Chapter 6

Large Matched-Index-of-Refraction (MIR) Flow Systems for Thermal Engineering Education

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The idea of employing large matched-index-of-refraction (MIR) flow systems for thermal engineering education is new to many in the international community. In a recent collaboration, Idaho National Laboratory (INL) and Universität Erlangen-Nürnberg (UE) have developed such unique systems, which are ideal for joint education and research. The benefit of the MIR technique is that it permits optical measurements for determining flow characteristics in complex passages and around objects to be obtained without locating a disturbing transducer in the flow field and without distortion of optical paths. The innovation of these systems is their large size relative to previous MIR experiments, yielding improved spatial and temporal resolution. This article discusses the benefits of the technique, characteristics of the systems, typical measurements possible for complex flows and some demonstrations of their application for international collaboration in engineering education. These experiments usually have provided new fundamental understanding plus benchmark data for assessment and validation of computational thermal fluid dynamic codes.

INTRODUCTION

Unique facilities can provide focus for a wide variety of collaborative activities in engineering education. The main objective of this paper is to demonstrate how the development of internationally unique systems can facilitate collaboration between institutions for the benefit of engineering education in the global arena. The flow systems to be discussed here evolved from an international advisory committee on experimental thermal science. Since their initiation, education of faculty, engineers and both undergraduate and graduate students has primarily been accomplished via the "learn-by-doing" technique. The two systems were designed and fabricated by collaboration between faculty, students, and engineers at INL and UE, thereby providing training in equipment, experiment and instrumentation design, and acquisition. Availability of unique systems permits development of many joint proposals for graduate and undergraduate education, providing training for new faculty along with improved chances of success. Faculty sabbatical leaves, postdoctoral training, doctoral dissertations, and masters theses, plus continued education courses, have all been accomplished with these facilities. Undergraduate students have participated in summer internship programs and, as consequences, received deeper understanding of the application and value of their related courses in physics, thermal engineering, and experimental techniques. High quality measurements may be provided to assess codes and their detailed assumptions in courses on computational thermal fluid dynamics. Conferences, workshops, industrial short courses, and review panels on related topical areas of interest yield further educational opportunities as do collaborative efforts to modify and improve the facilities and design new experiments. Some examples of the employment of these educational approaches will be demonstrated in the later section on "Examples of Typical Collaborative International Projects."

Thermal engineering education includes courses and independent study in thermodynamics, fluid mechanics, heat transfer, mass transfer, and reacting flows. For most flow problems in these disciplines, the limiting case (which must be handled properly to have confidence in other predictions) is non-compressed flow with constant thermodynamic and transport properties. This is the situation for which large matched-index-of-refraction (MIR) flow systems can provide fundamental insight and high-quality measurements for flows through and around complicated geometries. And, as shown by a current project, the application of the second law of thermodynamics to open systems can also be demonstrated; these large MIR systems are among the few that provide the possibility of measuring pointwise entropy generation rates. In addition to thermal engineering, introductory physics courses may be interested in large scale demonstration and application of Snell's Law. Likewise, optical scientists can find interesting practical problems relating to optical fluid measurements and their uncertainties.

In a recent international collaboration, INL and UE have developed large MIR flow systems [1], which can be ideal for joint graduate student research. The benefit of the MIR technique is that it permits optical techniques, such as particle image velocimeters (PIV) and laser Doppler anemometers (LDA), to measure flow characteristics in flow fields and near surfaces, in passages and around objects having complicated geometries without introducing an intrusive probe into the flow field and without distortion of optical paths. One way to eliminate optical interference in these systems is to employ suitable transparent solid materials for the models with fluids that possess the same refractive index as the model itself. In this way, the solid disappears optically (and therefore has no influence on the optical paths for lasers and cameras) 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 UE developments, no MIR flow facility existed that permitted the study of flow past complex geometries requiring high Reynolds numbers and fine spatial resolution at a large 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.

