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

Authors:

Donald M. McEligot, University of Idaho, Idaho Falls, Idaho 83402 USA, DonaldM@uidaho.edu
Stefan Becker, Uni. Erlangen, D-91058 Erlangen, Germany
Hugh M. McIlroy, Jr., Idaho National Laboratory (INL), Idaho Falls, Idaho 83415-2200 USA

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.*

Index terms ---- *Fluid mechanics, international collaboration, optical techniques, refractive-index-matching*

INTRODUCTION

In recent international collaboration, INL and Uni. Erlangen have developed large MIR flow systems [Stoots et al., 2001; McIlroy and Budwig, 2007] which can be ideal for joint graduate student research. The benefit of the MIR technique is that it permits optical measurements, such as particle image velocimeters (PIV) and laser Doppler anemometers (LDA), to determine flow characteristics near surfaces, in passages and around objects having complicated geometries without introducing an intrusive probe into the flow field and without distortion of the optical paths. One way to eliminate optical interference of LDA systems is by employing suitable transparent solid materials together with fluids that possess the same refractive index as the solid material itself. In this way, the solid disappears optically (and therefore has no influence on the laser beams) but maintains its full mechanical influence on the flow. With a transparent model of different refractive index than the working fluid, the light rays of optical measuring instruments can be refracted in such a manner that measurements are either impossible or require extensive, difficult calibrations. Without refractive index matching LDA beams may not cross to form the measurement control volume at the desired focal length, if they cross at all.

Before the INL and Uni. Erlangen developments, no matched-index-of-refraction (MIR) flow facility existed that permitted the study of flow past complex geometries requiring high Reynolds numbers, fine spatial resolution and larger scale. Examples of such geometries include heat exchanger and nuclear reactor tube bundles and boundary layers. A demonstration of the benefits of refractive-index-matching is shown in Figure 1 with a test model for an idealized ribbed annulus [McCreery et al., 2003].

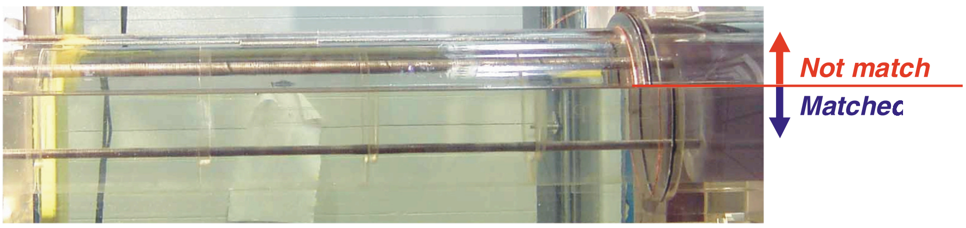

FIGURE 1
THIS EXAMPLE DEMONSTRATES THE BENEFITS OF REFRACTIVE-INDEX-MATCHING WITH A TRANSPARENT MODEL HAVING CURVED INTERFACES (FLOW THROUGH A HORIZONTAL RIBBED ANNULUS OF 164 MM DIAMETER [MCCREERY ET AL., 2003]). HORIZONTAL STRUCTURAL RODS ARE STEEL AND THEREFORE OPAQUE; THE RIGHT END IS PLASTIC, WHICH IS NOT MATCHED.

The MIR technique itself is not new; Corino and Brodkey [1969] employed it to measure turbulence structure in a circular tube. The *innovative advantage* of the INL and UE systems is their large size, leading to improved spatial and temporal resolution compared to others. Earlier, most experiments with index matching were small, with characteristic lengths on the order of five cm or less. No index-matched flow facility existed that permitted reasonably-sized flat plate boundary layers to be installed and, hence, provide the basic test facility to study laminar-to-turbulent boundary layer transition control in detail. In contrast, the MIR flow test sections at UE and INL have cross sections of the order of sixty cm and are about two meters long, allowing the use of models of substantial size. The working fluid is a light mineral oil. With the fluid temperature controlled, the quartz components can barely be seen at wave lengths in the visible spectrum (Figure 1).

Quantification of transitional boundary layers requires measurements very close to the wall for accurate determination of the wall shear stress. LDA measurements usually suffer from optical interference or blockage of the laser beams, especially when systems for two and three component measurements are employed. Facility size can help in making very near-wall velocity measurements by increasing flow length scales relative to measurement probe size. By using an index-matched boundary, one can measure instantaneous u, v, w and their gradients at locations extremely close to a surface, e.g., meaningful data to $y^+ < 0.1$ [Becker et al., 2002]. Increased size can also improve temporal resolution. Typical nondimensional time increments for sampling may be defined as $\Delta t^+ = \Delta t\ V / L$ so larger size gives effectively faster sampling.

THE MIR FLOW SYSTEMS

In previous MIR systems, the working fluids have often been either toxic or combustible. However, when designing large facilities, more attention must be paid to issues such as fumes, toxicity, flammability and especially expense [Stoots et al., 2001]. Since the system volume is over 11,000 liters, a light mineral oil was selected as the working fluid due to environmental and safety considerations; its refractive index matches that of some quartz at the wave lengths of the lasers employed. This particular fluid has the same index-of-refraction as fused quartz near room temperature, no odor, is non-toxic, relatively nonflammable and non-volatile, inexpensive and very stable.

Figure 2 is a photograph of the MIR facility at Uni. Erlangen. Flow is counterclockwise in the figure. The main flow pump is in the lower left corner. From the main pump, the oil passes through an expansion bellow, diffuser, two elbows and enters the settling chamber. The settling chamber has several screens and a honey comb for flow quality conditioning. After the settling chamber, the oil passes through a contraction and enters the test section. The refractive index of the fluid is maintained at the desired value by a temperature control system which maintains a constant temperature in the test section to within 0.1 C. Table 1 provides typical characteristics of the two systems.

