RERTR 2009 — 31st INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

November 1-5, 2009
Kempinski Hotel Beijing Lufthansa Center
Beijing, China

IMPLEMENTATION OF RELAP5-3D SYSTEM MODEL TO SUPPLEMENT THE DESIGN OF THE HYDRO-MECHANICAL FUEL TEST FACILITY

W.R. Marcum, A.C. Arnold, and B.G. Woods
Oregon State University, Department of Nuclear Engineering and Radiation Health Physics
Radiation Center, Corvallis, Oregon, 97331-5902 – United States

and

D.M. Wachs
Idaho National Laboratory, RERTR Fuel Development Program
Materials & Fuels Complex, Idaho Falls, Idaho, 83415-6188 – United States

ABSTRACT

Oregon State University (OSU) has been tasked by the RERTR Fuel Development Program to design, construct, and utilize a Hydro-Mechanical Fuel Test Facility (HMFTF) with the primary objective of producing a database of information to support the qualification of a new prototypic uranium-molybdenum (U-Mo) alloy, low enrichment uranium (LEU) fuel to be inserted into the five U.S. High Performance Research Reactors (HPRRs). This database of information will include fuel plate and element, plastic and elastic deformation, and vibration as a function of operating system pressure, temperature, and flow rate. The current design of the HMFTF permits for simulation of beyond design basis operating conditions of all the U.S. HPRRs including Lower Safety System Settings (LSSS) to Limiting Conditions of Operation (LCOs). Many unique challenges arise when designing a thermal-hydraulic test loop having such a wide range of operating conditions including the design of parallel pump operation. A RELAP5-3D model has been developed in order to verify component design calculations and characterize the thermodynamic balance of the facility. This model includes all primary loop components as well as a heat-exchanging bypass loop. A comparison has been made between the RELAP5-3D model and a thermal hydraulic system balance of the loop and was shown to produce good agreement.

1 Introduction

Oregon State University (OSU) has been tasked by the RERTR Fuel Development Program to design, construct, and utilize a Hydro-Mechanical Fuel Test Facility (HMFTF) with the primary objective of producing a database of information to support the qualification of a new prototypic uranium-molybdenum (U-Mo) alloy, low enrichment uranium (LEU) fuel to be inserted into the five U.S. High Performance Research Reactors (HPRRs) [1]. Focus on the HMFTF project is currently being directed toward refining the design of the test loop as well as tuning component sizing. A RELAP5-3D System model of the HMFTF has been developed in order to verify component sizing calculations and acquire a comprehensive understanding of this complex system during steady state and transient operations.

The results produced in the RELAP5-3D model are compared against some explicit calculations used as a part of the loop component sizing. A brief description of the methods used to produce these explicit calculations accompanies these results.

2 Description of Preliminary Test Loop

The HMFTF is a thermal hydraulic facility which consists of a closed primary loop containing a separate bypass leg and secondary loop. The purpose of the primary loop is to control the system fluid (water) for a prescribed temperature, flow rate, and pressure in order to examine the hydro-mechanics of the test specimen located in the test section of the primary loop. The purpose of the secondary side is to prepare the primary fluid (via pH and conductivity), and account for all necessary (1) heat removal and (2) fluid makeup requirements that may be determined by the primary loop.

Figure 2a presents a preliminary rendered sketch of the HMFTF primary loop and major components. Two centrifugal pumps drive the flow through the primary loop. The design of the loop incorporates these pumps in a parallel arrangement such that low flow rates are controlled by the small pump and high flow rates are driven by the large pump. The normalization of three independent homologous parameters produces analogous performance curves for both primary loop pumps. This is done by considering the relative volume flow rate ($v = Q/Q_R$), head ($h = H/H_R$), and torque ($\beta = \tau/\tau_R$), while the subscript R represents the pump's rated parametric value. The pump's corresponding rated parameters are presented as the upper bounding values in Table 1. Figure 1 presents the normalized head and torque curves through the entire volume flow spectrum for both pumps.

