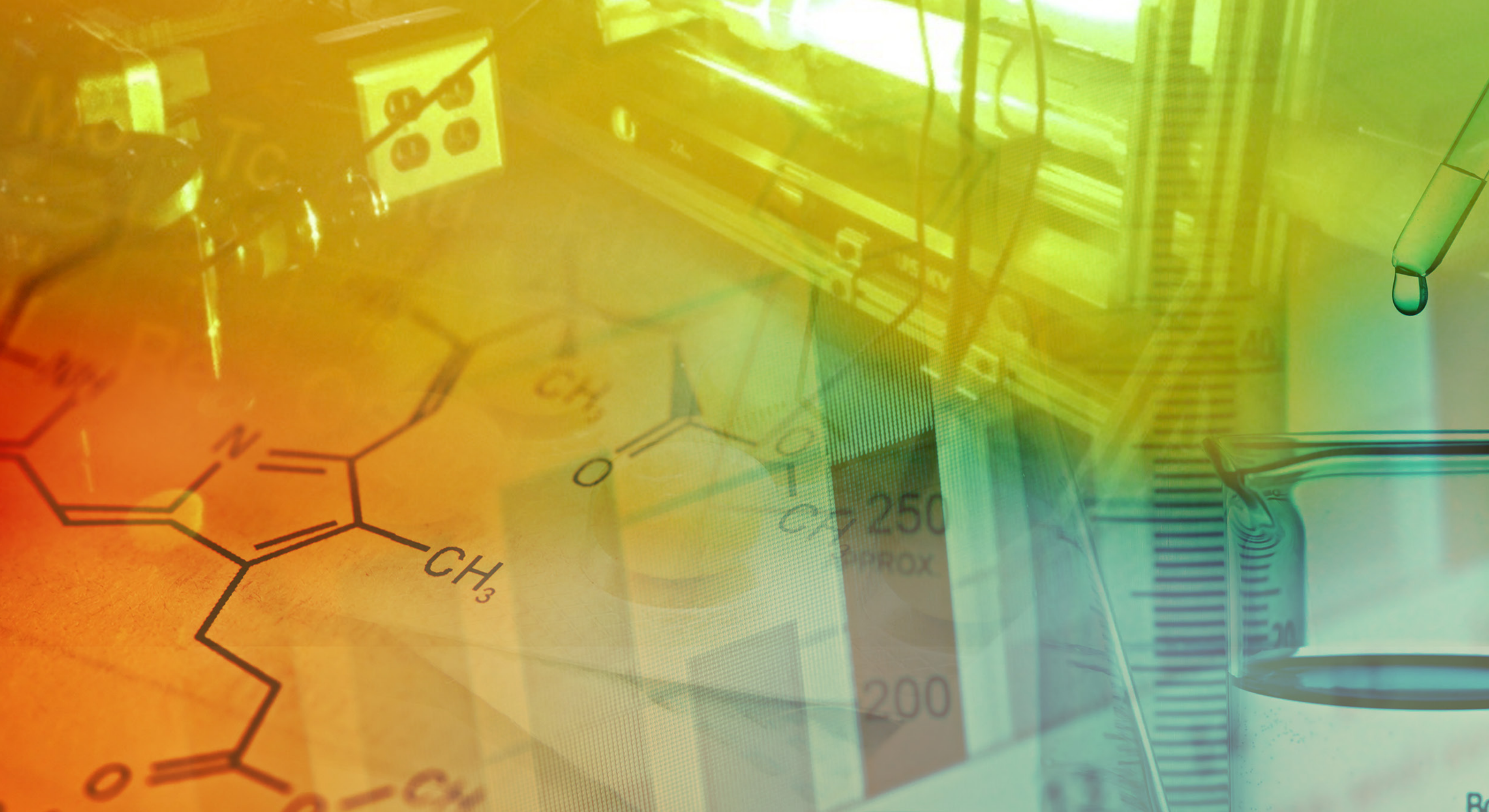
New research

Enver Karakas and Eric Wonhof, Ebara International Corp., USA, present recent research on two-phase expansion in cryogenic turbines.