The MIR technique itself is not new; in the late 1960s, Corino and Brodkey employed it to measure turbulence structures in a circular tube [2]. 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 centimeters or less. No index-matched flow facility existed that permitted reasonably-sized flat plate boundary layers to be investigated and, hence, provide the basic test facility to study laminar-to-turbulent boundary layer transition in detail. In contrast, the MIR flow test sections at INL and UE have cross sections on the order of sixty centimeters and are over 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 (see Figure 1).

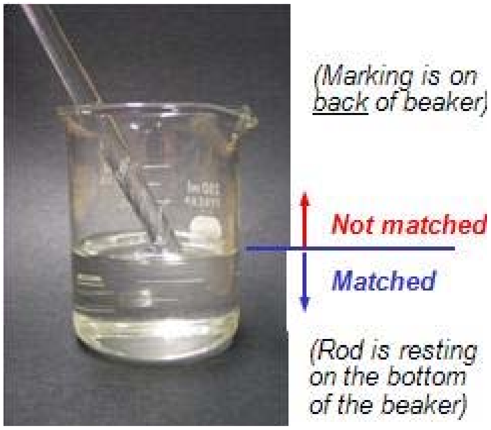

FIGURE 1
INDEX MATCHING OF FUSED QUARTZ AND LIGHT MINERAL OIL

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 make very near-wall velocity measurements by increasing flow-length scales relative to measurement probe size. By using an index-matched boundary, one can measure all three velocity components (u, v, w) and their gradients instantaneously at locations extremely close to a surface, e.g., meaningful data to $y^+ = y\, u_\tau / \nu < 0.1$ [3] where y is the wall-normal distance, u_τ is the friction velocity, and ν is the kinematic viscosity. Increased size can also improve temporal resolution. Typical nondimensional time increments for sampling may be defined as $\Delta t^{+} = \Delta tV/L$, so a larger size gives faster, more effective, sampling (here t is time and V and L are characteristic velocity and length scales).

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 [1]. 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 and because its refractive index matches that of some quartz at the wave lengths of the lasers employed. Light mineral oil has the same index-of-refraction as fused quartz near room temperature, is odorless, non-toxic, relatively nonflammable and non-volatile, inexpensive, and very stable.

Figure 2 is a photograph of the MIR facility at UE. Flow is counter clockwise in the figure. The main flow pump is in the lower left corner. From the main pump, the oil passes through an expansion bellows, a diffuser, two elbows, and then enters the settling chamber. The settling chamber has several screens and a honeycomb 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 0.1ºC of the prescribed matching temperature.

FIGURE 2
MIR FACILITY AT UE

Figure 3 is a photograph of the MIR facility at INL. Similar to the UE system, flow is counter clockwise in the figure. The main flow pump is in the lower left corner. From the main pump, the oil passes through a cylindrical section, a round bellows, a round-to-square transition, a five-vane diffuser, and a rectangular bend before entering the settling chamber. The settling chamber has several screens and a honeycomb for flow quality conditioning. After leaving the settling chamber, the oil passes through a contraction and enters the test section. The refractive index of the fluid is maintained within ±0.05ºC of the prescribed temperature by an external control system. Table 1 provides typical characteristics of the INL and UE systems.

