VALIDATION OF BEST ESTIMATE MODELS FOR FLUORIDE-SALT-COOLED, HIGH-TEMPERATURE REACTORS USING DATA FROM THE COMPACT INTEGRAL EFFECTS TEST (CIET 1.0) FACILITY

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ABSTRACT

The University of California, Berkeley is developing best estimate fluoride-salt-cooled, high-temperature reactor (FHR) models using RELAP5-3D and the novel one-dimensional FHR Advanced Natural Circulation Analysis (FANCY) code. For initial code validation, coupled steady-state single-phase natural circulation loops have been operated on the Compact Integral Effects Test (CIET 1.0) facility. Models of these experimental loops have been built in RELAP5-3D and FANCY, and computational results have been compared against each other and with experimental data. In this paper, the CIET 1.0 model in RELAP5-3D and FANCY is detailed, and verification and validation efforts are presented. For various heat input levels and temperature boundary conditions, mass flow rates are compared between RELAP5-3D and FANCY results, analytical solutions when available, and experimental data, for both single and coupled natural circulation loops. The study shows that both RELAP5-3D and FANCY provide excellent predictions of steady-state natural circulation in CIET 1.0, with mass flow rates within 13% of experimental data, suggesting that both codes are good candidates for design and licensing of FHR technology.

KEYWORDS

Fluoride-salt-cooled, high-temperature reactor; Best estimate code; Verification and validation; Integral effects test; Code-to-code comparison.

1. INTRODUCTION

The University of California, Berkeley (UCB) is developing methods to design and perform safety analysis of fluoride-salt-cooled, high-temperature reactors (FHRs) [1]. FHRs use a natural-circulation-driven system to passively remove decay heat from the reactor core during design basis accidents where the normal shutdown cooling system is not available. The capability to perform verification and validation (V&V) of steady-state and transient response system models is a key issue for licensing new reactor designs. UCB is developing thermal hydraulic models to predict FHR steady-state characteristics for design optimization, and transient response during licensing basis events for safety analysis. Best estimate FHR models are developed using RELAP5-3D and the novel FHR Advanced Natural Circulation Analysis (FANCY) code developed by UCB [2]. For code validation, coupled single-phase natural circulation loops have been operated on the Compact Integral Effects Test (CIET 1.0) facility at UCB [3]. Models of this experimental loop have been built in RELAP5-3D and FANCY, and steady-state computational results have been compared against each other and with experimental data. Future work will include uncertainty quantification, to verify that differences between the models and the experiment are within expected uncertainty levels from the best estimate codes, and will explore simulation of transient response in CIET 1.0.

CIET 1.0 is a scaled height, reduced flow area integral effects test (IET) facility, which reproduces the integral thermal hydraulic response of FHRs under forced and natural circulation. CIET 1.0 uses Dowtherm A oil as a low-temperature simulant fluid for the prototypical fluoride salt coolant flibe (Li_2BeF_4) [3]. Two coupled natural circulation loops on CIET 1.0 replicate natural-circulation-driven decay heat removal in FHRs. In the primary loop, heat is added to the fluid through an electrically heated tubular-annular heat exchanger that replicates the heat generation and pressure loss of an FHR core. CIET 1.0 has two heat sinks created by variable-speed, fan-cooled heat exchangers, one in the primary loop that replicates heat removal to the power conversion system and normal shutdown cooling system, and the second in a Direct Reactor Auxiliary Cooling System (DRACS) loop. In the DRACS loop, the DRACS heat exchanger (DHX) serves as the heat source, and heat is removed through a thermosyphon-cooled heat exchanger (TCHX), replicated by a variable-speed fan-cooled heat exchanger. Mass flow rates and bulk fluid temperatures along both loops are measured at various levels of heat input and temperature boundary conditions at the outlet of the TCHX. The RELAP5-3D and FANCY models of the CIET 1.0 facility reproduce its geometry, temperature and pressure boundary conditions, as well as working fluid thermophysical properties as implemented in the code [4]. CIET 1.0 is briefly described here, and details of the RELAP5-3D and FANCY models of the coupled natural circulation loops are provided.

As part of model verification, sensitivities of code solutions to initial and boundary conditions, as well as model discretization, are assessed. Validation is performed using experimental data from CIET 1.0. Steady-state natural circulation computational results from RELAP5-3D and FANCY are compared with experimental data, for both single loop natural circulation in the DRACS and coupled natural circulation loops in the the primary loop and the DRACS loop. For single loop natural circulation, results are also compared to analytical calculations for a simplified model with no heat losses along the piping, where such solutions exist for mass flow rate based on heat input, loop geometry and average fluid properties. The coolant mass flow rate is the main metric of interest throughout this study, since higher mass flow rates remove heat from the system with a smaller temperature difference between the hot and cold parts of the loop.

