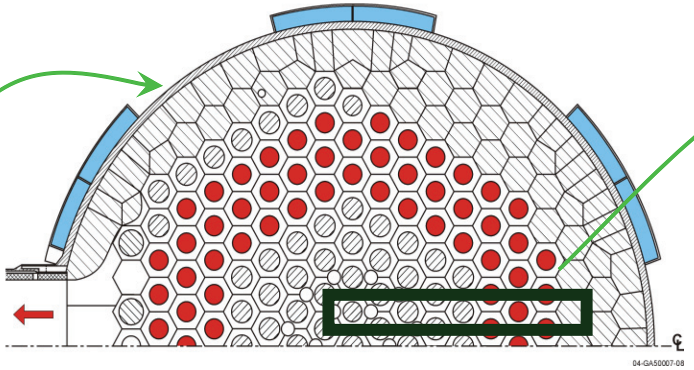
McEligot et al., 2005, "Advanced Computational Thermal Fluid Physics (CTFP) and its Assessment for Light Water Reactors and Supercritical Reactors, " INEEL/EXT-05-00901, 31 Oct.

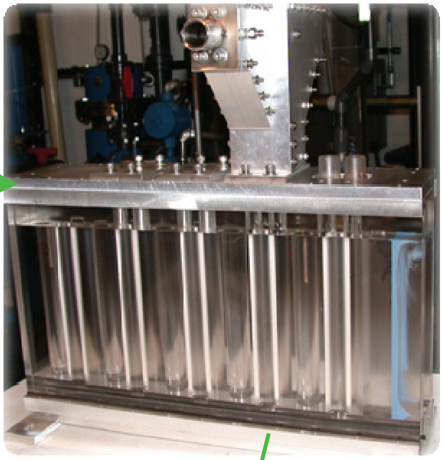
Flows in the lower plena of gas-cooled reactors (GCRs) –

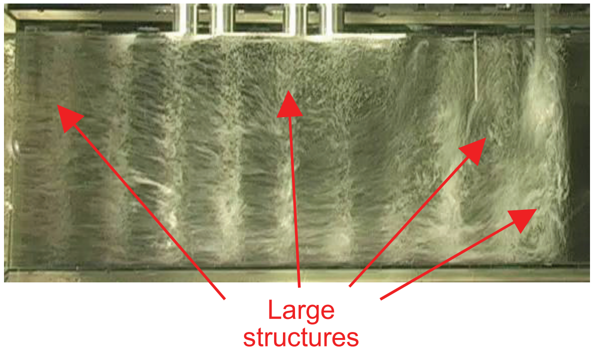
D. Tenchine, H. Paillere and F. Ducros, CEA, France, H. M. McIlroy, D. M. McEligot and R. J. Pink, INL, R. E. Spall and B. L. Smith, Utah State and W. D. Pointer and C. Tzanos, ANL, US

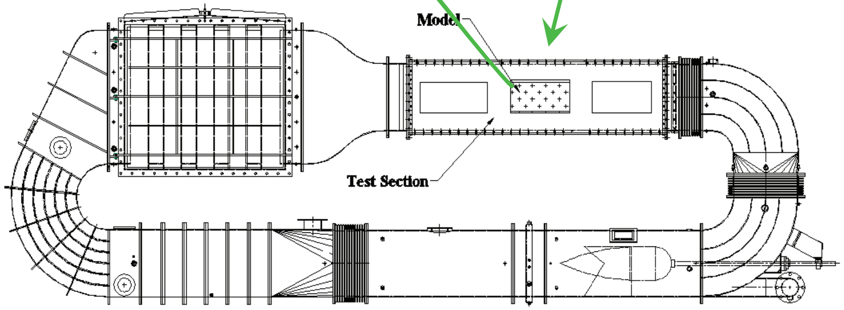
Objective = provide benchmark data for assessment and improvement of codes proposed for GCRs







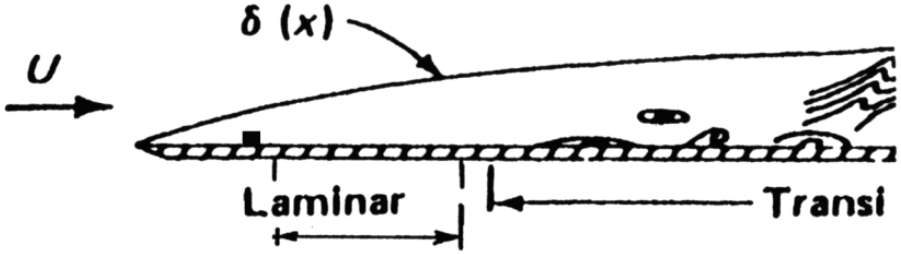




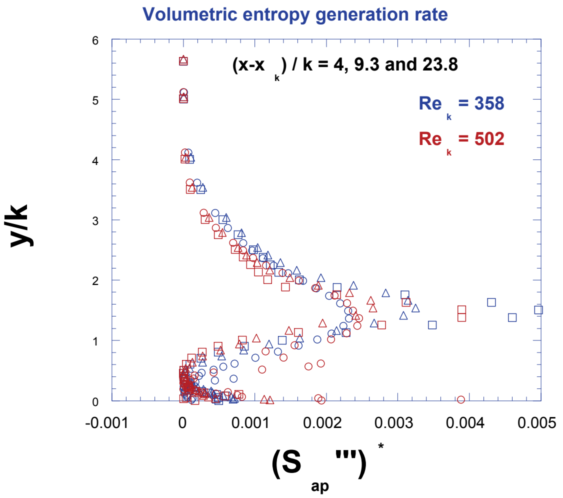
McIlroy, McEligot and Pink, 2010. *Nuc. Engr. Design*, 240, pp. 416-428.