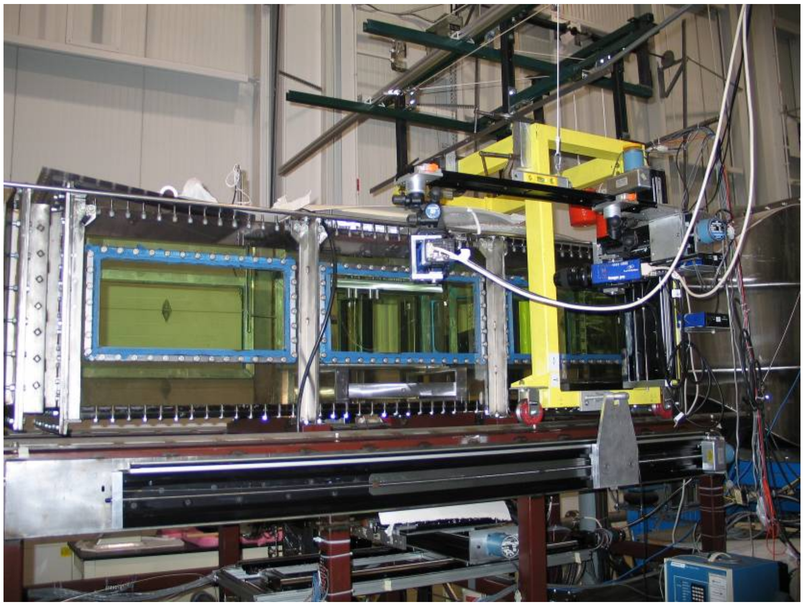

FIGURE 3
MIR FACILITY AT INL

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 main 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* include a synthetic jet interacting with an external boundary layer in a study by Professor Douglas R. Smith of the University of Wyoming [4] and a helical nozzle creating a swirling jet by Professor Barton L. Smith of Utah State University and their students. With guidelines for verification and validation of CFD (computational fluid dynamics), the models are designed in close collaboration with all participating partners; this coordination is essential to ensure that the measurements and dimensionless parameters from all experiments and computations are comparable.

Characteristic	***Idaho National Laboratory***	***Universität Erlangen-Nürnberg***
Test Section Cross Section (m)	0.62 x 0.62	0.60 x 0.45
Test Section Length (m)	2.4	2.52
Contraction Ratio	4:1	6:1
Working Fluid	Drakeol #5 (PENRECO)	Odino 913 (SHELL)
Index-Matching Temperature (ºC)	Wavelength Dependent	Wavelength Dependent
Refractive Index	Matching Temperature Dependent	Matching Temperature Dependent
Kinematic Viscosity	Matching Temperature Dependent	Matching Temperature Dependent
Temperature Control	External	Internal
Maximum Inlet Velocity (m/s)	1.9	5.0
Inlet Turbulence Intensity (%)	0.5 – 15	0.15

TABLE 2
TECHNICAL SPECIFICATIONS OF THE MIR SYSTEMS

Data are obtained primarily by optical techniques, such as LDA and PIV. Instantaneous velocity components may be obtained by measurements with existing two- (or one-) component LDA systems at fixed positions. In order to obtain good signal quality and high collection rates, it is desirable to employ the LDA in the forward scattering mode to avoid longer measuring times that would be needed if back scattering were used. A three-directional traversing mechanism is used with the LDA system in the forward scattering mode to avoid relative motion between the test section and the optics. Mean velocities along with mean turbulence gradients and statistics are calculated from the LDA algorithms. Typical results include time-resolved, pointwise distributions of the mean velocities (u, v, and w), velocity fluctuations, and their Reynolds stress components.

At INL, instantaneous velocity field measurements are primarily obtained with a 3-D PIV system from LaVision, Inc. The PIV cameras are mounted on the same 3-directional traverse system that is controlled by three separate electric stepping motors (as shown in Figure 3). The PIV system laser usually is mounted below the experiment model and produces a vertical light sheet approximately 1–3 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.

An additional flexible MIR system of intermediate scale has been developed by Professor Joseph Katz at Johns Hopkins University for turbomachinery studies (www.me.jhu.edu/lefd/ turbo/index.html). The test section is about thirty cm in diameter and the working fluid is sodium iodide so that the transparent models can be fabricated from acrylic [5]. Another is currently under development by Professor Kenneth T. Christensen at the University of Illinois. It too will employ sodium iodide and will have a test section about 0.4 x 0.4 m^2 in cross section and be 2.5 m long. Maximum velocity is expected to be near 3m/s.

EXAMPLES OF TYPICAL COLLABORATIVE INTERNATIONAL PROJECTS

The purposes of this section are to indicate some of the complex fluid flows that can be measured with a large MIR flow system and to demonstrate how the related experiments can encourage international collaboration in thermal engineering education.

Transition in Boundary Layers Induced by a Square Rib – Stefan Becker and Franz Durst, UE, Germany; and Keith G. Condie and Donald M. McEligot, INL, U.S.

