Development of Terry Turbine Analytical Models for RCIC Off-Design Operation Conditions

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Outline

• Background and overview
• Analytical two-phase Terry turbine nozzle models
• Benchmark results
• Summary
Overview of RCIC System

- The RCIC (Reactor Core Isolation Cooling) system
  - consists of a turbine and a turbine-driven pump, piping and valves.
  - RCIC system is nearly passive, except for the battery for control function.
  - Water mass flow rate through the pump into the primary system is about 10 times the steam mass flow rate flowing out through the turbine.
  - Without control, the RCIC will flood the reactor vessel.

RCIC system schematic (Credit of US NRC)
Before Fukushima accidents, it was generally considered in SBO analyses that loss of the DC power would result in flooding the steam line and turbine, where it is assumed that turbine would then be disabled.

This behavior, however, was not observed in the accidents, where the Unit 2 RCIC functioned for nearly three days, much longer than the assumed 4-6 hours battery life.

(Credit of R. Gauntt, et al., SAND2012-6173, 2012)
Terry Turbine Overview

- The Terry turbine has been used for all the BWR RCIC systems and for PWR AFW (Auxiliary Feed Water) systems.

- The Terry turbine is essentially a solid cylindrical wheel with multiple machined semi-circular ‘buckets’ that are shaped into the body of the wheel. Fixed nozzles and reversing chambers surround the wheel inside the turbine casing. High pressure steam is accelerated to supersonic flow through the turbine nozzle. The kinetic energy is then converted to shaft work by the impulse force on the turbine buckets.

Terry turbine bucket flow (left) and interior view of turbine case (right) (credit of Kross, et. al., 2015)
Challenges on RELAP5-3D system analysis code simulation of RCIC

- Very small time step sizes (1E-6 sec.) are required to simulate Terry turbine nozzle
- Need to develop fast running and accurate analytical models for RCIC systems

Schematic diagram for RELAP5-3D modeling of RCIC
Purpose of This Work

- Developing analytical models for the Terry turbine and pump, as part of the efforts to understand the unexpected “self-regulating” mode of the RCIC systems in Fukushima accidents and extend BWR RCIC and PWR TDAFW (Turbine Driven Auxiliary Feed Water) system operational range and flexibility.
- The new set of models can be implemented into systems analysis codes such as RELAP5-3D to provide fast running and accurate simulations of the RCIC systems such that they can be credited in accident management.
• Terry turbine model is composed of two parts:
  – Nozzle model: a ROM model for turbine bucket inlet velocity obtained from a large number of CFD simulations.
  – Turbine rotor model: angular momentum eq.

\[
L \frac{d\omega}{dt} + r^2 \dot{m}\omega(t) = \frac{-T_{pump}(t)}{1 + \cos\beta} + 2r\dot{m}V_j \frac{\cos\beta}{1 + \cos\beta}
\]

Figure 3.28. FLUENT velocity for Terry nozzle pressure drop from 1100 psia to 28 psia

Figure 3.30. Bucket inlet velocity as a function of nozzle pressure ratio
New Analytical Terry Turbine Nozzle Models

- For the RCIC turbine operating near its design operation condition, we postulate that treating saturated steam as an ideal gas would result in sufficiently accurate results. The under-expanded or over-expanded jet out of the nozzle can also be treated as ideal gas.

- The jet flow through a converging-diverging nozzle can be characterized with four distinct stages: (1) adiabatic expansion to sonic condition at the throat from the source and adiabatic expansion to supersonic condition in the expansion part of the nozzle; (2) adiabatic free expansion and reaching the ambient pressure (virtual nozzle); (3) zone of flow establishment (ZOFE); (4) free jet.
Terry Turbine Two-Phase Nozzle Model

- There are no direct measurements of two-phase flow regimes inside a supersonic convergent-divergent nozzle due to high pressure and high speed.

- It has been hypothesized (Moody, 1965) that bubbles form homogeneously in the decompression region near the pipe entrance, which leads to homogeneous critical flow condition. This condition is followed by phase separation with discharge in the annular or separated flow regime.

- We developed a two-phase nozzle expansion model according to this hypothesis:
  - bubble flow in the convergent section
  - transitions to slip flow in the divergent section

Two phase choking inside a convergent-divergent nozzle.
Two-Phase Choking Model

• Use classic choking models to calculate the mass flow rate, critical pressure and steam quality at the nozzle throat.

• Two choking models implemented:
  – Moody’s IHEM critical flow model: equal phasic velocities and temperatures.
  – Moody’s Critical Flow Model: thermal equilibrium between two phases but having different velocities.

• The choking models are solved with Golden Section Search algorithm and were validated with Moody’s critical mass flux and critical pressure figures.