Entropy generation in transitioning flows – D. M. McEligot, R. S. Budwig and A. Tokuhiro, U. Idaho, H. M. McIlroy, INL, J. R. Ferguson, Boise State, US, S. Becker, Uni. Erlangen, Germany, E. J. Walsh, U. Limerick, Ireland, L. Brandt and P. Schlatter, KTH, Sweden and T. A. Zaki, Imperial College, UK

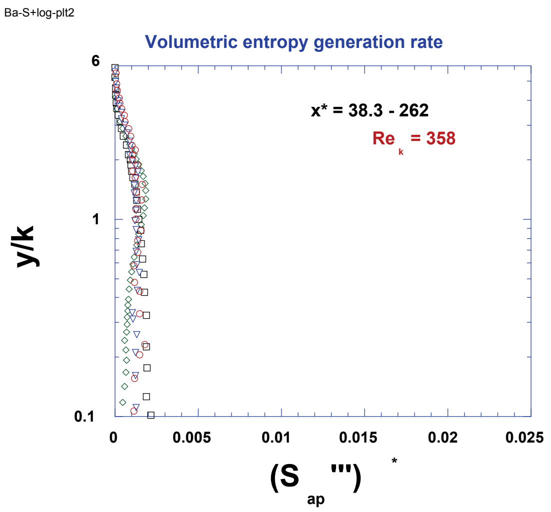
Objective = obtain basic understanding of local (pointwise) distributions of entropy generation rates in characteristic wall shear flows



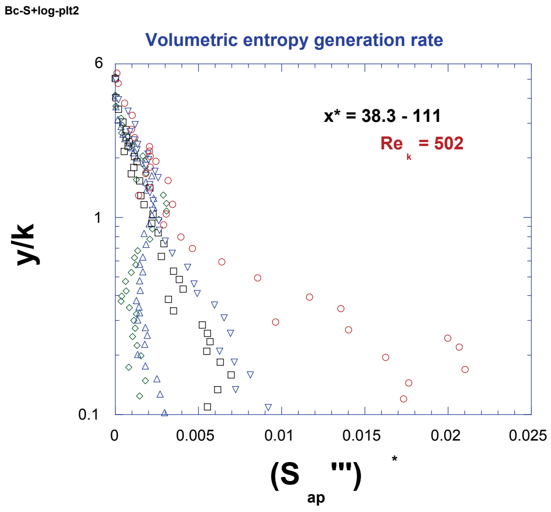
$$(S_{ap}''')^* = (TS_{ap}'''\delta/(\rho U_\infty^3))$$