This experiment provided data for the Habilitation dissertation of Dr. Becker. 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 roughness 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 [3]. 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 where y is the wall-normal distance. By varying velocity and rib height, the experiment investigated the following range of conditions: $k^+ \approx 5.5$ to 21, $0.3 < k/\delta_1 < 1$, $180 < Re_k < 740$, $6 \times 10^4 < Re_{x,k} < 1.5 \times 10^5$, $Re_\Theta < 660$ and $-125 < (x-x_k) / k < 580$, where k is the rib height, x_k is its location relative to the leading edge, δ_1 is the displacement thickness, and Re_k, $Re_{x,k}$, and Re_Θ are Reynolds numbers based on k, x_k and momentum thickness, respectively. Consequently, results covered boundary layers that 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.

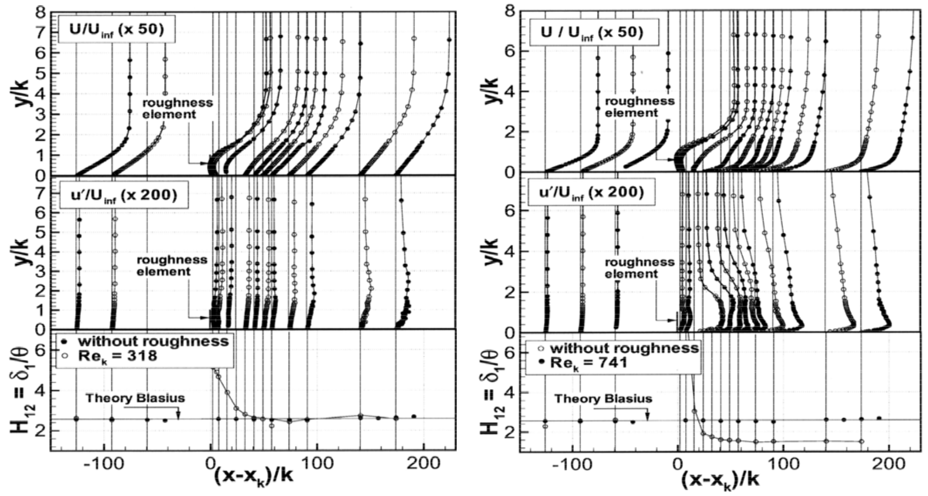

FIGURE 4

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., Japan; Shin-ichi Satake, Toyama U., Japan; J. Derek Jackson, U. Manchester, UK; Petar Vukoslavcevic, U. Montenegro, Montenegro; Richard H. Pletcher, Iowa State, U.S.; James M. Wallace, U. Maryland, U.S.; A. Shenoy and G. Baccaglini, General Atomics; and Keith G. Condie, Glenn E. McCreery, Robert J. Pink, and Donald M. McEligot, INL, U.S.

The *objective* of this laboratory/university/industry collaboration of coupled computational and experimental studies was a reliable approach to advanced reactor designs to improve performance, efficiency, and reliability; enhance safety; and reduce 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 [6].

Data from INL were employed by Prof. Satake to assess his DNS predictions in his doctoral thesis and by Prof. Pletcher's doctoral students to assess their LES predictions.

The INL MIR 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 Japan Atomic Energy Research Institute (JAERI). As expected, for laminar flow, the LDA 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 of streamwise and streamwise-normal velocities (u' and v') were also observed.

For turbulent flow, two-component (axial and radial) LDA measurements were obtained in the ribbed annulus at $Re_{Dh} \approx 6900$ [7] where Re_{Dh} is the Reynolds number based on hydraulic diameter. 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 (see Figure 5). The accelerating flow between the ribs induced reductions in the streamwise velocity fluctuations near the wall and in the central region (radially); 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.