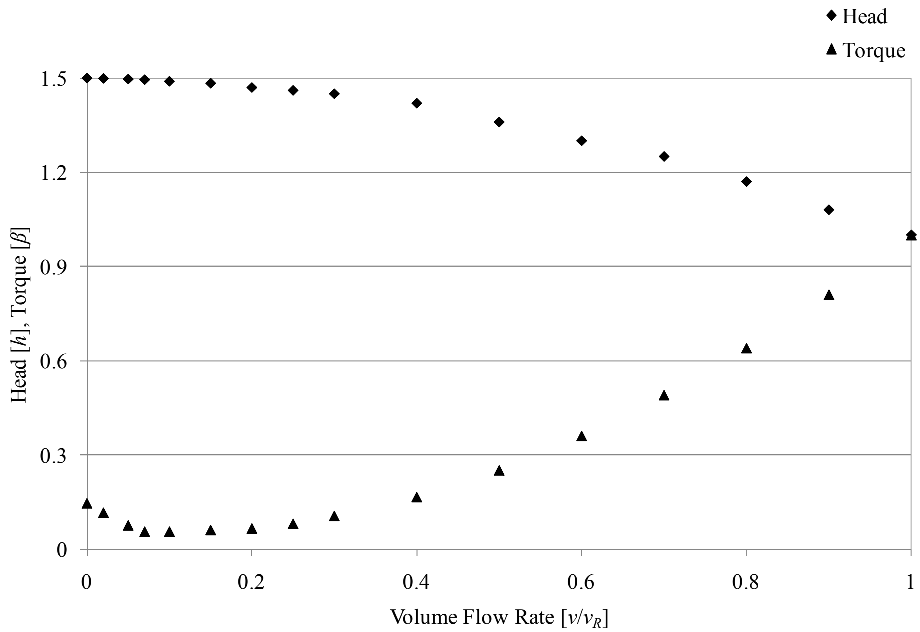
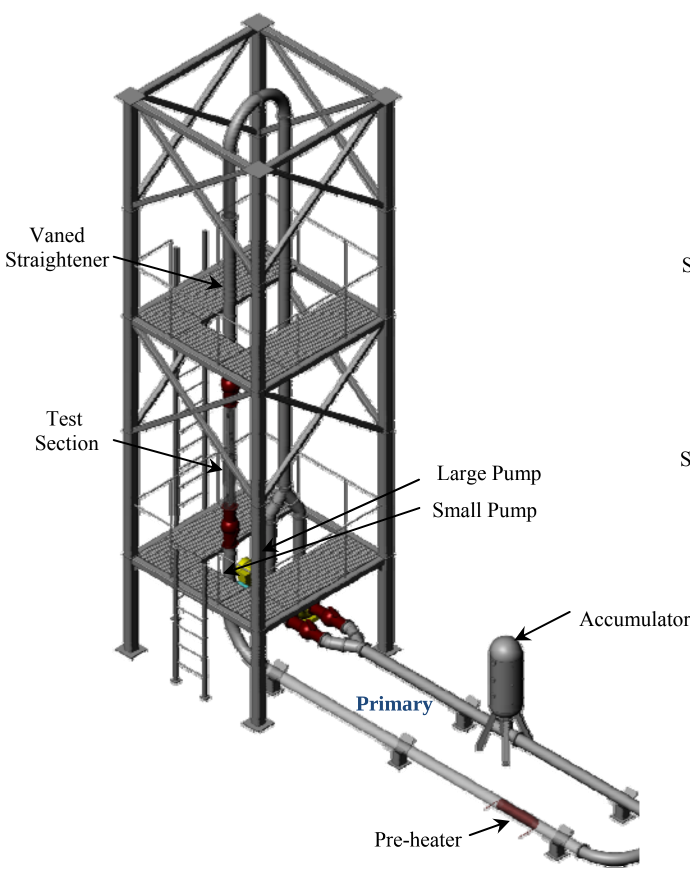
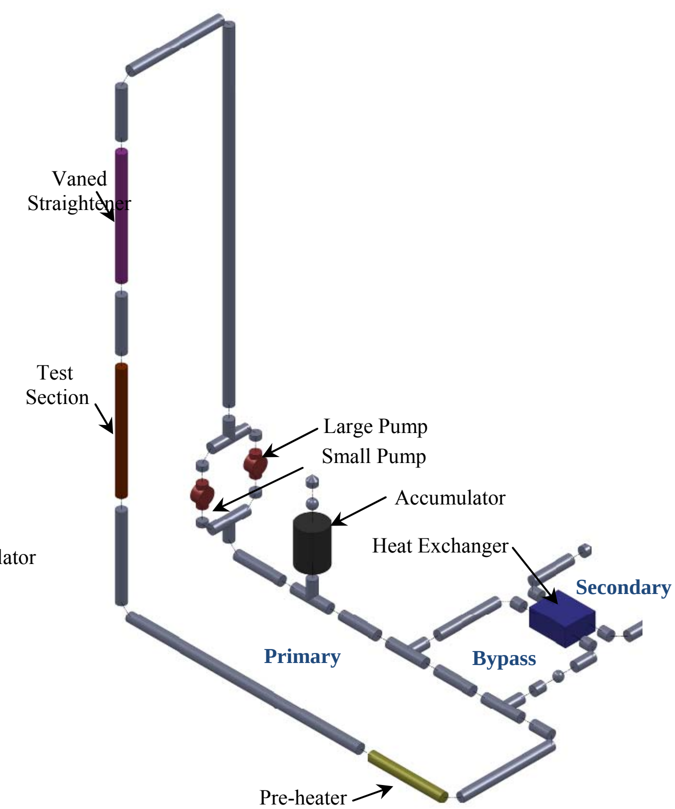