FIGURE 2
MATCHED-INDEX-OF-REFRACTION TUNNEL AT UNI. ERLANGEN

Experimental models have been employed to study external and internal flows as well as coupled external-internal flow situations. Internal flows are typically studied inside a quartz enclosure with the mean flow and test section windows providing a perpendicular optical interface for the transition from air in the laboratory to the oil in the test section. Examples of coupled internal-external flows are a synthetic jet interacting with an external boundary layer in a study by Prof. Douglas R. Smith of U. Wyoming and a helical nozzle creating a swirling jet by Prof. Barton L. Smith of Utah State. With guidelines for verification and validation of CFD, the models are designed in close collaboration with all participating partners; this coordination is essential to ensure that the dimensionless parameters from all experiments and computations are comparable.

	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)	13.9×10^{-6}	11.2×10^{-6}
Temperature control	External	Internal
Maximum inlet velocity (m/s)	1.9	5
Inlet turbulence intensity (%)	0.5 - 1	0.15

TABLE 1
TECHNICAL SPECIFICATIONS OF THE MATCHED-INDEX-OF-REFRACTION FLOW SYSTEMS.

Experimental models have been employed to study external and internal flows as well as coupled external-internal flow situations. Internal flows are typically studied inside a quartz enclosure with the mean flow and test section windows providing a perpendicular optical interface for the transition from air in the laboratory to the oil in the test section. Examples of coupled internal-external flows are a synthetic jet interacting with an external boundary layer in a study by Prof. Douglas R. Smith of U. Wyoming and a helical nozzle creating a swirling jet by Prof. Barton L. Smith of Utah State. With guidelines for verification and validation of CFD, the models are designed in close collaboration with all participating partners; this coordination is essential to ensure that the dimensionless parameters from all experiments and computations are comparable.

Data are obtained primarily by optical techniques such as laser Doppler velocimetry (LDV) and particle imaging velocimetry (PIV). Instantaneous velocity components may be obtained by measurements with existing two- (or one-) component LDV at fixed positions. Since its low velocities lead to inherently "slow" characteristic times for flow phenomena in the MIR system, it is desirable to employ forward scattering to avoid longer measuring times than needed. A three-directional traversing mechanism was designed to use the LDV in the forward scattering mode and to avoid relative motion between the test section and the optics (Figure 3 left). Mean velocities and mean turbulence gradients and statistics are determined from the LDV time series. Typical results include time-resolved, pointwise distributions of the mean velocities, U, V, W, and their Reynolds stress components.

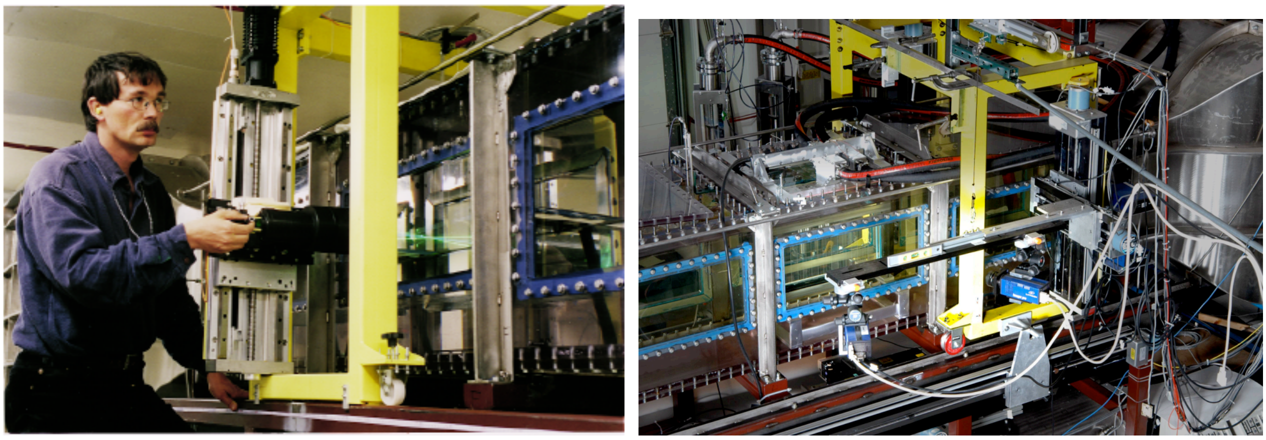

FIGURE 3
LEFT: DR. STEFAN BECKER OF UNI. ERLANGEN ADJUSTING CUSTOM RECEIVING OPTICS OF THE TWO-COMPONENT LDV AT INL. ALSO SHOWN IS THE THREE-DIRECTIONAL TRAVERSING MECHANISM AND A (BARELY VISIBLE) FLAT PLATE MODEL ABOVE THE BLACK HORIZONTAL SUPPORT BRACE. RIGHT: THE INL MIR FLOW SYSTEM FOR STUDYING FLUID PHYSICS PHENOMENA WITH 3-D PIV SYSTEM MOUNTED ON THREE-DIRECTIONAL TRAVERSE.

At INL instantaneous velocity field measurements are primarily obtained with a 3-D PIV system from LaVision, Inc. (Göttingen, Deutschland). The PIV cameras are mounted on the same 3-directional traverse system that is controlled by three separate electric stepping motors (Figure 3 right). The PIV system laser usually is mounted below the experiment model and produces a vertical light sheet approximately 2 mm thick. Resulting PIV measurements are instantaneous values of the three velocity components (u, v and w), their spatial gradients and Reynolds stresses in the plane of the light sheet. Mean statistics are calculated by averaging a sufficient time-series of the instantaneous data.