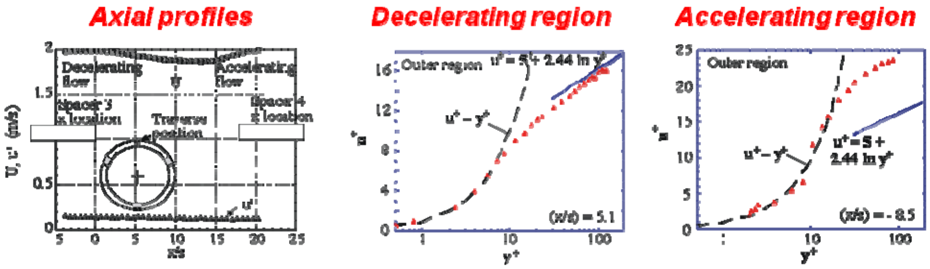

FIGURE 5
STREAMWISE MEAN VELOCITY MEASUREMENTS BY LDA

Suction in a Transitional Boundary Layer –
Stefan Becker and Jovan Jovanovic, UE, Germany and Carl M. Stoots, INL, U.S.

This experiment provided data for the Habilitation dissertation of Dr. Becker. Dr. Stoots assisted at UE for two years via a scientific leave from INL. 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 an airfoil 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 or variables.

This work was conducted in the large MIR flow system at UE [8]. Velocity measurements were obtained using LDA. 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 6 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.

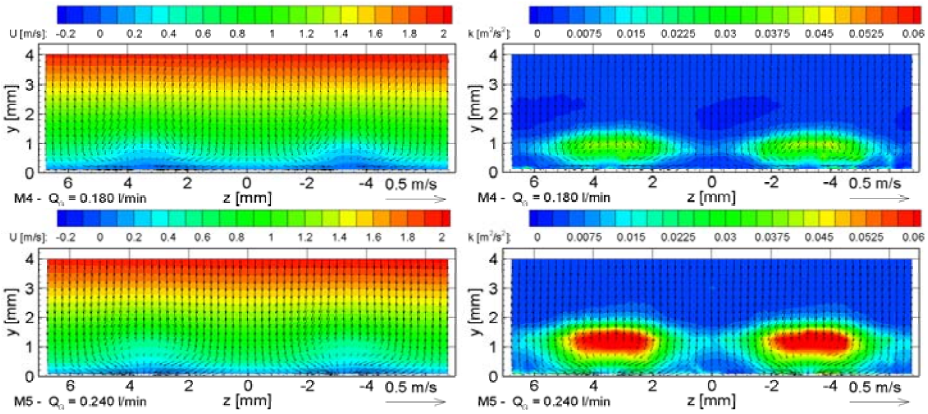

FIGURE 6

Streamwise Velocity Fields and Turbulent Kinetic Energy Distributions one diameter
downstream of suction holes in a transitional boundary layer;
top - subcritical; bottom - supercritical

Coolant Flows in Supercritical Water Reactors –

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

The *goal* of this Korean/U.S./laboratory/university collaboration of coupled fundamental computational and experimental studies is to improve predictive methods for Generation IV reactor systems, such as supercritical-pressure water reactors (SCWR). Prof. R.H. Pletcher extended LES to generic idealizations of their geometries with property variation; Professor J.Y. Yoo supported these studies with DNS. Prof. S.O. Park developed Domain-specific Modeling (DSM) models and evaluated the suitability of other proposed Reynolds-averaged Navier-Stokes (RANS) models by applying the DNS, LES, and experimental results. INL and Prof. B.L. Smith obtained fundamental turbulence and velocity data for an idealized complex geometry 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 assessing the effects of their property variations; 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 to apply to realistic designs and their predictive safety and design codes [9].

Data from INL were employed by Prof. Yoo to assess the DNS predictions in his doctoral student’s thesis; by Prof. Park’s postdoctoral associate for RANS predictions; and by Prof. Pletcher’s doctoral students to assess their LES predictions. In Montenegro, Prof. Vukoslavcevic provided training to Prof. Lee’s masters students in hot wire anemometry and probe design in addition to designing a multi-sensor probe for them. Prof. Smith and his students assisted in the PIV measurements at INL. As a postdoctoral research associate, Dr. McIlroy received training in use of 2-D and 3-D PIV systems and conducted the experiments.