Figure 1: Normalized pump performance curves



(a)



(b)

Figure 2: Rendered sketch of HMFTF (a) primary loop and major components and (b) RELAP5-3D system model

The fluid passes through the pumps as called for by the operator, up the upcomer, around the upper elbow and the vaned flow straightener. A helicoil heater wraps the length of the vaned flow straightener to allow for fine temperature control of the fluid as is passes into the test section. The vaned flow straightener is located approximately 20 hydraulic diameters upstream of the test section. This allow for complete turbulent flow development prior to entry in the test section. The vaned flow straightener is the same length as the test section to allow for swapping of these pipe sections.

The test section is approximately 80 inches in length with an internal pipe diameter of 6.065 inches. The test section houses the test specimens. Local and differential pressure tubes are located on the upstream and downstream side of the test section and vaned flow straightener.

A single plate-type heat exchanger resides as the heat sink for the primary loop. Control of the heat removal rate by the heat exchanger is accomplished through use of a servo driven valve which variably diverts fluid from the primary loop to the bypass leg. A helicoil heater (pre-heater) is located on the upstream side of the bypass leg to account for course fluid temperature control.

An accumulator is located just upstream of the primary loop pumps. The purpose of the accumulator is to control the primary loop system pressure. The accumulator is monitored by two independent pressure sensors located on opposite azimuthal sides of the vessel. Table 1 provides for a comprehensive description of the primary loop's component characteristics.

Table 1: Primary loop component characteristics

Description	Value
Piping	
Diameter [m] (in)	0.15405 (6.065)
Primary Loop Arc Length [m] (in)	30.6019 (1204.8)
Accumulator (Expansion Tank)	
Liquid Volume [m^3] (in^3)	0.17514 (10687.7)
Cylinder Height [m] (in)	1.06680 (42.0)
Pre-Heater	
Thermal Power [kW_{th}] (Btu/hr)	24.0 (81964.3)
Heat Exchanger	
Tube Side Flow Rate [m^3/sec] (gpm)	0.003155 (50.0)
Shell Side Flow Rate [m^3/sec] (gpm)	0.0001892 (3.0)
Shell Side Inlet Temperature [°C] (°F)	23.89 (75.0)
Shell Side Exit Temperature [°C] (°F)	47.22 (117.0)
Heat removal capacity [kW_{th}] (Btu/hr)	215.8013 (737,000)
Pump (Small)	
Flow Rate [m^3/sec] (gpm)	0-0.1009443 (0-400)

Head [m] (ft)	0-167.64 (0-350)
Rated Torque [N-m] (lb-ft)	93.822 (69.2)
Pump (Large)	
Flow Rate [m^3/sec] (gpm)	0.025236-(400-1600)
Head [m] (ft)	0-243.84 (0-500)
Rated Torque [N-m] (lb-ft)	478.33 (352.8)
Coolant	
Type	Deminerilized Water
Temperature Range [°C] (°F)	23.89-315.56 (75.0-600.0)
Pressure Range [MPa] (psig)	0.0-4.13685 (0-600.0)
Volume Flow Rate Range [m^3/sec]	0.003785-0.1009443 (60.0-1600.0)

3 RELAP5-3D Model Description

The RELAP5-3D model was developed to include all primary loop components as well as a heat exchanger bypass loop and heat exchanging secondary side. A component breakdown of the RELAP5-3D model is presented in Figure 2b [2]. The model was developed such that its components and input boundary conditions produce representative steady state and transient thermal hydraulic trends which are approximately equivalent to that of the HMFTF.

All pertinent pump parameters and necessary homologous pump curves (Figure 1) were input into the model as stated in the manufacturer's specification documents [3, 4]. The primary loop pumps are connected in parallel via branch junctions which have no form losses associated with them in the RELAP5-3D calculation. The primary loop is modeled using a 0.1524 m (6 in) nominal diameter pipe while the bypass and secondary loops contain 0.0508 m (2 in) DIA piping. Although the physical loop has the ability of running reverse flow (up-flow through the test section) the RELAP5-3D model has a single primary loop which simulates down-flow conditions only. A surface roughness of 2.14 μm is assumed on all internal pipe walls.

