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MATCHED-INDEX-OF-REFRACTION FLOW FACILITY FOR FUNDAMENTAL AND APPLIED RESEARCH

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I. INTRODUCTION

Significant challenges face reactor designers with regard to thermal hydraulic design and associated modeling for advanced reactor concepts. Computational thermal hydraulic codes solve only a piece of the core. There is a need for a whole core dynamics system code with local resolution to investigate and understand flow behavior with all the relevant physics and thermo-mechanics. The matched index of refraction (MIR) flow facility at Idaho National Laboratory (INL) has a unique capability to contribute to the development of validated computational fluid dynamics (CFD) codes through the use of state-of-the-art optical measurement techniques, such as Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV). PIV is a non-intrusive velocity measurement technique that tracks flow by imaging the movement of small tracer particles within a fluid. At the heart of a PIV calculation is the cross correlation algorithm, which is used to estimate the displacement of particles in some small part of the image over the time span between two images. Generally, the displacement is indicated by the location of the largest peak. To quantify these measurements accurately, sophisticated processing algorithms correlate the locations of particles within the image to estimate the velocity (Ref. 1).

Prior to use with reactor deign, the CFD codes have to be experimentally validated, which requires rigorous experimental measurements to produce high quality, multi-dimensional flow field data with error quantification methodologies. Computational thermal hydraulic codes solve only a piece of the core. There is a need for a whole core dynamics system code with local resolution to investigate and understand flow behavior with all the relevant physics and thermo-mechanics. = Computational techniques with supporting test data may be needed to address the heat transfer from the fuel to the coolant during the transition from turbulent to laminar flow, including the possibility of an early laminarization of the flow (Refs. 2 and 3). Such studies are complicated enough that computational fluid dynamics (CFD) models may not converge to the same conclusion. Thus, experimentally scaled thermal hydraulic data *with uncertainties* should be developed to support modeling and simulation for verification and validation activities. The fluid/solid index of refraction matching technique allows optical access in and around geometries that would otherwise be impossible while the large test section of the INL system provides better spatial and temporal resolution than comparable facilities. Benchmark data for assessing computational fluid dynamics can be acquired for external flows, internal flows, and coupled internal/external flows for better understanding of physical phenomena of interest.

The core objective of this study is to describe this MIR system and its capabilities, and mention current development areas for uncertainty quantification, mainly the uncertainty surface method and cross-correlation method. Using these methods, a suitable approach to quantify PIV uncertainty for experiments performed in the MIR will be established.

II. MATCHED-INDEX-OF-REFRACTION FLOW FACILITY

The MIR flow system was modeled after a typical wind tunnel and was designed and fabricated by collaboration between scientists and engineers at INL and Universität Erlangen-Nürnberg (Ref. 4). The key objective of this facility is to help better understand fundamental physical phenomena and to provide experimental data for assessment and validation of computational fluid dynamics and nuclear reactor system safety codes. The MIR facility permits non-intrusive velocity measurement (state-of-the-art) techniques, such as Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry, through complex models/geometries without requiring probes and other instrumentation that could disturb the flow (Refs. 4 and 5). The large MIR system enables high spatial and temporal resolution. In this facility, the flow models are constructed from fused quartz and submersed in temperature-controlled mineral oil (the working fluid). Quartz and mineral oil have similar refractive indices (near room temperature); thus, the model optically disappears, making high-resolution optical measurement possible. The MIR was designed as an isothermal facility capable of sustaining a precise temperature in its test section. The facility consists of several components, including a settling chamber, square contraction, test section, and a separate auxiliary loop to provide independently controllable internal flow to installed models as shown in Figure 1. The settling chamber is comprised of a single stainless-steel honeycomb structure and several screens that straighten the flow and remove non-uniformities. The 4:1 square contraction is attached downstream of the settling chamber and produces nearly uniform flow at the entrance of the test section. The test section is made from a polycarbonate material and contains large, optical glass windows to permit PIV and LDV measurements of the flow (Refs. 5 and 6). The large size of the test section provides high spatial resolution that makes it easier to obtain accurate data near the wall, which is not easy with smaller-scaled facilities.