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 that induces generic flow features of typical light water reactor (LWR)/super critical reactor (SCR) designs (e.g., periodicity, grid spacers, small pitch-to-diameter ratios, etc.), as well as ease in construction and modeling (for code developers). Spacing is tight, so probe instrumentation should not be used because probes would disturb the flow to be measured; optical techniques were used with refractive-index-matching to avoid this difficulty. For the model, a two-rod configuration including some flow aspects of proposed thermal supercritical water reactor (SCWR) concepts was selected. An idealized ring-cell spacer configuration was chosen. The geometry was scaled to be six to seven times larger than typical fuel pins. Based on nominal design dimensions, the Reynolds number Re_{Dh} (Reynolds number based on hydraulic diameter) was about 8040.

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

Figure 7 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; several cross stream planes and 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 spacer blockage 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 over 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.

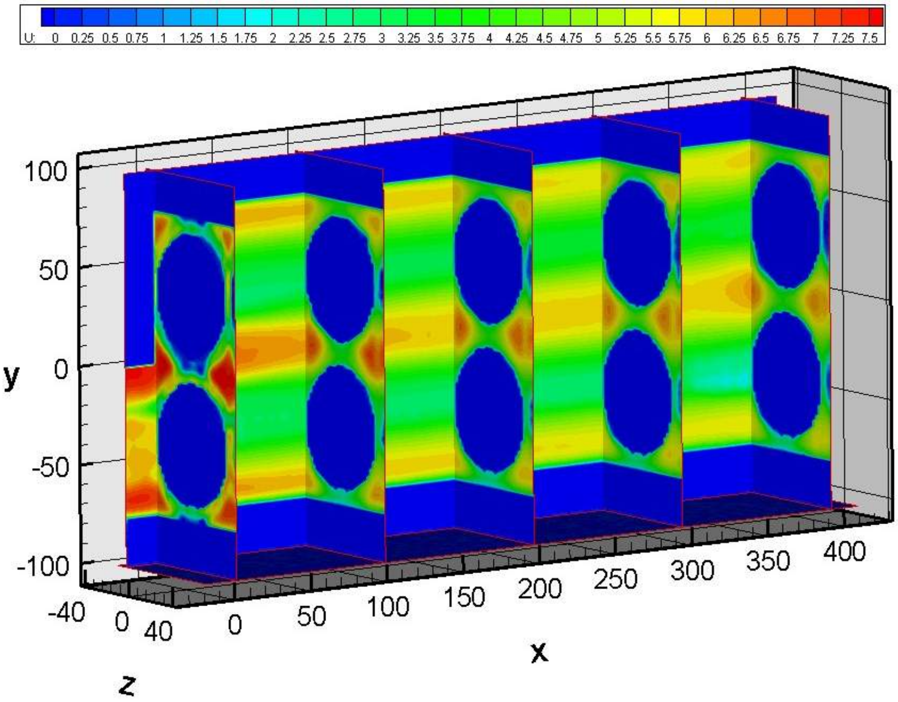

FIGURE 7
DEVELOPMENT OF FLOW BETWEEN PERIODIC SETS OF GRID SPACERS IN MIR MODEL OF A PARTIAL SCWR COOLANT CHANNEL, CONTOURS OF STREAMWISE MEAN VELOCITY

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, USU;
and W. David Pointer and Constantine Tzanos, ANL, U.S.

The *objective* of this collaborative experimental and computational research is to provide benchmark data for assessing and improving thermal-fluid-dynamics codes proposed for evaluating decay heat removal concepts and designs in the gas-cooled reactor (GCR) programs of the Next Generation Nuclear Plant (NGNP) program in the International Generation IV Initiative, such as the Very High Temperature Reactor (VHTR) and Gas-cooled Fast-spectrum Reactor (GFR). 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 [10]. Dr. McIlroy continued his postdoctoral training with this experiment. 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 (see Figure 8) 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 based on the diameter of the jet inlet ducts. 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 8 also presents an overview of the flow behavior and displays mean 3-D velocity vector arrows with the mean velocity magnitudes displayed as colors. The dark regions between the vertical vector fields are the solid columns along the centerline of the model. The four inlet jets can be observed entering the plenum model from the top right corner of the image. The inlet jets then interact with the outer reflector wall of the model and the columns and turn slightly downstream. Recirculation regions can be observed in the lower right corner, the middle of the image just to the left of the second column (dark region), and in the upper left of the image just left of the third column (dark region). Also, the wakes on the downstream side of the columns (left side) are clearly visible.