The loop's temperature is controlled through the pre-heater located in the primary loop, and a bypass valve which is adjusted as necessary to increase or decrease mass flow through the heat exchanger and therefore control the heat sink of the loop. A PID controller is setup to monitor the bypass valve's position. A heat structure connects the bypass leg to the secondary loop. The heat structure is composed of a single stainless steel volume which contains the equivalent surface area and mass of that which is found in the heat exchanger of the HMFTF. The secondary loop assumes a constant inlet flow rate, pressure, and temperature of 0.00019 m^3/sec (3 gpm), 0.5171 MPa (75 psig) and 23.88 °C (75 °F), respectively.

4 Results

4.1 Steady State

A verification of pressure drop as a function of prescribed flow rates through the test section is conducted. This is done by comparing the RELAP5-3D model pressure drop values under steady state conditions to that produced in previous studies [5, 6] as well as an explicit calculation. Effective form loss (K_{eff}) values were input assuming sudden contraction and sudden expansion orifices corresponding to an ATR elemental geometry. Similarly, an explicit value for the pressure drop through the test section is estimated by implementing the Bernoulli equation in the following form:

$$\Delta P_L = \sum \frac{\rho v^2}{2g}\left(f\frac{L}{d_h} + K_{eff} \right) \tag{1}$$

For simplicity the Reynolds number (*Re*) is defined using the superficial velocity

$$Re_D = \frac{v_f d_h}{\upsilon} \quad \rightarrow \quad \frac{4\Gamma}{P_w \upsilon} \tag{2}$$

where $d_h = (4\mathrm{A})/P_w$, $v_f = \Gamma/\mathrm{A}$ and an explicit version of the Colebrook equation is used to estimate the fanny friction factor (*f*) as [7]:

$$f = 1.325\left(\ln\left(\frac{\varepsilon/d_h}{3.7} \right) + \frac{5.74}{Re_D^{0.9}} \right)^{-2} \tag{3}$$

Steady state values of pressure drop as a function of *Re* are presented in Figure 3. Five methods were used to verify pressure drop across the test section including three FLUENT® simulations using a *Spalart-Almaras*, *k-ε*, and *Reynolds-Stress* turbulence models, as well as the explicitly calculated pressure drop and RELAP5-3D solution. All show good agreement throughout the flow range considered with the largest difference of 0.079 MPa occurring at a *Re* of 5.63×10^5. Based on the numerous methods presented and their agreement it is assumed that the major form losses corresponding to an ATR type element in the test section are correctly accounted for in the RELAP5-3D model.

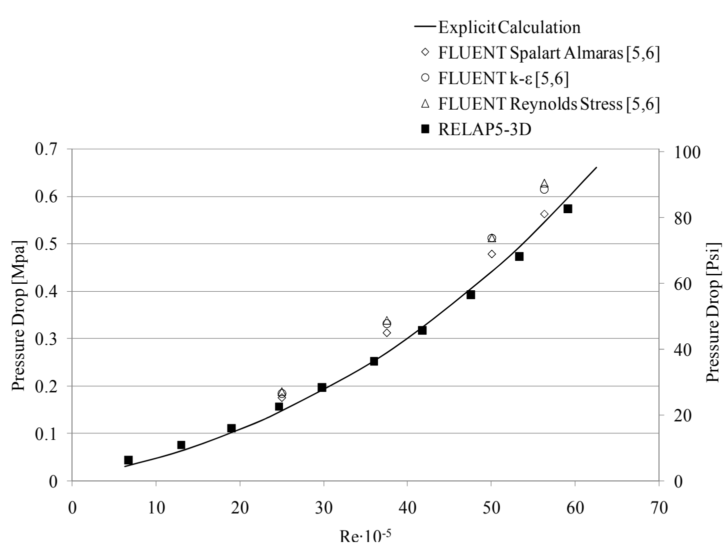


Figure 3: Pressure drop across test section

4.2 Transient

Three RELAP5-3D model transients are compared to a set of explicit calculations conducted to verify the results produced from the model. An energy balance is used to explicitly calculate the necessary heat removal (Q_{hx}) and heater thermal output (Q_{heater}),

$$\rho(T)c_p(T)V\frac{dT}{dt}=Q_{pump}+Q_{heater}-Q_{hx}\,. \tag{4}$$

Temperature and mass flow rate profiles are input as boundary conditions. The pumps' isentropic efficiency and state power required at the shaft are used to calculate enthalpy deposited to the fluid by the pumps' impellers as a function of flow rate. The heat removal is calculated as a function of mass flow rate by adjusting the bypass loop valve position in incremental steps changing flow rate through the heat exchanger as necessary to force both sides of equation (4) to zero. The Dittus Boelter correlation [8] is used to estimate the heat transfer coefficient and the secondary side temperature (T_s) is assumed to be constant at 23.9 °C (75 °F), this is seen below in equation (5).