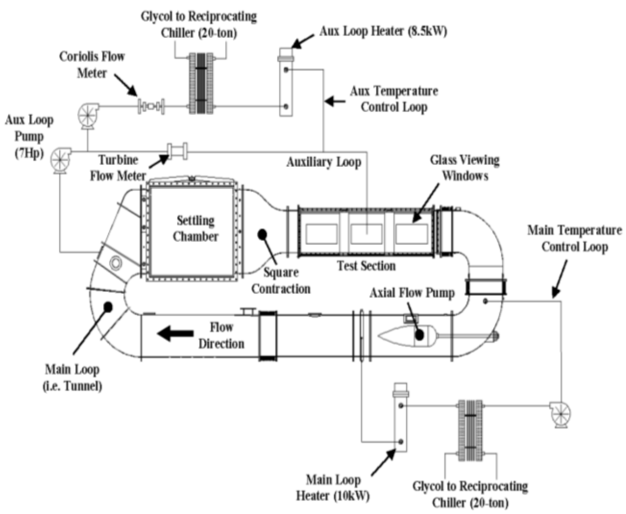

Fig. 1. INL MIR flow facility.

The refractive index-matching temperature of the fluid is maintained within ±0.05ºC of the prescribed index-matching temperature by an external control system. Table 1 displays the technical specifications of the INL MIR system.

Table 1. Technical Specifications of INL MIR System

Characteristic	Specification
Test Section Cross-section	0.61 m x 0.61 m (24 in x 24 in)
Test Section Length	2.44m (8ft)
Contraction Ratio	4:01
Working Fluid	Drakeol #5 light mineral oil
Index-Matching Temperature (deg C)	Laser Wavelength Dependent
Mineral Oil Density	Matching Temperature Dependent
Refractive Index of Mineral Oil and Fused Quartz	Matching Temperature Dependent
Mineral Oil Kinematic Viscosity	Matching Temperature Dependent
Temperature Control	External
Maximum Inlet Velocity	1.9m/s (6.2 ft/s)
Inlet Turbulence Intensity	0.5%-15%

III. MEASUREMENT TECHNIQUE

Instantaneous velocity field measurements are primarily obtained with a stereo PIV system. Two charge-coupled device cameras are mounted on a three-directional traverse system that is controlled by three separate electric stepping motors. The PIV system uses double-pulsed, neodymium-doped yttrium aluminum garnet lasers that are usually mounted below the experiment model and produce vertical light sheets approximately 1–3 mm thick (Ref. 4). The three-directional traversing mechanism is mounted on rails parallel to the test section and is shown in Figure 2. This traversing system has a positional accuracy of ±2 µm (7.87×10^{-5} in) (Refs. 5 and 6). Figure 2 shows the MIR flow system with the 3-D PIV system mounted on three-directional traverse.

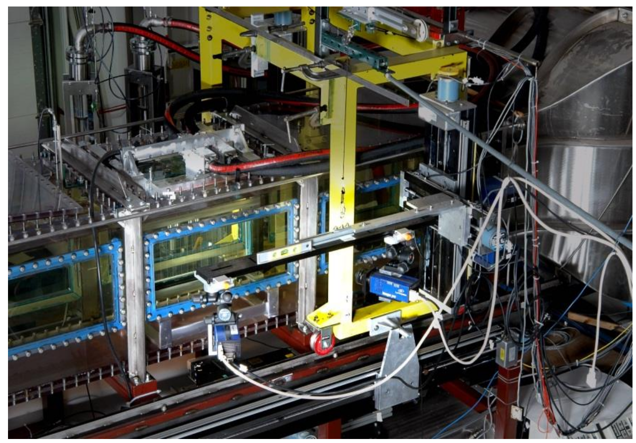

Fig.2. INL MIR flow system for studying fluid physics phenomena with 3-D PIV system mounted on three-directional traverse