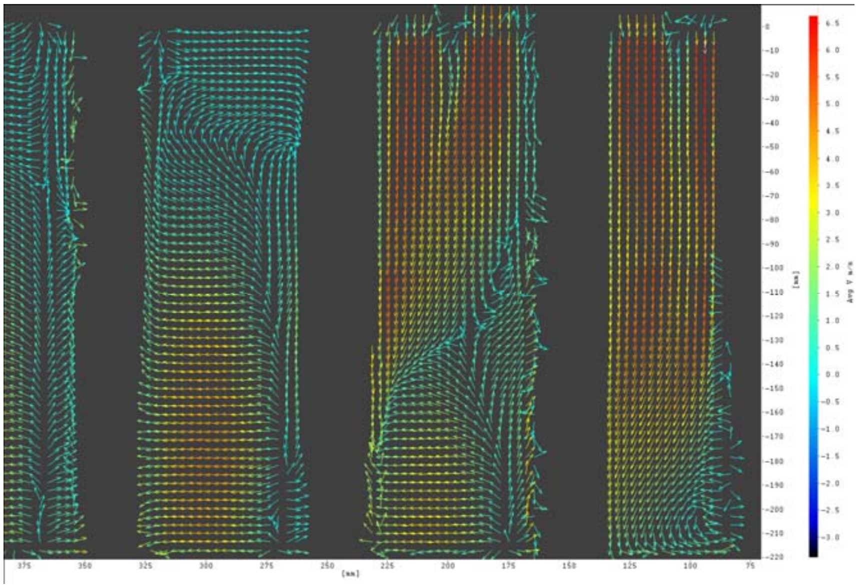

FIGURE 8

THE MEAN 3-D VECTOR FIELD ALONG THE STREAMWISE CENTERLINE OF THE GCR LOWER PLENUM MODEL MEASURED WITH THE INL 3-D PIV SYSTEM.

Entropy Generation in Transitioning Flows –

Donald M. McEligot, Ralph S. Budwig and Akira Tokuhiro, U. Idaho, U.S.; Hugh M. McIlroy, INL, U.S.; James R. Ferguson, Boise State, U.S.; Stefan Becker, Uni. Erlangen, Germany; Edmond J. Walsh, U. Limerick, Ireland; Luca Brandt and Philipp Schlatter, KTH, Sweden; 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 key to increasing energy efficiency and sustainability, thereby reducing fuel consumption, greenhouse gases, and/or waste. For entropy generated by fluid friction, the rates are reasonably predictable for developed turbulent flows and pure laminar flows [11]. The main difficulty now lies in predicting 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 applying boundary layer and other approximations, Rotta has suggested (indirectly) that the volumetric entropy generation rate S''' can be calculated *approximately* as $(S_{ap}''')^{+} \approx (\partial U^{+}/\partial y^{+})^{2} - (\overline{uv})^{+}(\partial U^{+}/\partial y^{+})$ where $(S_{ap}''')^{+}$ is defined as $T\nu S_{ap}'''/(\rho u_{\tau}^{4})$, T is absolute temperature, ρ is density, $\overline{uv}$ is the Reynolds shear stress, and the superscript + represents non-dimensionalization by wall variables [12]. Existing MIR transition measurements [3, 13] are being examined to deduce entropy generation rates. With transition induced by a square rib, Becker et al. [3] 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 $(S_{ap}''')^* = (TS_{ap}'''\delta / (\rho U_\infty^{3}))$ where δ is boundary layer thickness and U_∞ is the freestream velocity. The development of $(S_{ap}''')^*$ after reattachment downstream of the rib is presented in Figure 9. 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.

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, Prof. Budwig's 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. Students of Profs. Ferguson and Tokuhiro and Drs. Brandt, Schlatter, Walsh, and Zaki will conduct the computational studies.