$$Q_{hx}=\left(\frac{k}{L}0.023\,\mathrm{Re}_{hx}^{4/5}\,\mathrm{Pr}_{hx}^{2/5}\right)(T-T_s) \tag{5}$$

The heater thermal output is controlled by a logic proportional switch; the heater output is increased if the bypass valve was not incrementally opened in the previous iteration and is decreased if the valve was adjusted toward its closed position.

Three transients were considered as a part of this study. Case 1 was chosen as it ranges from ambient (shutdown) conditions to the maximum thermal hydraulic conditions observed when conducting testing on the MITR, MURR, and NBSR while ramping through the entire range of the smaller pump. Case 2 was chosen as it ranges from the lower to upper limit of thermal hydraulic conditions observed when conducting testing on the ATR and HFIR. Case 3 was chosen to demonstrate the pump 'leap-frogging' when ramping up through the smaller pump's maximum flow rates and into the range where the larger pump operates.

<u>Case 1</u>

The small pump is ramped from 0.0 to 0.0252 m^3/s (400 gpm) as pressure and temperature increase asymptotically from ambient values with a time constant of 100 s^{-1} remaining at least 20 °C (68 °F) below the saturation limit to a maximum value of 0.3792 MPa (55 psig) and 54.44 °C (130 °F), respectively. The pressure and flow rate boundary condition profiles for Case 1 are presented in Figure 4.

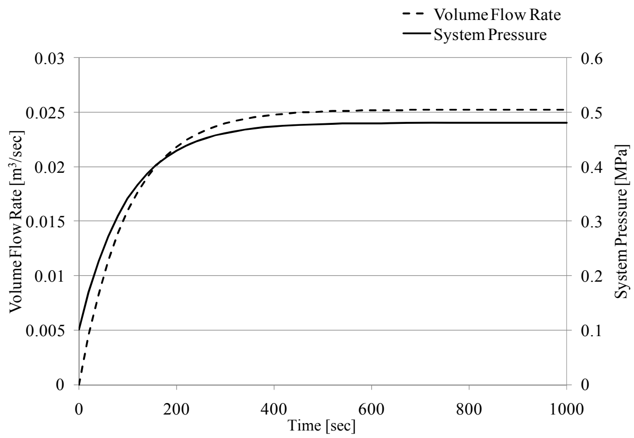


Figure 4: Boundary conditions (Case 1)

Figure 5 presents both explicit and RELAP5-3D solutions as a function of time for the required heater and heat exchanger thermal power to produce the described transient. Both explicit and RELAP5-3D solutions show good agreement overall however, a slight lag in response is seen by the RELAP5-3D solution. This is because the inertia of the pump is taken into consideration as a part of the RELAP5-3D solution while it is neglected in the explicit solution.

The loop's average fluid temperature is shown in Figure 6. The effect of the pump's thermal output on the fluid can be seen again. While a slight lag in asymptotic increase is seen at the beginning of the transient, at approximately 275 seconds when the pump is near its maximum flow rate a slight additive increase temperature rate can be seen. This is onset by the pump's isentropic efficiency decreasing near the end of the pump curve.

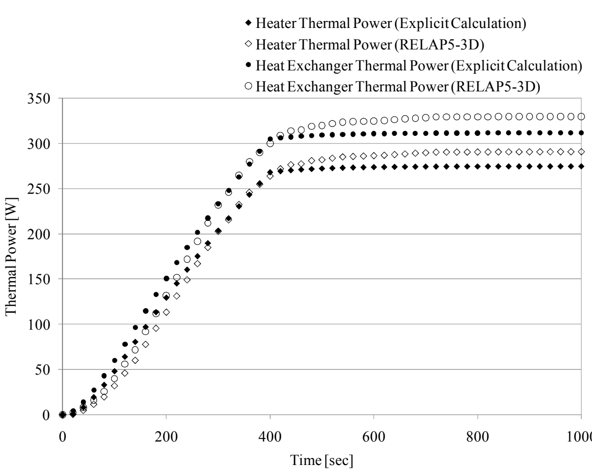


Figure 5: Thermal power results (Case 1)

