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Advanced Computational Thermal Studies and Their Assessment for Supercritical-Pressure Reactors (SCRs)

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Abstract - *Accomplishments of a computational and experimental US/Korea/Germany partnership, aimed at improving prediction of heat transfer to supercritical-pressure fluids, are reviewed.*

I. INTRODUCTION

The goal of this *laboratory / university collaboration* of coupled computational and experimental studies is the improvement of predictive methods for supercritical-pressure reactors. The general **objective** is to develop supporting knowledge needed of advanced computational techniques for the technology development of the various concepts and their safety systems.

This basic thermal fluids research applied first principles approaches (Direct Numerical Simulation - DNS and Large Eddy Simulation - LES) coupled with experimentation (heat transfer and fluid mechanics measurements). Turbulence is one of the most important unresolved problems in engineering and science, particularly for the complex geometries and fluid property variations occurring in these advanced reactor systems and their safety systems. DNS, LES and differential second moment closures (DSM or Reynolds-stress models) are *advanced computational concepts* in turbulence "modeling" whose development is being *extended to treat complex geometries and severe property variation* for designs and safety analyses of SCRs.

Variations of fluid properties along and across heated flows are important in Supercritical-pressure Carbon-dioxide Reactor (SC-CO2R) concepts. Significant differences and uncertainties have been found between thermal hydraulic correlations for these conditions. Improved computational techniques and supporting measurements are needed to assist the developers of codes for reactor design and systems safety analyses to treat the property variations and their effects reliably for some operating and hypothesized accident scenarios of these reactors. Most of the coolant channels in SCR concepts are more complex than those that have been used to generate the empirical correlations employed in the thermal hydraulic codes. Advanced computational techniques may be applied but measurements with realistic geometries are needed to assess the reliability and accuracy of their predictions.

II. APPROACH

Prof. Pletcher extended LES to generic idealizations of such geometries with property variation; Prof. Yoo supported these studies with DNS. Prof. 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. Prof. Laurien examined the difficulties of modeling the large fluctuations of fluid properties in the pseudo-critical region for commercial RANS codes [Zhu and Laurien, 2009]. INL obtained fundamental turbulence and velocity data for generic idealizations of the complex geometries of these advanced reactor systems. Profs. Wallace and Vukoslavcevic developed miniaturized multi-sensor probes to measure turbulence components in heated supercritical flows in the experiments of Profs. Lee and Yoo.

DNS employs no turbulence modeling; it solves the unsteady governing equations directly. Consequently, along with measurements, it can serve as a benchmark for assessing the capabilities of LES, DSM and general RANS techniques. It also can be applied for predictions of heat transfer at low flow rates in reduced power operations and transient safety scenarios, such as loss-of-coolant or loss-of-flow accidents, in SCRs. Once validated, LES and DSM techniques can be applied for predictions at higher flow rates, such as near normal full-power operating conditions, for these reactor concepts. The flow facility developed at SNU provides means of measuring heat transfer to supercritical CO_2 for assessment of the effects of their property variations and the miniaturized multi-sensor probes from U. Montenegro and U. Maryland will permit measuring the turbulence which is modeled by the codes. INL has developed the World's largest Matched-Index-of-Refraction flow system (web site = http://www.inl.gov/physics/mir/). By using optical techniques, such as laser Doppler velocimetry (LDV) and particle image velocimetry (PIV), measurements can be obtained in small complex passages without disturbing the flow. The refractive indices of the fluid and the model are matched so that there is no optical distortion. The large size provides good spatial and temporal resolution. This facility provides the means to investigate the complex flow features of SC-CO2 reactor geometries.

III. ACCOMPLISHMENTS AND CONCLUSIONS

Prof. Yoo extended his DNS code to obtain the first treatment of heat transfer to supercritical fluids by that numerical technique and completed seventeen cases with conditions spanning the pseudocritical temperature; significant effects of buoyancy and property variation on the turbulence were demonstrated. Predictions were compared to measurements from Prof. Lee. He then extended the code to annular flow in the pseudocritical region with a heated central rod (Fig. 1) and examined the effects of property variation on turbulent heat flux and other turbulent statistics [Bae et al., 2008].

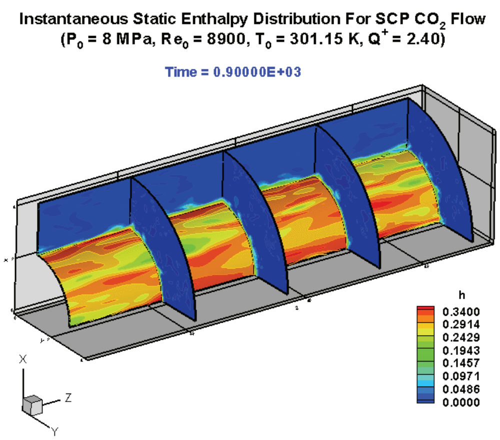

Figure 1. DNS of supercritical CO_2 flow

Prof. Pletcher extended his quasi-developed turbulent LES code for circular tubes to include supercritical fluid properties (Fig. 2) and validated its performance by comparison to DNS from Prof. Yoo and experiments. He then extended it to developing flows and to complex geometries such as annuli, ribbed annuli and an idealization of flow phenomena in coolant channels of an SCR concept [Wang and Pletcher, 2007].

Prof. Park applied his DSM code to examine the capabilities of a wide range of turbulence models for heat transfer to superheated gas flows and to supercritical flows -- with and without buoyancy influences -- and compared predictions to DNS from Prof. Yoo and experiments. He found that results depended strongly on the individual models and concluded that one could not be chosen as a best model; some predicted wall temperatures satisfactorily for some cases but not for others. None was universally good [Baek and Park, 2005].