In January 2016, Ebara International Corp. (EIC Cryo) and the Mechanical Engineering Department at the University of Nevada, Reno partnered together to design and develop hydraulic components for LNG turbomachinery applications. The objective of the project has been to expand the understanding of two-phase flow and to improve the overall efficiency of cryogenic turbines, specifically those utilised in the LNG liquefaction process. Two-phase flow is a mix of gas and liquid together which has completely different attributes than either on its own. Historically, the two-phase condition has been avoided because cavitation can be damaging to the equipment. However, when the boundary and location of the two-phase expansion is controlled, cavitation damage can be avoided, allowing for substantial return to the customer in the form of recovered energy and reduced waste. The foundation of this laboratory will lead to the prediction, experimental verification, and further advancement in the field, not only to advance the turbine hydraulic technology, but also to broaden overall education and knowledge in the rotating equipment and turbomachinery fields.



Great beginnings – how we got here

17 years ago, the first prototype two-phase turbine (EIC Cryo 'expander') was designed and built. Back in 2000 – 2001, the capabilities of the available design and analysis tools were limited. Unfortunately, verification of a multi-phase flow design through physical testing at EIC Cryo's testing facilities in Sparks, Nevada, US, was not yet possible – only single-phase (liquid) was available. Two-phase testing and verification had to be conducted at the customer's facility. After a suitable (and willing) customer relationship was established, multiple hydraulic components were manufactured and installed to optimise the turbine design. Each configuration had to be tested in stages lasting several years. This testing process substantially increased the total cost and design cycle of this first two-phase turbine.

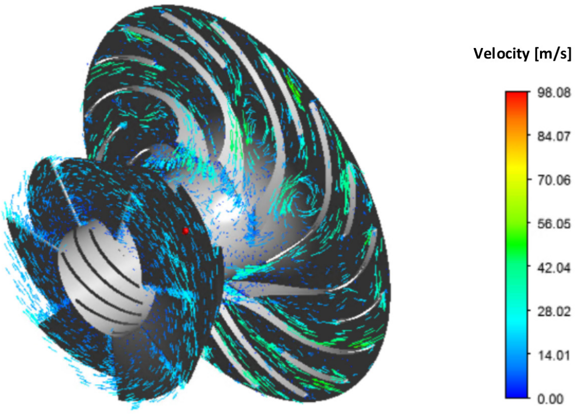


Figure 1. Computational fluid dynamics (CFD) analyses of EIC Cryo's two-phase turbine hydraulic components by the University of Nevada, Reno turbomachinery laboratory.

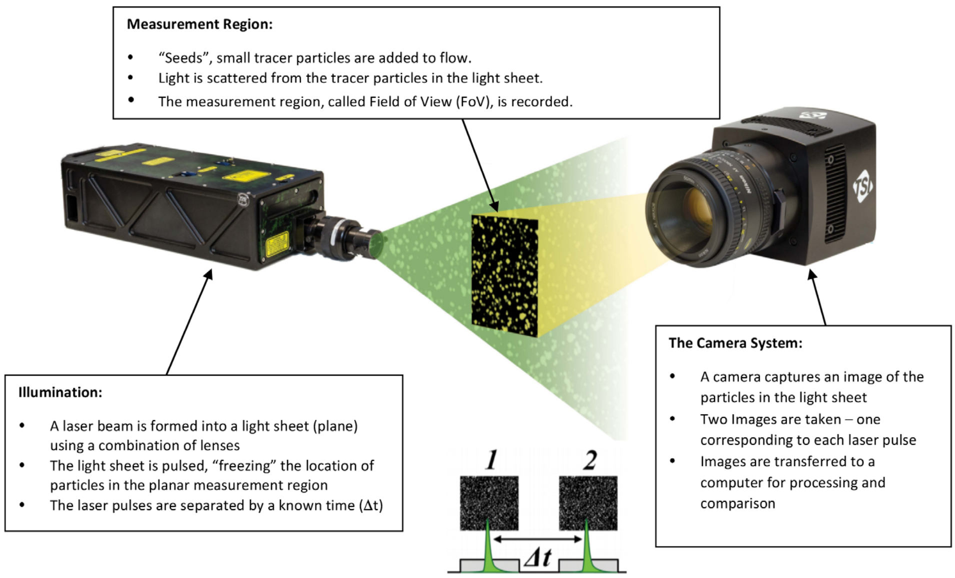


Figure 2. The basics of the particle image velocimetry (PIV) system.