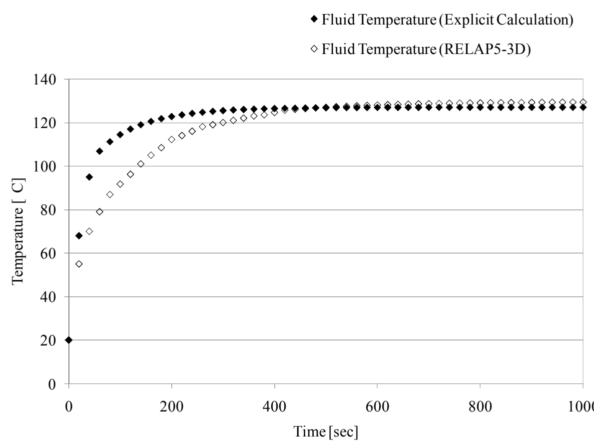


Figure 6: Temperature results (Case 1)

<u>Case 2</u>

The large pump is ramped from 0.0239 to 0.1009 m^3/s (380 to 1600 gpm) as pressure and temperature increase asymptotically from 20 °C (68 °F) and 0.1034 MPa (15 psig) with a time constant of 150 s^{-1} remaining below the saturation limit by at least 20 °C (68 °F) to plateau at a pressure and temperature of 3.44737 MPa (500 psig) and 260 °C (500 °F), respectively. The pressure and flow rate boundary condition profiles for Case 2 are presented in Figure 7.

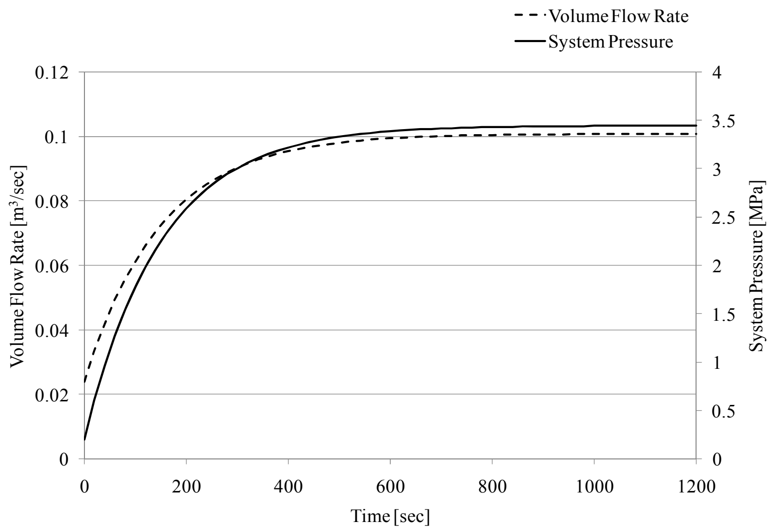


Figure 7: Boundary conditions (Case 2)

The thermal power output for the bypass loop and pre-heater are presented in Figure 8. Similar to that seen in Case 1, the inertia of the pump forces the pre-heater and bypass loop to overshoot in there required thermal output. If Figure 8 was extend its display out to 1800 seconds, the RELAP5-3D solutions would converge to the explicit solution showing that the overshoot is significant enough to delay steady state operation of approximately 10 minutes during this particular transient.

Figure 9 shows that the RELAP5-3D and explicit solution converge at the end of the transient however there is a significant time delay in the bulk coolant temperature increase in the RELAP5-3D model. This is due to the thermal storage of heat structures that occurs in the RELAP5-3D calculation which was not accounted for in the explicit calculation. The heat structures which add thermal mass in the RELAP5-3D model include the heat exchanger, accumulator, and heater; no heat structure was included to simulate the thermal mass of the piping, which will further lag the thermal response toward steady state. Although a fluid temperature boundary condition was added through the accumulator which includes a time constant of 150 s^{-1}, the RELAP5-3D calculated time constant is determined to be approximately 170 s^{-1} based on these additive thermal masses.