Separated flow behind rib



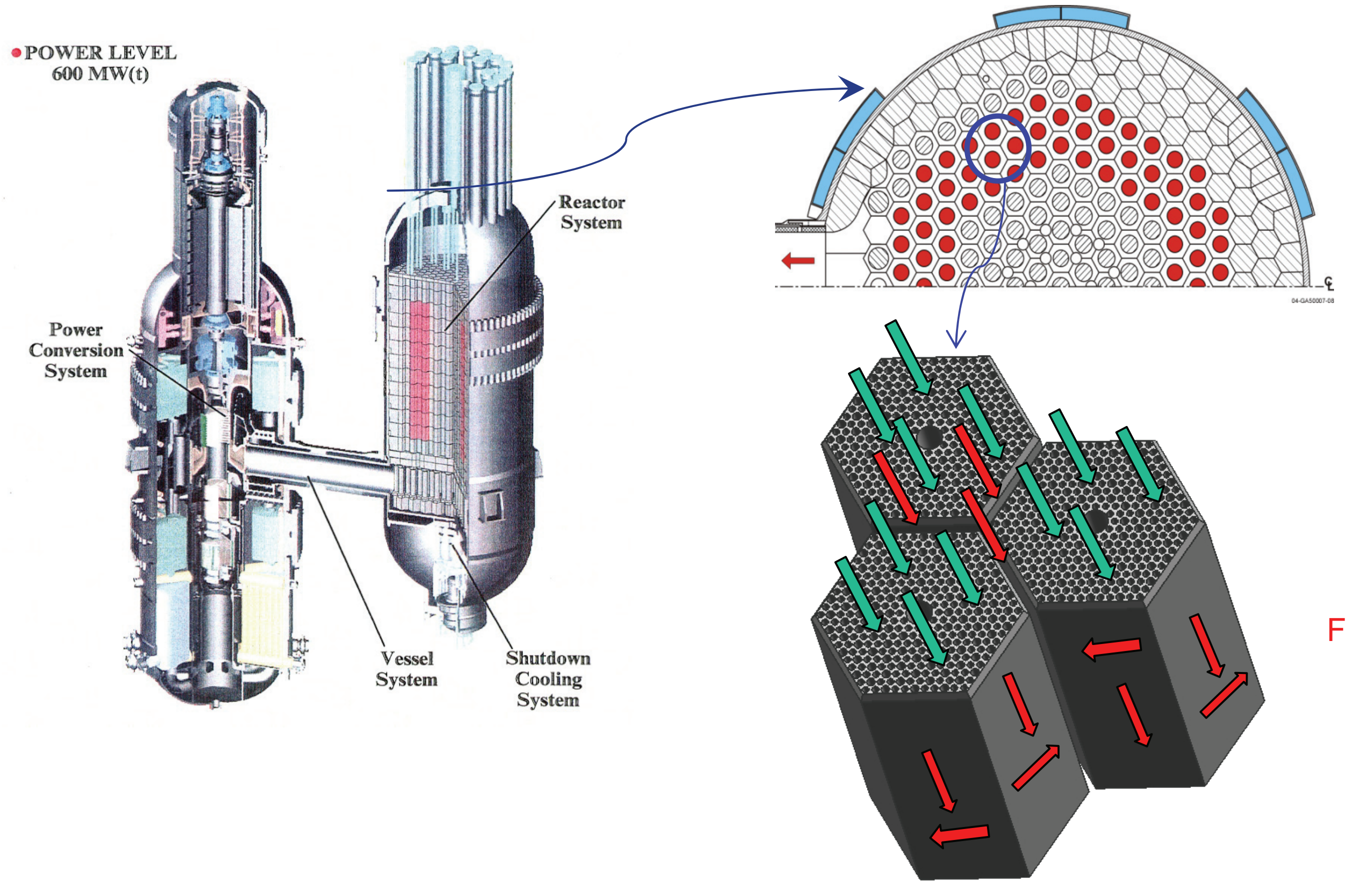
Laminar recovery

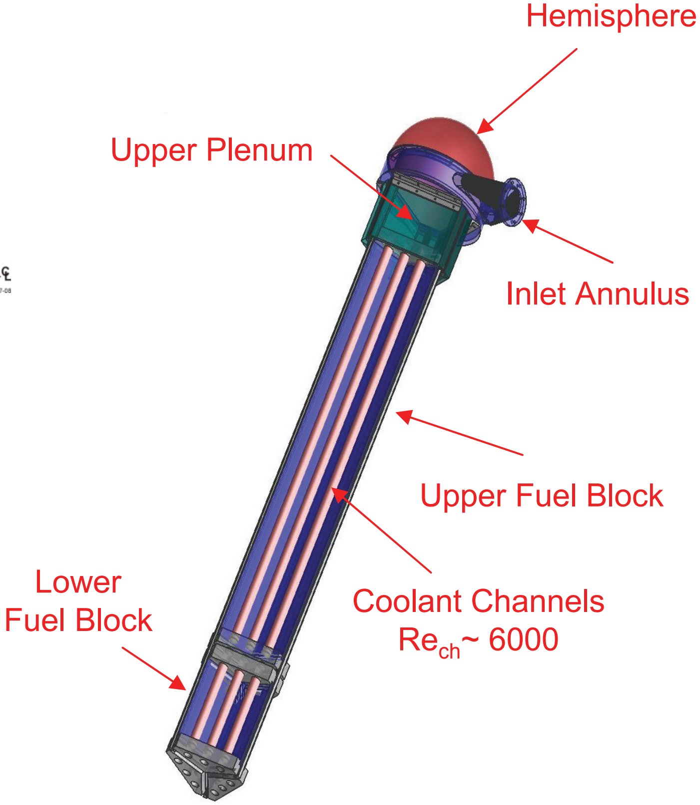


Transitioning boundary layer

Bypass flows in prismatic GCRs – G.-C. Park, SNU, and M.-H. Kim, KAERI, Korea, H. M. McIlroy and R. R. Schultz, INL, US

Objectives = understanding bypass flows and developing improved estimates of associated loss coefficients and surface friction for normal power, reduced power and residual heat removal





Potential collaborative interactions

- Faculty projects in fluid mechanics areas of mutual interest
- Faculty collaborative research proposals
- Faculty sabbatical leaves
- Doctoral dissertations and masters theses
- Training students by participation in ongoing experiments
- Training post doctoral associates
- Fluid mechanics conferences and workshops on topical areas of interest
- Modifications of facilities to expand capabilities of interest
- Advisory committees and review panels

Concluding remarks

- The U. Erlangen and INL MIR systems are versatile, useful tools for examining flows in complicated situations
- Benchmark data can be acquired for external, internal and coupled flows
- They are excellent bases for interesting international collaboration in graduate education

Further details

McEligot, Becker and McIlroy, ICEE-2010 Proceedings
McEligot, Becker and McIlroy, 2010. Tech. rpt. INL/EXT-10-18835.
Internet site = www.inl.gov/mir

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