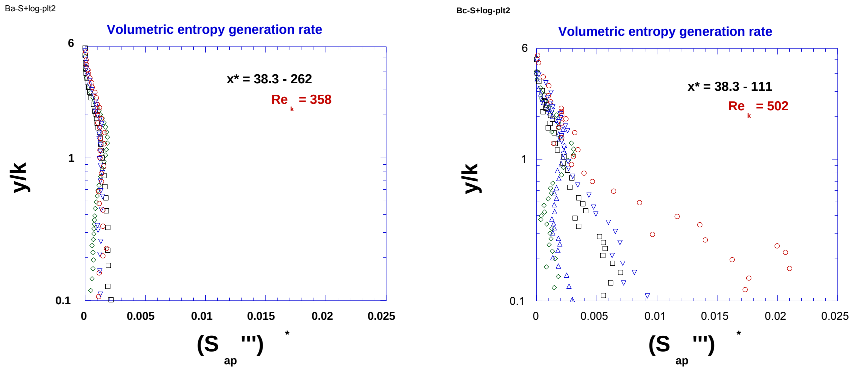

FIGURE 9

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

Bypass Flows in Prismatic GCRs –

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The “bypass flows” in a prismatic gas-cooled reactor are of potential concern because they reduce the desired flow rates in the coolant channels, thereby increasing 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 assessing CFD solutions of the momentum equations, scalar mixing and turbulence models for geometries of typical VHTRs 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 stereo PIV. Figure 10 shows the current design of the experimental model. The model is presently being assembled for installation into the INL MIR system test section. Prof. Budwig’s doctoral student will conduct experiments for assessment of the computations.

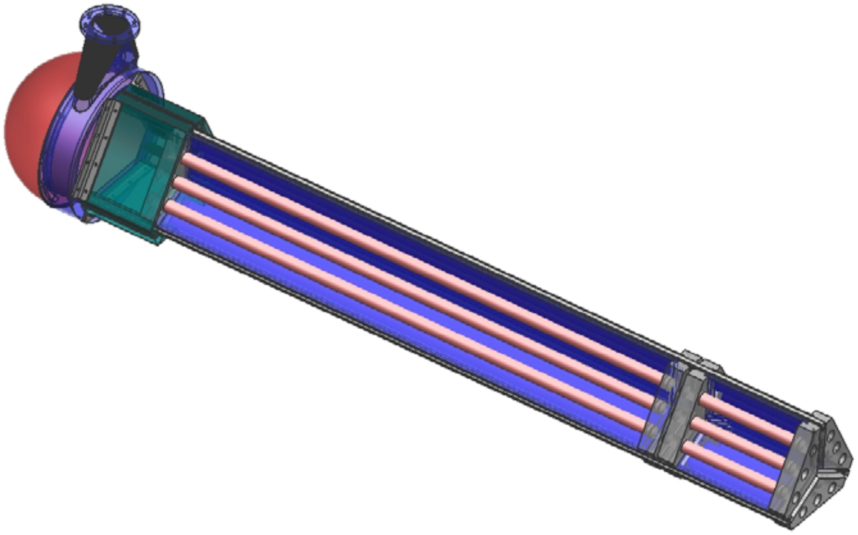

FIGURE 10
MODEL DESIGN FOR MEASUREMENTS OF BYPASS FLOWS
IN THE TEST SECTION OF THE INL MIR FLOW SYSTEM

DISCUSSION AND SUMMARY

The idea of employing large matched-index-of-refraction (MIR) flow systems for engineering education is new to many in that international community. The large MIR flow systems discussed here have demonstrated themselves to be excellent bases of interesting international collaboration in engineering education, which includes learning to accomplish significant engineering 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 UE and INL systems provide better spatial and temporal resolution than comparable facilities. Teaming is a normal mode of operation. Benchmark data for assessing computational fluid dynamics can be acquired for external flows, internal flows and coupled internal/external flows. This paper has demonstrated how the development of internationally unique systems can facilitate collaboration between institutions for the benefit of engineering education in the global arena. It has indicated some of the complex fluid flows that can be measured with a large MIR flow system and has shown how the related experiments provide international collaboration in engineering education. Further details of these MIR systems and their collaborative projects are available in a technical report [14] and on the INL MIR website (www.inl.gov/MIR).

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