While overall performance of the original prototype was ultimately optimised to meet customer and engineering expectations, specific internal workings and flow behaviour remained unconfirmed due to limited instrumentation and visibility within the machine itself. Some of the machine's operating characteristics were not initially predicted and questions still remain regarding certain specific behaviours of the hydraulic components under two-phase flow conditions. Better understanding and prediction of the two-phase condition is absolutely necessary in order to progress turbine technology and ultimately deploy it to larger facilities, which carry greater investment and higher risk.

Building a laboratory for analysis and verification

Hydraulic components, such as runners and nozzle vanes, are the most critical elements in a cryogenic turbine's operation. The design of these components directly influences efficiency and is also critical to the reliability and dependability of the rotating machinery. Each hydraulic component design receives detailed review in stages, often categorised but not limited to:

- Theoretical prediction, analysis, and simulation.
- Experimental verification, validation, and demonstration.

Theoretical prediction, analysis, and simulation

In order to satisfy the first step of the analysis and prediction process, high speed computers are utilised at the University of Nevada, Reno turbomachinery laboratory to design and accurately model the hydraulic components using computational fluid dynamics (CFD) software specifically written for turbomachinery applications. The hardware and software combination is capable of simulating design cases in excess of supersonic speeds in two-phase flow conditions. While CFD has been used to simulate single-phase flow for decades, newer high-speed computers and software advancements now allow for detailed analysis of the previously out-of-reach two-phase flow. A two-phase expander CFD result plot is shown in Figure 1.

Experimental verification, validation, and demonstration

Testing and verification of hydraulic components is extremely costly to perform in a full scale LNG environment. This is primarily due to cryogenic temperatures and the hazardous nature of LNG. Also challenging, the size of a full scale LNG expander can be as high as 3 MW in generator rating, which makes it impossible to test under limited laboratory conditions. In order to simulate these larger hydraulics, scaled models of various turbine components are manufactured to validate CFD results. In addition to typical measurements, such as temperature, pressure, flow, power, and rotational speed, particle image velocimetry (PIV) is used in the laboratory to determine the performance and also to visually observe and understand the flow characteristics of each component.

PIV is a more advanced method of flow imaging. Compared to historical photography and video, PIV adds detailed computer tracking and measurement. This laser-based technique combines high-accuracy point measurements with digital imaging in order to obtain instant velocity data over the entire flow region. Most importantly for two-phase flow study, the PIV can accurately determine the product phase, liquid or gas or mixture, by analysing reflected wavelength.

The basics of a PIV system and its operation can be observed in Figure 2. 'Seeds', typically very small glass particles, are added to the fluid flow. At each time step, a laser illuminates the seeds for high-speed photography. The PIV software processes and records the seeds' movements, calculating both velocity and direction. Within the measurement region, all seed data is combined to analyse the entire flow field. Figure 3 is the PIV testing of straight pipe with laminar flow, which was performed for calibration purposes in November 2016. Figure 4 is the PIV testing of a three-bladed propeller. Figure 5 is the simulation results (CFD) and PIV measurement side-by-side, illustrating the velocity contour of flow through an orifice. PIV images may look like computer simulations, but they are actual measured and calculated velocities.

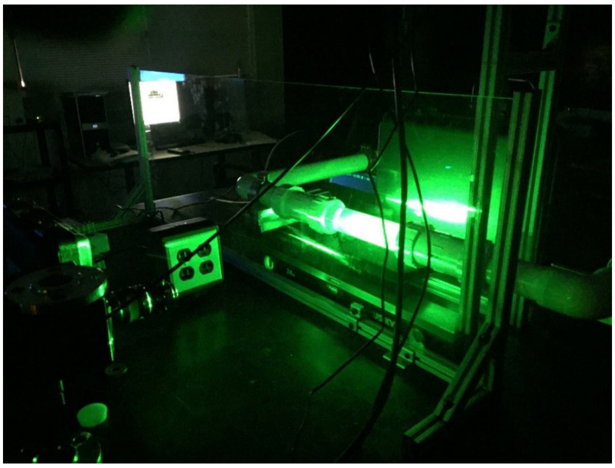


Figure 3. First PIV test at the University of Nevada, Reno turbomachinery laboratory (November 2016). Straight pipe laminar flow calibration.