EXAMPLES OF TYPICAL PROJECTS

Transition in boundary layers induced by a square rib – Stefan Becker and Franz Durst, Uni. Erlangen, Germany and Keith G. Condie and Donald M. McEligot, INL, US

Laminar-to-turbulent flow transition is a phenomenon which continues to be of interest to fluid mechanics scholars. In many technical applications, laminar boundary layers are induced by roughnesses to undergo transition to a turbulent flow at lower Reynolds numbers than the natural flow transition in order to enhance heat, mass or momentum transfer. These studies were initiated to extend the knowledge of the structure of the transition process induced by a 2-D square roughness element. New fundamental measurements are presented for the transition process in flat plate boundary layers downstream of two-dimensional square ribs [Becker et al., 2002]. By use of LDA and the INL MIR system, data for wall-normal fluctuations and Reynolds stresses were obtained in the near wall region to $y^+ < 0.1$ in addition to the usual mean streamwise velocity component and its fluctuations. By varying velocity and rib height, the experiment investigated the following of range of conditions: $k^+ \approx 5.5$ to 21, $0.3 < k/\delta_1 < 1$, $180 < Re_k < 740$, $6 \times 10^4 < Re_{x,k} < 1.5 \times 10^5$; $Re_\Theta < 660$; $-125 < (x-x_k) / k < 580$. Consequently, results covered boundary layers which retained their laminar characteristics through those where a turbulent boundary layer was established shortly after reattachment beyond the forcing rib as shown in Figure 4.

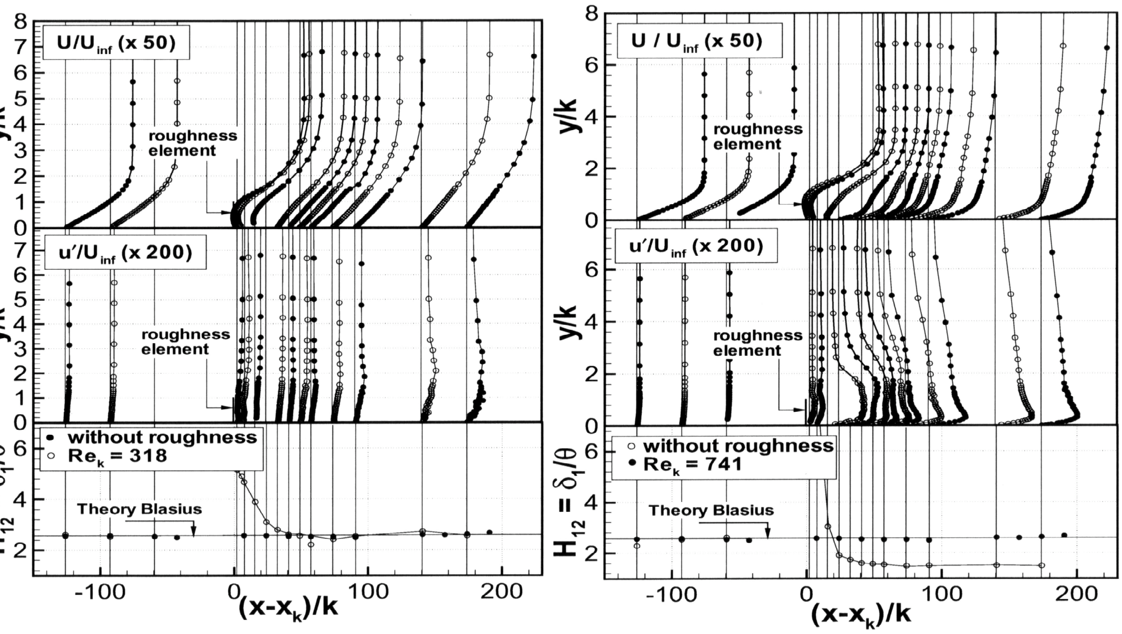

FIGURE 4
EVOLUTION OF FLOW OVER A TWO-DIMENSIONAL SQUARE RIB: LAMINAR RECOVERY (LEFT) AND RAPID TRANSITION TO A TURBULENT BOUNDARY LAYER (RIGHT).

Coolant flows in advanced gas-cooled reactors (GCRs) – Tomoaki Kunugi, Kyoto U., and Shin-ichi Satake, Toyama U., Japan, J. Derek Jackson, U. Manchester, UK, Petar Vukoslavcevic, U. Montenegro, Richard H. Pletcher, Iowa State, James M. Wallace, U. Maryland, A. Shenoy and G. Baccaglini, General Atomics and Keith G. Condie, Glenn E. McCreery, R. J. Pink and Donald M. McEligot, INL, US

The objective of this laboratory/university/industry collaboration of coupled computational and experimental studies addressed fundamental science and engineering to develop supporting knowledge required for reliable approaches to new and advanced reactor designs for improved performance, efficiency, reliability, enhanced safety and reduced costs and waste. This basic thermal fluids research applied first principles approaches (Direct Numerical Simulation and Large Eddy Simulation) coupled with experimentation (heat transfer and fluid mechanics measurements). *Prof. Pletcher* extended LES to generic idealizations of the complex geometries involved; *Profs. Satake and Kunugi* supported these studies with DNS. *Profs. Wallace and Vukoslavcevic* developed miniaturized multi-sensor probes to measure turbulence components in high temperature flows. *INL* conducted experiments to obtain fundamental turbulence and velocity data for generic idealizations of the complex geometries of advanced reactor systems. *Prof. Jackson* conducted measurements of the effects of buoyancy forces on flow in circular tubes, channels and annuli. *Drs. Shenoy and Baccaglini* provided thermal-hydraulic data needs for Modular Helium Reactors and reviewed the computational techniques and supporting results to determine their applicability to gas-cooled reactor operation [McEligot et al., 2002].