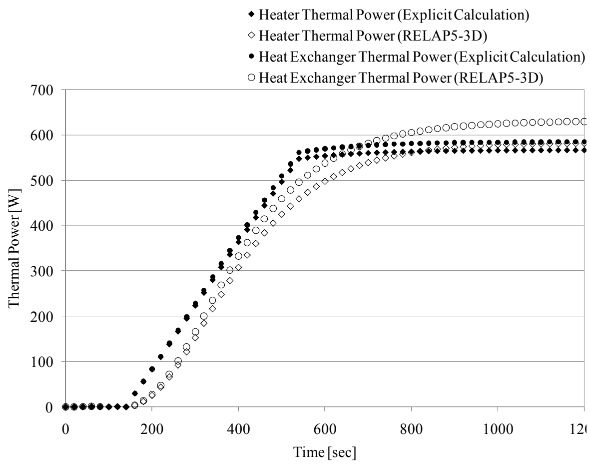


Figure 8: Thermal power results (Case 2)

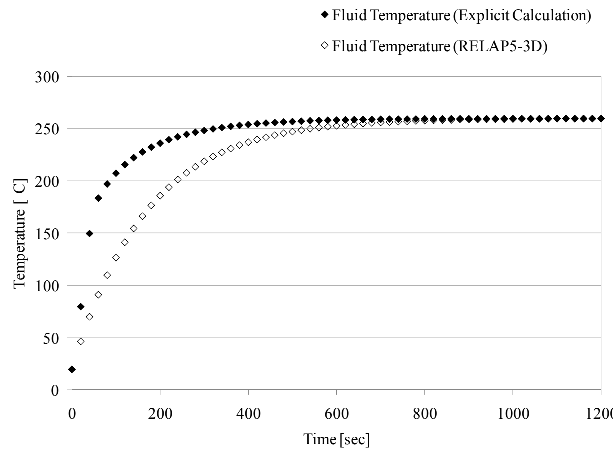


Figure 9: Temperature results (Case 2)

Case 3

The small pump is ramped from 0.0 to 0.0252 m^3/s (400 gpm) as pressure and temperature increase asymptotically from ambient values with a time constant of 250 s^{-1}. As the small pump reaches its rated flow limit it coasts down and the larger pump starts. The large pump is ramped from 0.0239 to 0.1009 m^3/s (380 to 1600 gpm) as pressure and temperature continue to increase asymptotically to reach a maximum value of 3.44737 MPa (500 psig) and 260 °C (500 °F) respectively. The pressure and flow rate boundary conditions profiles for Case 3 are presented in Figure 10.

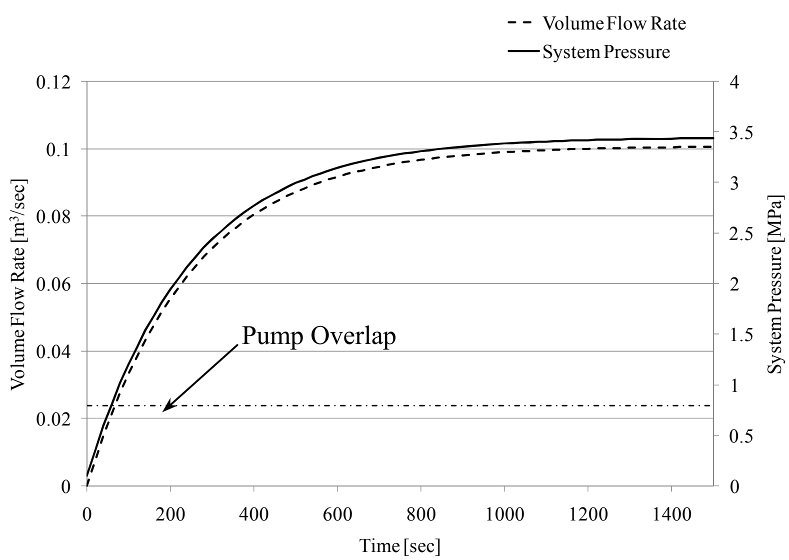


Figure 10: Boundary conditions (Case 3)

The thermal output required for the pre-heater and bypass loop are presented in Figure 11 for Case 3. As seen in previous cases the RELAP5-3D model overshoots the required thermal output relative to that explicitly calculated and then converges at a later time. In this case the RELAP5-3D model overshoots and starts to turn toward the explicit solution within the 1500 second view graph. Both methods produce similar solutions through the first four hundred seconds until the larger pump decelerates in the explicit model. The inertia of the pumps in the RELAP5-3D model carries the solution above that seen in the explicit solution beyond 400 seconds.

Figure 12 shows that the explicit calculation and RELAP5-3D solution have good agreement overall in their solution for bulk coolant temperature. An asymptotic increase in flow, pressure and temperature are controlled with a time constant of 250 s^{-1} during this transient. As seen in Case 2 (Figure 9), the thermal storage of the heat structures in the RELAP5-3D model added a lagging effect in the loops ability to reach steady state. By increasing the time constant during Case 3's transient the largest time constant is no longer the thermal storage found in the heat structures and thus the explicit and RELAP5-3D solutions agree overall.

