Computational Predictions of the Reactor Simulator Subsystem at NASA GRC

Nuclear and Emerging Technologies for Space (NETS)
February 23 – 26, 2015

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OUTLINE

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OBJECTIVE

• Support the Space Technology Mission Directorate and Game Changing Development Program Office in developing technologies for space missions.

• Explore the capability of computational modeling to assist in the development of the Fission Surface Power (FSP) technologies.

• Develop a computational model that will assist in evaluating the capacity adequacy of an Annular Linear Induction Pump (ALIP) in the FSP Technology Demonstration Unit (TDU).

• Verify and validate the prediction results. Use them to determine if the ALIP can supply the needed pressure capacity at the nominal mass flow rate of 1.75 kg/sec.
• The RxSim (Reactor Simulator) subsystem utilizes an ALIP to drive the working fluid throughout the loop.

• The ALIP is an electromagnetic pump that moves liquid metal by applying an alternating magnetic field.

• The ALIP must have the pressure capacity to overcome the pressure losses produced by the loop components (piping, Core Simulator, and Heat Exchanger Manifold for the dual ASC convertors).

• The TDU ALIP and the FSP ALIP are available electromagnetic pumps for the RxSim subsystem.
BACKGROUND

• The RxSim Subsystem was extracted from the CAD model of the FSP TDU. A flow meter was added and the HX Manifold removed.

Mesher -> ANSYS Mesher
Solver -> ANSYS Fluent
MODEL DETAILS
 RxSim Loop: Stations 0 through 9

• The geometry that describes this version of the RxSim subsystem is shown on the right.

• ALIP is removed and the planes at Stations 0 & 9 will have applied (mass flow) boundary conditions.

• Applied mass flows will encompass the range of laboratory testing.

• Primary pressure loss sources are expected at Stations 2 & 3, and Stations 4 & 5, but will be book kept from Stations 0 through 9.
The Reactor Simulator consists of 37 rods.

Rod 1 (in the schematic on the right) contains wires and instrumentation.

Rods 2 through 37 introduce heat to the working fluid as it flows through the small gaps between the rods.

Focus is on pressure distribution rather than thermal distribution.
• Wedge flow meter manufactured by ABB was added to the RxSim Subsystem.

• Consists of 1½ inch carbon steel Schedule 40 pipe with a wedge removed. Pipe wall roughness is 0.00015 ft.

• Calculations depicting the pressure drop as a function of mass flow were provided by ABB. However, a model of just the flow meter was created at GRC and predictions over the same mass flow range generated.

• GRC prediction results were compared to ABB calibration curve to generate confidence in future GRC predictions.
MODEL DETAILS

Flow Meter: Stations 4 through 5

• After validating predictions of pressure loss with ABB calibration curve, the flow meter was added to the RxSim subsystem computational model.

• ANSYS Fluent results compared to OpenFOAM results for consistency.

• Spalart-Allmaras single equation turbulence model used for both solutions.
• Mass flow boundary conditions were applied at the inlet and exit starting at 1 kg/sec to 3 kg/sec. The pressure loss at each station is shown in the plot below.

Design requirement of 28 kPa (4.1 psi) is verified from the prediction results.
RESULTS

• The plot below shows the measured performance curves for the FSP ALIP, measured at NASA MSFC in the ALIP Test Circuit (ATC). Symbols have been added to this plot that represents predictions and actual measured data. Lines going through the data represents curve-fits of that particular set of data. Curve-fit equations are shown on the right. Simultaneously solution of the ALIP curve-fit equation with any of the other curve fits will reveal their intersection point (or the ALIP maximum capacity).

Prediction results generated using:

**Spalart Allmaras** (S-A) one equation turbulence model. Less complex model, and uses little computer resources.

**Realizable k-ε** two-equation turbulence model. More complex model, but uses more computer resources. *(k is the turbulent kinetic energy and ε is its dissipation rate)*

Objective of using two different turbulence models is to observe the effect of each resulting predictions when compared to measured data.
CONCLUSIONS

- Comparisons of the predictions and measurements to the ALIP performance curves suggest that
  - Pump can provide 2.223 kg/sec (according to predictions using k-ε Turb Model)
  - Pump can provide 2.333 kg/sec (according to measured data)

which indicates an acceptable 4.7% difference in mass flow at nominal flow.

- The plots below show the deviation of the pressure predictions when compared to measured pressure data, which indicates a 0.5 psi difference in loop pressure loss at nominal flow.
SUMMARY

- RxSim subsystem was modeled using the computational solver ANSYS Fluent.

- Computational results were compared to measured data.

- Results confirm the ability of the FSP ALIP to supply the required pressure.

- Further use of the model anticipated for system testing.
Spalart-Allmaras one-equation turbulence model

The transported variable in the Spalart-Allmaras model, \( \tilde{\nu} \), is identical to the turbulent kinematic viscosity except in the near-wall (viscosity-affected) region. The transport equation is

\[
\frac{\partial}{\partial t} (\rho \tilde{\nu}) + \frac{\partial}{\partial x_i} (\rho \tilde{\nu} u_i) = G_v + \frac{1}{\sigma_{\tilde{\nu}}} \left[ \frac{\partial}{\partial x_j} \left\{ (\mu + \rho \tilde{\nu}) \frac{\partial \tilde{\nu}}{\partial x_j} \right\} + C_{b2} \rho \left( \frac{\partial \tilde{\nu}}{\partial x_j} \right)^2 \right] - Y_v + S_{\tilde{\nu}}
\]

where

- \( G_v \) is the production of turbulent viscosity
- \( Y_v \) is the destruction of turbulent viscosity that occurs in the near wall region
- \( \sigma_{\tilde{\nu}} \) and \( C_{b2} \) are constants
- \( \nu \) is the molecular kinematic viscosity
- \( S_{\tilde{\nu}} \) is a user-defined source term
The realizeable $k$-$\varepsilon$ model differs from the standard $k$-$\varepsilon$ model in two important ways:

- The realizeable $k$-$\varepsilon$ models contains an alternative formulation for the turbulent viscosity
- A modified transport equation for the dissipation rate, $\varepsilon$, has been derived from an exact equation for the transport of the mean-square vorticity fluctuation.

The term “realizeable” means that the model satisfies certain mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows. Neither the standard $k$-$\varepsilon$ model nor the RNG (Renormalization Group) $k$-$\varepsilon$ model is realizeable. The transport equation is

$$
\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k
$$

$$
\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S_k \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} \frac{C_{1\varepsilon}}{k} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon
$$

where:

- $G_k$ is the generation of turbulence kinetic energy due to mean velocity gradients
- $G_b$ is the generation of turbulence kinetic energy due to buoyancy
- $Y_M$ is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
- $S_k$ and $S_\varepsilon$ are turbulent Prandtl numbers for $k$ and $\varepsilon$
- $C_2$ and $C_{1\varepsilon}$ are constants and $S_k$ and $S_\varepsilon$ are user-defined source terms