The INL Matched-Index-of-Refraction flow system was applied for the first time to obtain fundamental data on flows through complex geometries important in the design and safety analyses for advanced reactors. The experimental model was a ribbed annulus comparable to the fuel channels of the High Temperature Engineering Test Reactor of JAERI. As expected, for laminar flow the LDV data showed that a slow recirculating region formed behind a rib. This region could be expected to produce a "hot spot" if the inner surface were heated. However, frequency spectra for the flow in this region demonstrated an oscillating flow characteristic of eddy shedding from a circular cylinder. Increased levels of fluctuations u' and v' were also observed.

For turbulent flow, two-component (axial and radial) LDV measurements were obtained in the ribbed annulus at $Re_{Dh} \approx 6900$ [McCreery et al., 2003]. Data were obtained along radial and axial traverses, at locations downstream from spacer ribs and furthest removed from the spacer ribs, both horizontally and circumferentially. The accelerating flow between the ribs induced reductions in the streamwise velocity fluctuations near the wall and in the central region (radially) and increases were observed in the subsequent decelerating flow. Near the end of the acceleration region the mean velocity profile shows evidence of possible laminarization. Consequently, the convective heat transfer coefficient could be expected to be reduced compared to that predicted by typical turbulence models in general-purpose CFD codes and a relative "hot spot" might be observed.

Suction in a transitional boundary layer – Stefan Becker and Jovan Jovanovic, Uni. Erlangen, Germany and Carl M. Stoots, INL, US

The aircraft industry has always been interested in reducing aerodynamic drag, hoping to achieve enhanced fuel economy, range and flight performance and/or reduce weight, noise and emissions. In the pursuit of less drag, an important area of research has been in aircraft wing design. Fluid flow along a surface is usually laminar near the leading edge. Engineering attempts to maintain the laminar state at either Reynolds numbers or downstream distances beyond that which is normally turbulent or transitional is called Laminar Flow Control (LFC). In many cases, LFC entails ingesting a portion of the boundary layer flow through the wall. Unfortunately, continuous wall suction is impractical from a fabrication viewpoint and suction is usually implemented via discrete holes or sometimes slots in the wall surface. Discrete holes can lead to hole-to-hole interactions, trailing vortices, and additional suction parameters / variables.

The work was conducted in the large MIR flow system at Uni. Erlangen [Becker and Jovanovic, 2009]. Velocity measurements were obtained using glass-fibre-based laser Doppler anemometry. The measurements took place in different planes upstream and downstream of the suction holes. Results include evolution of the streamwise velocity and the turbulence intensity profiles for a subcritical and supercritical suction flow rate in comparison to the profiles without suction. These data reveal that large disturbance peaks develop behind the suction holes and gradually move away from the wall in the downstream direction. Figure 5 shows the two-dimensional velocity fields and the turbulent kinetic energy distributions in a plane section behind the suction holes for subcritical and supercritical suction flow rates. Clearly recognizable is the strong interaction between neighboring suction holes; this influence strongly increases with increasing suction rate. In contrast to DNS predictions, a recirculation zone could not be observed between the holes.

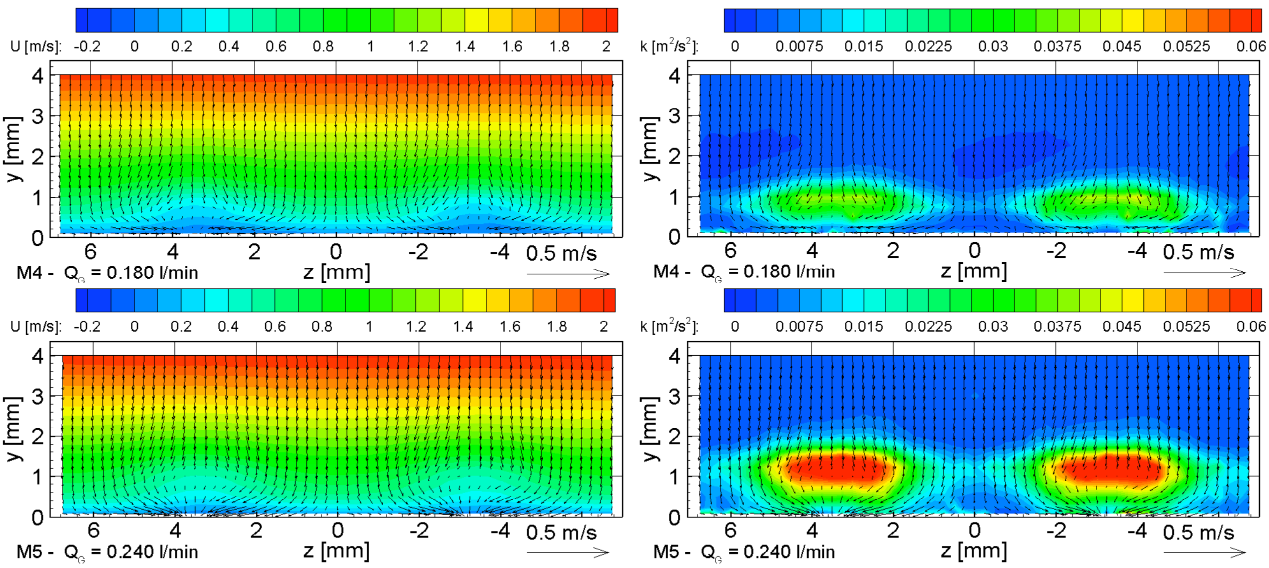

FIGURE 5

STREAMWISE VELOCITY FIELDS AND TURBULENT KINETIC ENERGY DISTRIBUTIONS ONE DIAMETER DOWNSTREAM OF SUCTION HOLES IN A TRANSITIONAL BOUNDARY LAYER; TOP = SUBCRITICAL AND BOTTOM = SUPERCRITICAL.