IV. UNCERTAINTY QUANTIFICATION

MIR results are typically in the form of three-component time averaged velocities and Reynolds stresses. McEligot et al. (Ref. 6 and 7) quantified the uncertainty associated with velocity, positioning, fluid property, geometry, flow rates, and Reynolds number. Coleman and Steel (Ref. 8) present a method of uncertainty quantification, methods for modeling and simulating error propagation (Monte Carlo Method, and Taylor Series Method) and tools needed to be able to determine a degree of goodness for a set of data. Despite extensive research on the accuracy of various PIV implementations, to date there is no standard methodology established for quantifying the uncertainty associated with individual vector evaluations. The PIV measurement uncertainty is affected by the numerous elements present in the instrumentation chain, and in the vast majority of the cases those uncertainties are interconnected and coupled. To address this issue, two-research teams (Utah State University-USU and Virginia Tech-VT) collaborated with INL to develop two complementary and integrated approaches that will quantify PIV uncertainty and will be able to be freely disseminated and serve the PIV community and the INL needs in future.

IV.A Uncertainty Surface Method

To use the technique, the relationship between four error sources and their contributions to PIV error is first determined. The sources, or parameters, considered were particle image diameter, particle density, particle displacement, and velocity gradient, although this choice in parameters is arbitrary and may not be complete. This information provides a four-dimensional “uncertainty surface” specific to the PIV algorithm used. After PIV processing, the code ‘‘measures” the value of each of these parameters and estimates the velocity uncertainty due to the PIV algorithm for each vector in the flow field. While, in principle, any number of inputs can be tested, thus far, four have been used: flow shear, particle displacement, particle image density, and particle image size. These parameters were varied to create an array of synthetic images that mimic known flows, and then evaluated against the true flow to establish uncertainty.

The code that is produced is based on the following procedure, as described in Timmons, Smith, and Vlachos’ 2011 article (Ref. 9):

1. Identify and select contributors to PIV error (e.g., particle images size, seeding density, shear rate, etc.)
2. Generate synthetic images for rectilinear flow varying each contributor identified in Step 1.
3. Compute vector fields for the synthetic images and compare them to known solutions to find the errors as a function of each of the parameters.
4. Compute the uncertainty estimates from the distribution of errors found in Step 3 and formed into the uncertainty surface
5. Estimate the parameters found in Step 1.
6. Combine the estimates from Step 5 with the uncertainty surface from Step 4 to determine the uncertainty for each vector.
7. Verify the methods effectiveness by generating new synthetic images for several flows and comparing the true solution of known flows to the calculated.

The values of other uncertainties associated with PIV, which cannot be incorporated into this method, can be root-sum-squared with the results to obtain a total combined uncertainty estimate.

Flat Plate Experiment

A flat plate of polished quartz was submerged in the MIR test section and a considerable amount of data of the flow over the flat plate was collected (~9Tb). Both large and mezzo images, on the order of 5” and 0.25”, respectively, were captured near the plate surface. Further, after the initial collection, a turbulence generator (TG) – array of round bars – was installed upstream of the plate. Following the turbulence generator a diverging plate was installed on top of the flow to create an adverse pressure gradient (APG) on the boundary layer, as opposed to the test section walls themselves acting as a negligible zero pressure gradient (ZPG).

As an example of the Uncertainty Surface Method a Large FOV dataset was processed through the Uncertainty Surface Method. Using the before mentioned four-dimensional “uncertainty surface,” namely: particle image diameter, particle density, particle displacement, and velocity gradient; an uncertainty surface was generated for the flat plate flow. It shows that the regions of highest uncertainty are within the boundary layer, i.e., region of high shear, but for the uniform freestream flow the uncertainty is relatively minimal (~0.005 m/s). Figure 3 shows a zoomed in view of a wall-normal profile of streamwise mean velocity with its corresponding uncertainty and the percentage of the uncertainty to its flow measurement at x = 201 mm downstream from the leading edge.