Choking flow rates according to IHEM (Moody, 1965)
Steam Supersonic Nozzle Expansion Model

• In the divergent section, we only consider the steam phase using a similar model as for the single-phase case by assuming that the liquid phase would slip along the wall with a much slower speed and will not contribute to the impulse on the rotor.

• We also modify the stagnation conditions according to two-phase choking conditions at the throat and the cross-sectional areas for steam at the nozzle throat and at the nozzle exit.

• The steam expands following an isentropic process. The Mach number (M) at the nozzle exit is calculated with:

\[
\frac{A_{eG}}{A_{tG}} = \left(\frac{\gamma + 1}{2}\right)^{-\frac{\gamma + 1}{2(\gamma - 1)}} \left(1 + \frac{\gamma - 1}{2} M^2\right)^\frac{\gamma + 1}{2(\gamma - 1)}
\]

• When Mach number is available, the pressure, temperature, density, and velocity can be calculated.
Virtual Nozzle Model for Free Expansion

- For the non-isentropic adiabatic free expansion process from the nozzle exit to ambient pressure, the pressure, temperature, velocity, and density vary rapidly while the jet diameter expands significantly over a short distance from the nozzle exit.
- The mass entrained by the jet during this expansion process is insignificant compared to the jet mass flow rate from the nozzle exit.
- According to mass, momentum, energy balances and the ideal gas law, four equations can be formulated to calculate jet velocity, temperature, density, and diameter at the end of this stage, i.e.,

\[ u_v = \frac{p_e - p_v + \rho_e u_e^2}{\rho_e u_e} \]

Schematic depicting the initial expansion process of an underexpanded jet.
**Benchmark With Steam Nozzle Experiment**

- The same steam nozzle experiment used for benchmark in the Sandia research* was used for validating the proposed analytical model and comparing with Sandia CFD results.
- This nozzle test only had in-nozzle velocity data (near 90% nozzle length). The analytical model assumes dry saturated steam at the nozzle inlet.

Comparison of velocities near test nozzle exit between the analytical models, Sandia CFD models, and test data
Terry Turbine Nozzle Benchmark

- The Terry turbine geometry specified by the Sandia study is used for the Terry turbine benchmark study.
- The Sandia CFD results are used for benchmarking the analytical model.

<table>
<thead>
<tr>
<th>Model variable</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine wheel diameter</td>
<td>61 cm (24 inches)</td>
</tr>
<tr>
<td>Turbine wheel and bucket width</td>
<td>7 cm</td>
</tr>
<tr>
<td>Number of nozzles and reversing chamber sets</td>
<td>5</td>
</tr>
<tr>
<td>Number of reversing chambers per nozzle set</td>
<td>4</td>
</tr>
<tr>
<td>Number of buckets on wheel</td>
<td>84</td>
</tr>
<tr>
<td>Nozzle length</td>
<td>1.7 cm</td>
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<tr>
<td>Nozzle circular throat diameter</td>
<td>0.56 cm</td>
</tr>
<tr>
<td>Nozzle square exit side length</td>
<td>0.64 cm</td>
</tr>
<tr>
<td>Distance from nozzle exit to bucket entrance</td>
<td>≈1.5 cm</td>
</tr>
</tbody>
</table>
Turbine bucket inlet velocity for the low outlet pressure case (193 kPa)
Two-Phase RCIC System Test Model

- The goal is to create a Fukushima-acidents-like scenario, with a reasonable self-regulating behavior appearing in the simulation.
- Periodic two-phase condition given at the turbine inlet.
- The turbine inlet pressure is 7.5 MPa and the turbine outlet pressure is 193 kPa.
- The simulation was run for two more cycles of dry-flood stages.

Terry turbine RCIC system test model
Specified turbine inlet steam quality for the RCIC system simulation with periodic inlet condition
Calculated mass flow rates through the RCIC system—mixture and steam through the turbine nozzle exit, water through the pump for RCIC system simulation with periodic inlet condition and the IHEM model.
Summary

- The two-phase Terry nozzle model is divided into three parts: (1) expansion and choking models from the nozzle inlet to the throat, (2) expansion in the divergent section of the nozzle, and (3) the free expansion stage from the nozzle exit to the turbine bucket entrance.
- The new two-phase Terry turbine model has been benchmarked with the steam nozzle tests.
- A RCIC system test with a periodic steam quality inlet condition was developed to simulate Fukushima-like accident scenarios, and a reasonable self-regulating behavior appears in the simulation.
- These analytical models can be implemented into systems analysis codes such as RELAP5-3D to provide accurate and fast running capability once they are validated with Terry turbine test data.