Coolant flows in supercritical water reactors – J. Y. Yoo and J. S. Lee, SNU, S. O. Park, KAIST, Korea, J. Derek Jackson, U. Manchester, UK, Petar Vukoslavcevic, U. Montenegro, Lawrence E. Hochreiter, Penn. State, Richard H. Pletcher, Iowa State, Barton L. Smith, Utah State, James M. Wallace, U. Maryland and Keith G. Condie, Glenn E. McCreery, Donald M. McEligot, Hugh M. McIlroy and Robt. J. Pink, INL, US

The goal of this *Korean / US / laboratory / university collaboration* of coupled fundamental computational and experimental studies is the improvement of predictive methods for Generation IV reactor systems such as supercritical-pressure water reactors. *Prof. R. H. Pletcher* extended LES to generic idealizations of their geometries with property variation; *Prof. J. Y. Yoo* supported these studies with DNS. *Prof. S. O. Park* developed DSM models and evaluated the suitability of other proposed RANS (Reynolds-averaged Navier-Stokes) models by application of the DNS, LES and experimental results. *INL and Prof. B. L. Smith* obtained fundamental turbulence and velocity data for an idealization of the complex geometries of these advanced reactor systems. *Profs. J. M. Wallace and P. Vukoslavcevic* developed miniaturized multi-sensor probes to measure turbulence components in supercritical flows in tubes. *Profs. J. S. Lee and J. Y. Yoo* developed experiments on heat transfer to supercritical flows. The flow facility developed at SNU provides means of measuring heat transfer to supercritical fluids for assessment of the effects of their property variations and the miniaturized multi-sensor probes permit measuring the turbulence which is modeled by the codes. *Profs. L. E. Hochreiter and J. D. Jackson* provided industrial insight and thermal-hydraulic data needs and reviewed the results of the studies for application to realistic designs and their predictive safety and design codes [McEligot et al., 2005].

INL installed a large-scale model for simulating flow in SCWR passages in their MIR flow system. With Prof. Smith, they acquired two- and three-dimensional PIV data. An aim of the experiment design was to select a model which induces generic flow features of typical LWR / SCR designs (e.g., periodicity, grid spacers, small pitch-to-diameter ratios, etc.) as well as ease in construction and in modeling (for code developers). Spacing is tight so probe instrumentation should not be used since probes would disturb the flow to be measured. Optical techniques are desired. However, useful optical flow measurements in this realistic configuration could be impractical without refractive-index-matching. For the model a two-rod configuration which includes some flow aspects of proposed thermal SCWR concepts was selected. We chose an idealized ring-cell spacer configuration. The geometry is scaled to be six to seven times larger than typical fuel pins. Based on nominal design dimensions, the Reynolds number Re_{Dh} was about 8040.

From 400 instantaneous *u* and *v* velocities collected at each spatial point, the mean streamwise and vertical velocity components were calculated, as well as the in-plane Reynolds stresses (normal and shear) and the turbulent kinetic energy. This file and some images and animations from it are archived on Prof. Smith's internet web site (www.mae.usu.edu/faculty/bsmith/EFDL/KNERI/KNERI.html).

Figure 6 presents an overview of the flow behavior measured in terms of contours of mean streamwise velocity U. Comparable results are available for mean vertical velocity V and a two-dimensional "turbulence kinetic energy." Flow is from left to right and several cross stream planes as well as one near-wall plane are shown in an isometric format. The first cross stream plane is close to the upstream grid spacers. One sees that the highest streamwise velocities occur there due to the blockage of the spacers reducing the flow area. The centerline of the model passes through the point where the two spacers meet, so the flow there is comparable to that after a backward-facing step. It is retarded and, close to the spacers, one finds recirculation in a small region. The flow redevelops in the streamwise direction and appears to approach a fully-developed condition for a rectangular duct enclosing two axial rods.

Flows in the lower plena of gas-cooled reactors (GCRs) – Denis Tenchine, Henri Paillere and Frederic Ducros, CEA, France, Hugh M. McIlroy, Donald M. McEligot and Robert J. Pink, INL, Robert E. Spall and Barton L. Smith, Utah State and W. David Pointer and Constantine Tzanos, ANL, US

The *objective* of this collaborative experimental and computational research is to provide benchmark data for the assessment and improvement of thermal-fluid-dynamics codes proposed for evaluating decay heat removal concepts and designs in the gas-cooled reactor (GCR) programs of the international Gen IV Initiative, such as the VHTR (Very High Temperature Reactor) and GFR (Gas-cooled Fast-spectrum Reactor). These reactors feature *complex geometries* and wide ranges of temperatures, leading to *significant variations of the gas thermodynamic and transport properties plus effects of buoyancy* during loss-of-flow and loss-of-coolant scenarios and during reduced power operations. A variety of CFD and experimental tasks was accomplished by the partners.