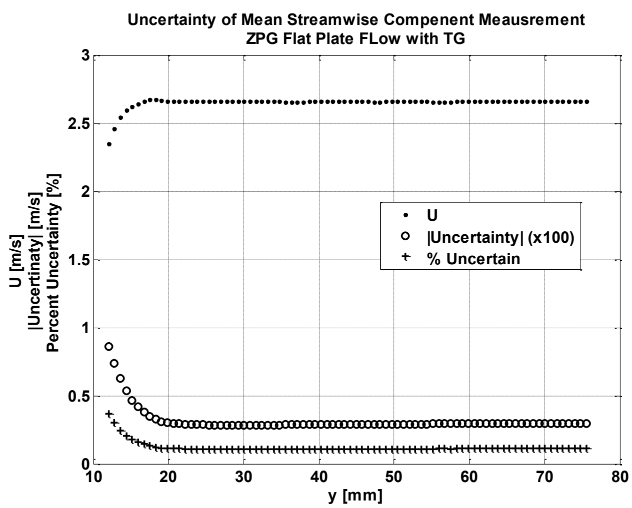

Fig.3. Wall-normal streamwise velocity profile of flow over a flat plate (x = 201 mm) as measured in the MIR, utilizing PIV and the Uncertainty Surface Method.

IV.B Cross-Correlation Peak Ratio Method

This method is based on the hypothesis that the cross-correlation contains information about uncertainty, with the goal being to estimate the uncertainty bounds to within a given confidence interval for a specific, individual measurement. The results showed that the ratio of the largest correlation peak to the second largest was an excellent predictor of uncertainty for the Robust Phase Correlation (RPC) displacement estimator implemented in PRANA, regardless of flow condition or image quality. The peak ratio was also a good predictor of the uncertainty for a standard cross correlation (SCC) displacement estimator, which is more commonly used. Using an analytical model of the relationship derived from synthetic data sets, the uncertainty bounds at a 95% confidence interval were then computed for several artificial and experimental flow fields, and the resulting errors were shown to match closely to the predicted uncertainties. Using the peak height (Q), Charonko and Vlanchos (Ref. 10) modeled the uncertainty for an SCC-based measurement as:

$$U_{SCC} = \left[\left(13.1\, exp\left(-\frac{1}{2}\left(\frac{Q-1}{0.317}\right)^2 \right) \right)^2 + \left(\frac{0.226}{Q}\right)^2 + 0.0064 \right]^{0.5}$$

Similar relationships were also given for the RPC-based approach, and better fits were obtained. Initial tests of this method against experimental stagnation flow data showed predicted uncertainty values at a 95% confidence interval that closely matched the estimated true errors as based on a fit of the analytical solution for this flow (Ref. 10).

V. CONCLUSIONS

The MIR flow facility at INL is used to produce velocity data for CFD code validation. The data is obtained by performing separate effects experiments, which replicate a flow as it travels in and around a representative model. The MIR facility enables optical measurements for determining flow characteristics in complex passages/geometries (such as turbomachinery passages, nuclear reactor tube bundles, nuclear reactor coolant channels, and boundary layers) in and around objects without distortion of optical paths through the use of Particle Image Velocimetry. However, the uncertainty with PIV measurements is currently not well understood and is difficult to determine; no standard methodology yet exists that quantifies the uncertainty. Two independent methods for computation of uncertainty from two-component PIV measurements are being developed to quantify uncertainty and obtain accurate and reliable experimental data. These methods are Uncertainty Surface Method and the Cross-Correlation Method (Signal-to-Noise Ratio method). In the Uncertainty Surface Method, an algorithm is tested to determine its response to various uncertainty contributors; in the cross-correlation method, the magnitude of the correlation peak is quantified to determine the uncertainty.

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