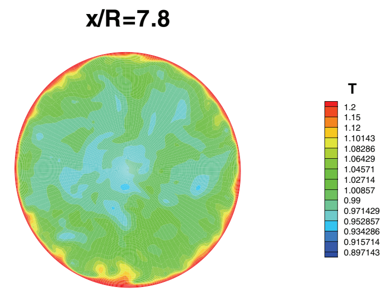

Figure 2. LES of supercritical CO_2 flow, instantaneous temperature contours

Prof. Laurien derived a turbulence model accounting for the large fluctuations of specific heat c_p in the pseudo-critical region [Laurien, Rashid and McEligot, 2007]. This model (Fig. 3) improves CFD predictions of the onset of deterioration.

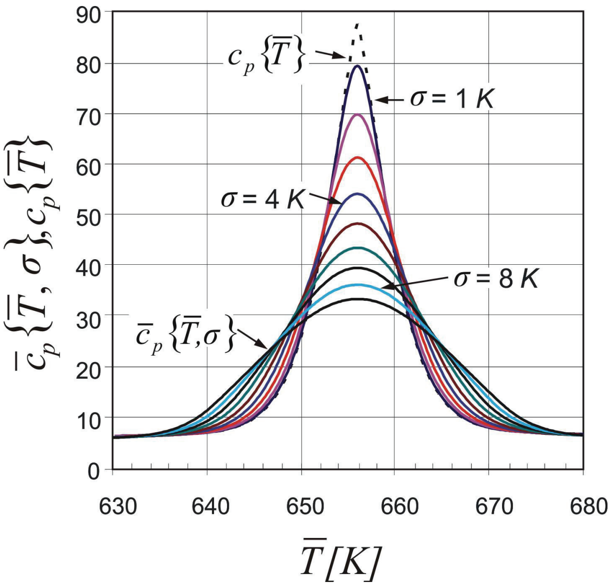

Figure 3. Specific heat model accounting for turbulent fluctuations in the pseudocritical region.

INL installed a large-scale model for simulating flow in SCR passages in their Matched-Index-of-Refraction flow system [McEligot et al., 2005]. With Prof. Smith, they acquired two- and three-dimensional PIV data for the streamwise-periodic, three-dimensional region between successive grid spacers (Fig. 4). Results of this benchmark database are archived electronically at USU for assessment of DNS, LES, DSM and RANS codes (www.efdl.usu.edu).

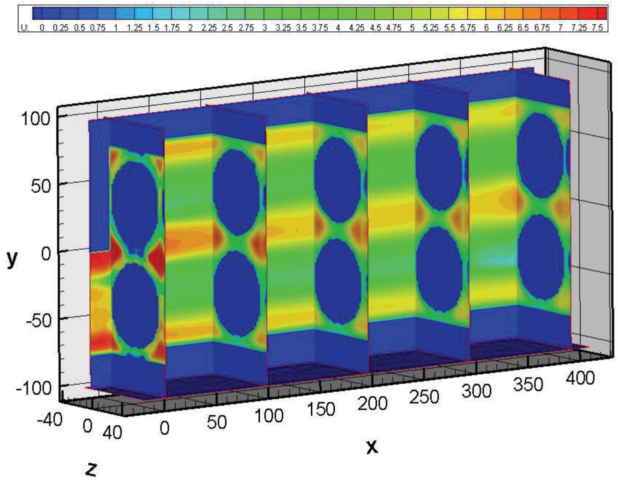

Figure 4. PIV data for flow in complex geometry of an SCR channel, streamwise velocities.

Profs. Vukoslavcevic and Wallace developed two-sensor miniaturized hot-wire probes and a calibration facility (Fig. 5) for use in supercritical CO_2 heat transfer experiments, calibrated the probes [Vukoslavcevic, Radulovic and Wallace, 2005], derived response algorithms and trained SNU students in the use of their probes for measurement of instantaneous temperature and velocities in a supercritical fluid. They designed and constructed a mechanism to traverse the probe inside a high pressure CO_2 flow and provided the design to SNU.

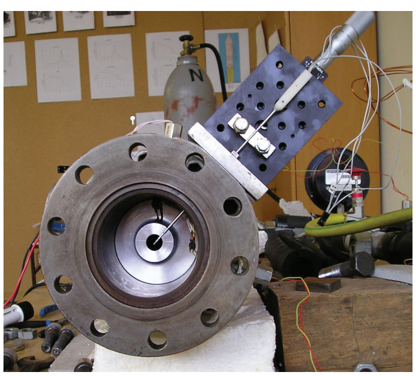

Figure 5. Two-sensor probe in calibration facility for heated supercritical CO_2.

Profs. Lee and Yoo built an experiment to measure heat transfer, pressure drop and velocity and temperature distributions in supercritical CO_2 in tubes. They obtained the first measurements of heat transfer to supercritical flow in small square and triangular tubes (Fig. 6) and measured heat transfer and pressure drop to supercritical CO_2 with small and large circular tubes for over 160 sets of conditions overall [Kim et al., 2005].

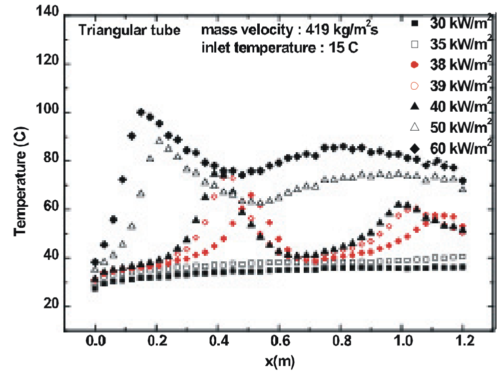

Figure 6. Heat transfer to supercritical CO_2 in triangular tube.

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