Measurements of flow phenomena expected in the lower plenum of a prismatic GCR were made by PIV in INL's MIR system [McIlroy, McEligot and Pink, 2010]. Flow in the lower plenum consists of multiple jets from the coolant channels injected into a confined cross flow - with supporting posts as obstructions. Mean-velocity-field and turbulence data were obtained to measure turbulent flow phenomena in an approximately 1:7 scale model of a region of the lower plenum of a typical prismatic GCR similar to a General Atomics Gas-Turbine-Modular Helium Reactor design.

The experimental model consists of a row of full circular posts along its centerline with half-posts on the two parallel walls to approximate geometry scaled to that expected from the staggered parallel rows of posts in the reactor design. Mineral oil enters into the model jet inlets on the top of the model from four inlet manifolds. The four inlet jet flows (Figure 7) merge in the lower plenum and flow toward the outlet end of the model where the flow exits and merges with the primary loop flow. Inlet jet Reynolds numbers are approximately 4,300 and 12,400. The measurements reveal developing, non-uniform, turbulent flow in the inlet jets and complicated flow patterns in the model lower plenum. Data include three-dimensional vector plots, data displays along the coordinate planes and presentations that describe the component flows at specific regions in the model.

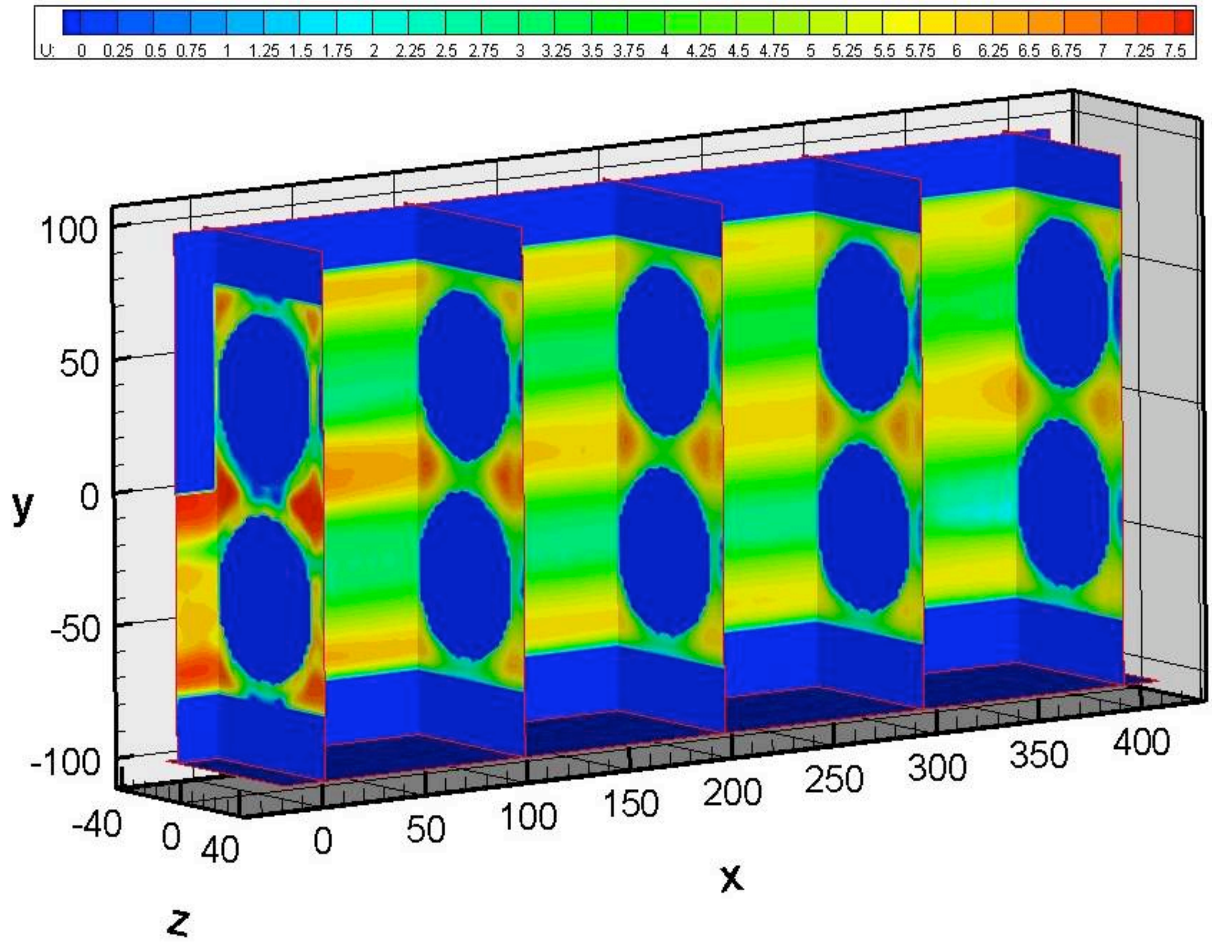

FIGURE 6
DEVELOPMENT OF FLOW BETWEEN PERIODIC SETS OF GRID SPACERS IN MIR MODEL OF A PARTIAL SCWR COOLANT CHANNEL, CONTOURS OF STREAMWISE MEAN VELOCITY

Entropy generation in transitioning flows – Donald M. McEligot, Ralph S. Budwig and Akira Tokuhiro, U. Idaho, Hugh M. McIlroy, INL, James R. Ferguson, Boise State, US, Stefan Becker, Uni. Erlangen, Germany, Edmond J. Walsh, U. Limerick, Ireland, Luca Brandt and Philipp Schlatter, KTH, Sweden and Tamer A. Zaki, Imperial College, England

The overall technical objective of this study is to address the scientific issue of obtaining basic understanding of local (pointwise) distributions of entropy generation rates in characteristic wall shear flows, because *fundamental understanding of entropy generation in such flows is a key to increasing energy efficiency and sustainability* and, thereby, reducing fuel consumption, green house gases and/or waste. For entropy generated by fluid friction, the rates are reasonably predictable for developed turbulent flows [McEligot et al., 2008] and pure laminar flows. The *main difficulty now* lies in prediction for flows undergoing so-called "bypass" transition from laminar to turbulent states in streamwise pressure gradients; such situations are important for turbomachinery in proposed nuclear, fossil, wave and biofuel power plants and for blade shapes of wind- or hydro-turbines.