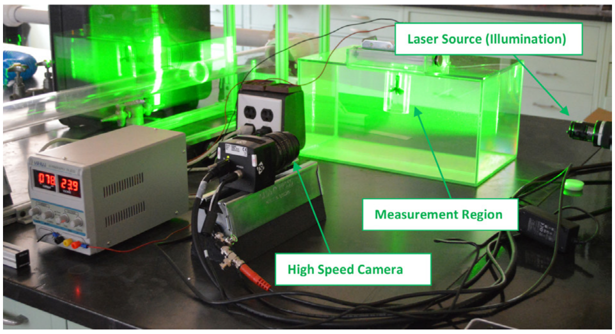


Figure 4. PIV calibration measurements being performed on three-bladed propeller.

Laboratory turbine set-up and arrangement

The turbine test set-up is being designed and built to validate the performance of the hydraulic components and determine flow characteristics of two-phase cryogenic turbines. This closed-loop system is based on an Organic Rankine Cycle (ORC) – an arrangement very similar to geothermal applications where the working fluid experiences thermal heating and cooling as it passes through booster pumps and turbines. Within the University of Nevada, Reno turbomachinery laboratory, located on the university campus, safety is top priority. A special eco-friendly refrigerant has been selected which is both non-flammable and non-hazardous. The fluid also experiences two-phase transition, between gas and liquid, at ambient temperature, making it easy and safe to manage within a lab environment through simple minor adjustments to temperature and pressure. This will allow many experiments to be conducted with minimum effort, investment, and time. By applying proven similarity and scaling laws, the results of these experiments will translate to cryogenic liquids, such as LNG in full scale production liquefaction applications.

The testing arrangement includes a storage tank, a booster pump, heat exchangers, and a turbine apparatus. The booster pump supplies controlled pressure and flow to the system by utilising a variable frequency drive (VFD), which governs the rotational speed. The two heat exchangers subsequently cool or heat the test fluid as necessary. Combined, this allows for carefully regulated inlet flow to the turbine apparatus. The turbine apparatus, housed within clear casings for PIV imaging, will initially only include a rotating exducer – a special turbine wheel designed to drop pressure and recover energy from the phase change and expansion. At later stages, more hydraulic components can be added to the turbine apparatus, such as fixed vanes or rotating runners. A data acquisition system (DAQ) is also used to monitor and record temperature and pressure at various locations, density of the fluid, flowrate, and turbine speed.

The turbine's overall efficiency is a ratio of inlet power to outlet power. Input power is determined by the differential head (head drop) and flowrate. Output power is calculated from the torque output of the turbine shaft, which is a function of rotational speed. In addition to the turbine's efficiency, flow characteristics and velocity field within the internal passages of the turbine hydraulic components are monitored and recorded by PIV to pinpoint any deficiencies.

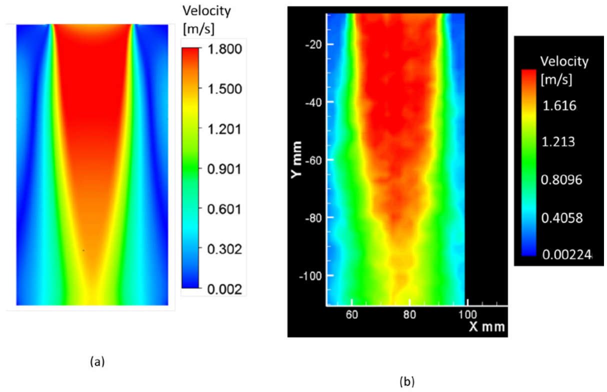


Figure 5. CFD simulation (a) and PIV measurement (b) results for flow through a restriction orifice. Velocity contour is shown.

Conclusion

The first phase of the experiment at the University of Nevada, Reno turbomachinery laboratory involves re-testing the original two-phase flow exducer that was built in 2001 by EIC Cryo with new verification technology and tools. The main purpose is to accurately model and replicate site performance data from the customer's facility and also verify CFD simulation results. It is crucial to validate these CFD simulations to confirm the assumptions made in computer modelling.

The second phase of the experiment will be the performance enhancement of the existing two-phase turbine. Once the testing is completed successfully, new scaling and similarity laws for two-phase turbine applications will be formed and verified. Flow behaviour and performance characteristics of each hydraulic component under two-phase flow will be better understood by utilising the PIV technology. Design methodology for hydraulic components will then be established by comparing simulations to the actual test results.

Once verified and confirmed, this methodology can and will be applied to countless future two-phase turbine applications with unique custom requirements. Ultimately, this study will allow the industry to adopt two-phase expander technology with confidence and security. Machine performance and return on capital investment will be ensured for long-term economic and environmental benefit. **LNG**

Acknowledgement

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