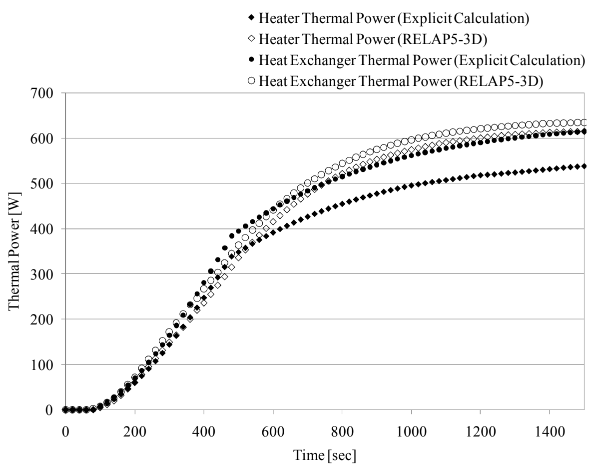


Figure 11: Thermal power results (Case 3)

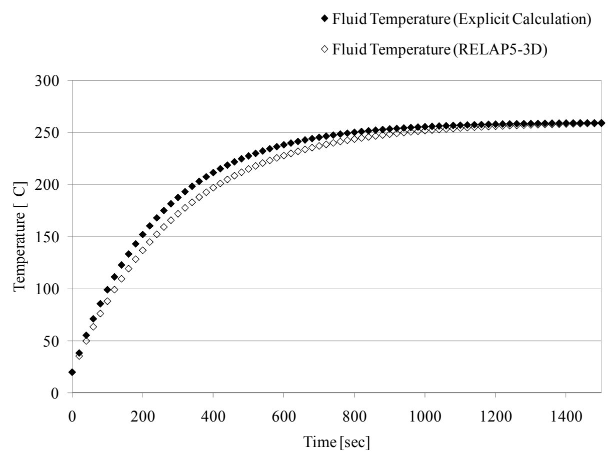


Figure 12: Temperature results (Case 3)

5 Conclusions

The purpose of this study was to verify component calculations of the integral thermal hydraulic loop which play a role in its thermodynamic balance during both steady state and transient operation. Several conclusions can be drawn as a result of this study:

(1) The steady state RELAP5-3D results agree well with the explicit calculation and results from FLUENT® produced during in previous studies.

(2) Although several significant assumptions were made when conducting the explicit calculations, in general they matched well to those result produced by the RELAP5-3D system model.

(3) Both thermal inertia and impeller inertia play a significant role in temporal response of the RELAP5-3D model, lagging the loop's response by considerable periods of time.

(4) Further work should be done to include the effective thermal mass of the loop piping to be included in the RELAP5-3D model in order to acquire a more accurate relation between transients and specific phenomenon time constants.

The RELAP5-3D model that has been developed as a part of this study will continue to be expanded upon in order to further verify more specific component performance parameters as they be come available as a part of the HMFTF program.

6 References

1. Marcum, W.R., B.G. Woods, and D.M. Wachs, *High Performance Research Reactor Fuel Development Hydraulic Test Loop*, in *RERTR 2008*. 2008, Oregon State University: Washington DC, USA.

2. Arnold, A., *System Modeling of the Hydro-Mechanical Fuel Test Facility Using RELAP5-3D*. 2009, Oregon State University. p. 14.

3. Marcum, W.R. and B.G. Woods, *Primary Loop Pump (1), Motor, and Drive Specification for Hydro-Mechanical Fuel Test Facility*. 2009, Oregon State University, Department of Nuclear Engineering and Radiation Health Physics. p. 18.

4. Marcum, W.R. and B.G. Woods, *Primary Loop Pump (2), Motor, and Drive Specification for Hydro-Mechanical Fuel Test Facility*. 2009, Oregon State University, Department of Nuclear Engineering and Radiation Health Physics. p. 18.

5. Marcum, W.R., B.G. Woods, and R.B. Jackson. *Numerical Flow Benchmark Model of the Advanced Test Reactor Using FLUENT*. in *American Nuclear Society Annual Meeting*. 2009. Atlanta Georgia: American Nuclear Society.

6. Marcum, W.R. and B.G. Woods, *Numerical Flow Study of Advanced Test Reactor Fuel Element Using FLUENT*, in *Modeling Experimentation and Validation Summer School*. 2009, Idaho National Laboratory: Idaho Falls, ID.

7. White, F., *Fluid Mechanics*. Fifth ed. 2003: McGraw-Hill Higher Education.

8. Incropera, F.P., et al., *Fundamentals of Heat and Mass Transfer*. 6 ed. 2006: John Wiley & Sons, Inc. 997.