By application of boundary layer and other approximations, Rotta has suggested (indirectly) that the volumetric entropy generation rate can be calculated *approximately* as $(S_{ap}''')^+ \approx (\partial U^+/\partial y^+)^2 - (\square)^+(\partial U^+/\partial y^+)$ where $(S_{ap}''')^+$ is defined as $T\nu S_{ap}'''/(\rho u_\tau^4)$. Existing MIR transition measurements [Becker et al., 2002; McIlroy and Budwig, 2007] are being examined to deduce entropy generation rates. With transition induced by a square rib, Becker et al. measured the evolution of the Reynolds stresses, v^2 and $\overline{uv}$, in addition to the usual mean streamwise velocity component and its fluctuation in transitional boundary layers on a flat plate by two-component LDA in the INL MIR system. The pointwise entropy generation rate is here non-dimensionalized with boundary layer quantities as $(S_{ap}''')^* = (TS_{ap}'''\delta/(\rho U_\infty^3))$. The development of $(S_{ap}''')^*$ after reattachement downstream of the rib is presented in Figure 8. In the region near (y/k) of unity profiles show a slight, gradual maximum to persist from the mixing layer created above the rib. For laminar recovery the values remain small. For the second case, as the flow proceeds downstream and undergoes transition towards a turbulent boundary layer, $(S_{ap}''')^*$ grows in the wall region as more "turbulent" entropy generation occurs.

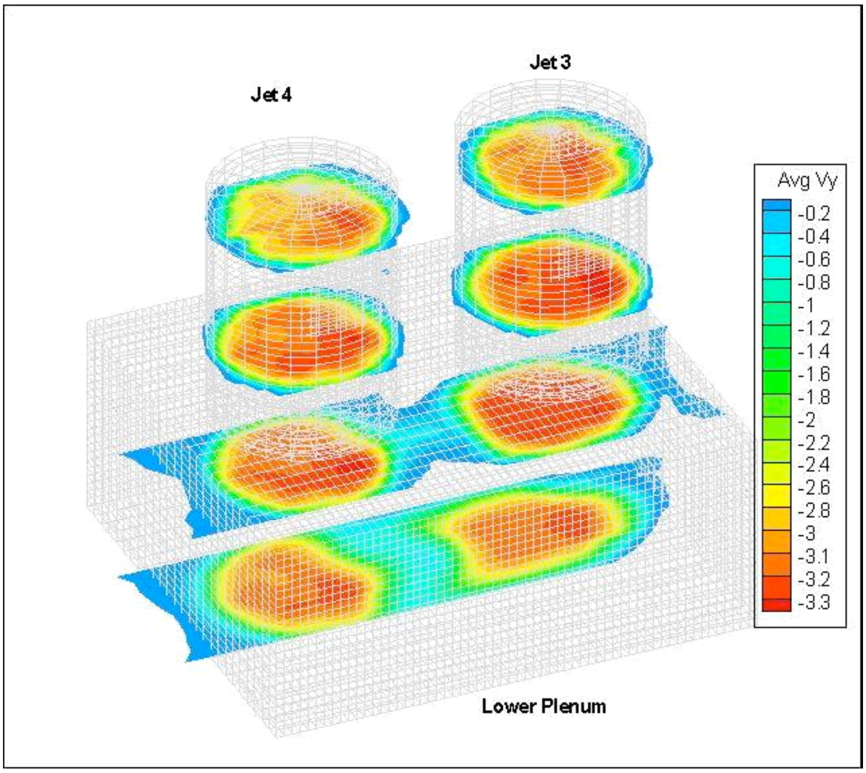

FIGURE 7
3-D PIV MEASUREMENTS WITHIN JET INLET DUCTS: VERTICAL MEAN VELOCITY CONTOURS (LEFT) AND TURBULENCE INTENSITIES (RIGHT).

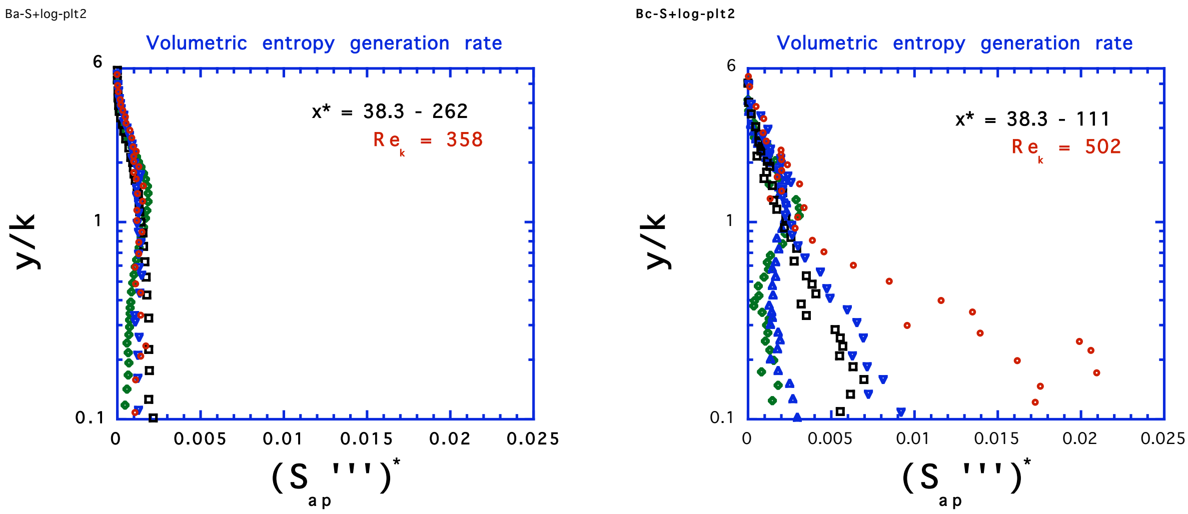

FIGURE 8
DEVELOPMENT OF POINTWISE ENTROPY GENERATION RATE IN A BOUNDARY LAYER WITH LAMINAR RECOVERY (LEFT) AND IN A TRANSITIONING BOUNDARY LAYER (RIGHT). DIAMONDS = FIRST PROFILES AND CIRCLES = LAST.

Planned studies address the scientific objective of obtaining fundamental understanding of pointwise distributions of entropy generation rates in disturbed laminar and bypass transition with streamwise pressure gradients using both experiments and analyses. They couple experiments using optical techniques and thermal anemometry with direct numerical simulations (DNS) and CFD. Using the large MIR flow system and optical techniques at INL, *students* will determine the pointwise entropy generation rates in the developing pre-transitional and transitional flows, emphasizing the near-wall layer where it is concentrated and where other experimental approaches are inadequate.

Bypass flows in prismatic GCRs – Goon-Cherl Park, SNU, and Min-Hwan Kim, KAERI, Korea, Hugh M. McIlroy and Richard R. Schultz, INL, US

The "bypass flows" in a prismatic gas-cooled reactor are of potential concern because they reduce the desired flow rates in the coolant channels and, thereby, can increase outlet gas temperatures and maximum fuel temperatures. In existing literature, bypass flows of one to thirty per cent of the total flow rate have been estimated. Consequently, it is appropriate to account for bypass flows in reactor thermal gas dynamic analyses.

The purpose of the *fluid dynamics experiments* to be conducted in the INL MIR system is to develop benchmark databases for the assessment of CFD solutions of the momentum equations, scalar mixing, and turbulence models for geometries of typical Very High Temperature Reactors (VHTR) in the limiting case of negligible buoyancy and constant fluid properties. The MIR VHTR bypass flow experiment will measure flow characteristics in the coolant channels and interstitial gaps between typical prismatic blocks. The experiments will use optical techniques, primarily PIV. Figure 9 shows the current design of the experimental model.

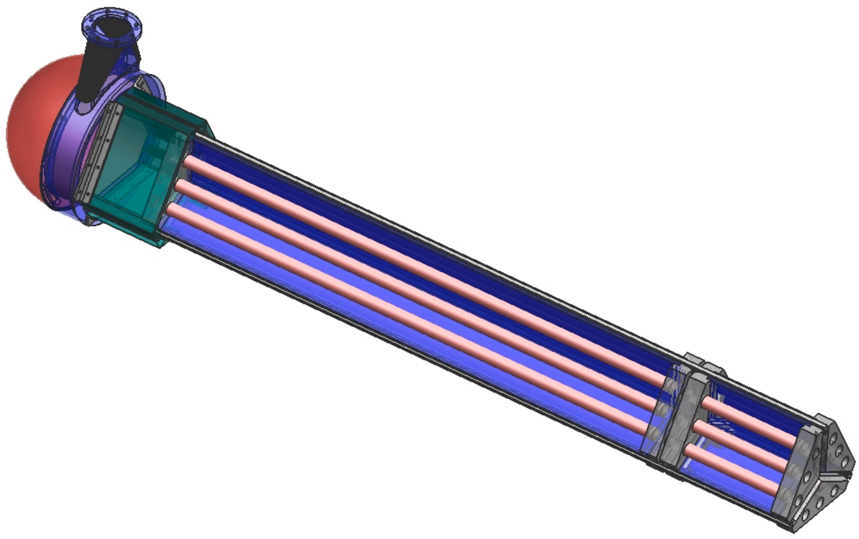

FIGURE 9
SKETCH OF MODEL BEING DEVELOPED FOR MEASUREMENTS OF BYPASS FLOWS IN THE TEST SECTION OF THE INL MIR FLOW SYSTEM.

POTENTIAL COLLABORATIVE INTERACTIONS

For user facilities such as these unique large Matched-Index-of-Refraction flow systems there are many ways to collaborate productively for international education and research. Some examples are

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

These large MIR flow systems have demonstrated themselves to be excellent bases of interesting international collaboration in graduate education and research. They are versatile, useful tools for examining flows in complicated situations such as turbulent and transitional flows, flows through porous media and two-phase particulate flows – for basic and/or applied studies. The MIR technique allows measurements which otherwise would be impractical if not impossible; the large sizes of the Uni. Erlangen and INL systems provide better spatial and temporal resolution than comparable earlier facilities. Teaming is a normal mode of operation. Benchmark data for assessment of computational fluid dynamics can be acquired for external flows, internal flows and coupled internal/external flows. Further details of these MIR systems and their collaborative projects are available in a technical report [McEligot, Becker and McIlroy, 2010] and on the INL web site = www.inl.gov/mir.

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