2. CIET 1.0 EXPERIMENTAL CONFIGURATION AND RELAP5-3D/FANCY MODELS

The CIET 1.0 geometry, boundary conditions and instrumentation are introduced here, along with the RELAP5-3D and FANCY models of the facility. While only relevant information for the V&V effort is presented, a more detailed discussion of design aspects of CIET 1.0 is provided in a companion paper [3].

2.1. CIET 1.0 Natural Circulation Loops

The CIET 1.0 facility replicates the main flow paths in the primary loop and the DRACS loop of prototypical FHRs. In particular, for emergency decay heat removal through the DRACS, natural circulation is established in the primary system, with flow upwards through the core, then downwards through the DHX and downcomer. This natural circulation loop, simply called *primary loop* in the remainder of the paper, consists of a vertical annular heated section, the shell side of a vertical single-pass straight shell-and-tube DHX, and the connected piping. For simplicity in these experiments, the segment of the primary system that includes the primary pump and the primary loop oil cooler were valved off. The primary loop hot leg is the piping connecting the top of the heater to the top of the DHX. The primary loop cold leg is the piping connecting the bottom of the DHX to the bottom of the heater. Similarly, the DRACS loop consists of the tube side of the DHX, the TCHX, and the connected piping. The DRACS hot leg is the piping connecting the top of the DHX to the inlet of the TCHX. The DRACS cold leg is the piping connecting the outlet of the TCHX to the bottom of the DHX. Table I gives the physical dimensions of each segment.

Table I. Physical parameters of the CIET 1.0 natural circulation loops.

	Primary Loop				DRACS Loop			
	Heater	Hot Leg	DHX shell	Cold Leg	DHX tubes	Hot Leg	TCHX	Cold Leg
Length [m]	1.924	3.521	1.187	3.165	1.483	4.274	1.564	4.915
Elevation Change [m]	1.924	1.276	-1.187	-2.013	1.483	3.696	-0.416	-4.763
Hydraulic Diameter [mm]	6.6	27.9	5.7	27.9	6.9	27.9	11.9	27.9
Flow Area [10^{-4} m^2]	3.64	6.11	9.43	6.11	7.18	6.11	13.3	6.11

All parts of the loop are fabricated from Schedule 10 stainless steel piping, except for the DHX and the TCHX, both fabricated from copper tubing. The vertical heated section uses computer-controlled solid-state DC power supplies capable of providing power in the range of 0 to 10 kW, connected to the heater outer tube using copper electrodes. The TCHX is a computer-controlled fan-cooled heat exchanger, with variable fan speed to automatically control bulk oil outlet temperatures to desired levels. All parts of the loop are covered with 5-cm-thick fiberglass insulation to limit heat losses to the ambient air, except for the TCHX. An infrared camera was used to identify locations with insufficient insulation, such as valve stems, so that additional insulation could be added to further reduce heat losses. An expansion tank with atmospheric pressure boundary is installed at the uppermost elevation of each loop, to allow for volumetric expansion of the fluid. In modeling the loops, it is thus assumed that the boundary conditions are:

- Adiabatic on the inner tube of the annular heater,
- Uniform heat flux to solid on the outer tube of the annular heater,
- Stainless steel piping with 5-cm-thick fiberglass insulation on the hot and cold legs of each loop,
- Copper piping with 5-cm-thick fiberglass insulation on the shell side of the DHX,
- Bare copper piping on the TCHX,
- Controlled bulk oil outlet temperature at the TCHX,
- 20°C ambient temperature around the rest of the loop,
- Atmospheric pressure at the free surface of each expansion tank.

The loop is instrumented with type-T inline thermocouples (TCs) with 0.5-mm-diameter sheaths and ungrounded junctions to measure bulk fluid temperatures at the inlets and outlets of the heater, DHX shell side, DHX tube side and TCHX. The type-T TCs accuracy is ±0.5°C in the 0-200°C range. Mass flow rates are directly measured in each loop using Coriolis flowmeters with accuracies of ±2% over the range of flow rates of interest. For each run, the heat input is set through the power supplies' controls. To collect the data used in this study, temperatures and mass flow rates in each loop are recorded when steady-state conditions have been reached.

2.2. CIET 1.0 RELAP5-3D and FANCY Models

The RELAP5-3D and FANCY models of CIET 1.0 reproduce its geometry (i.e. components lengths, elevations, hydraulic diameters and flow areas), pressure and temperature boundary conditions, and working fluid thermophysical properties. Material properties for the stainless steel and copper tubing, as well as the fiberglass insulation, are manually implemented in the models. In particular, thermal mass of the system will have an impact on future transient modeling and validation. Therefore, masses of individual components were measured and recorded throughout the assembly process of CIET 1.0, and these individual masses can be added to heat structures in the RELAP5-3D and FANCY models when transient model validation is performed. Figure 1 shows a labeled 3-dimensional model of CIET 1.0 and the corresponding nodalization diagram for the RELAP5-3D and FANCY models. On the diagram, the primary loop and the DRACS loop are highlighted in green.

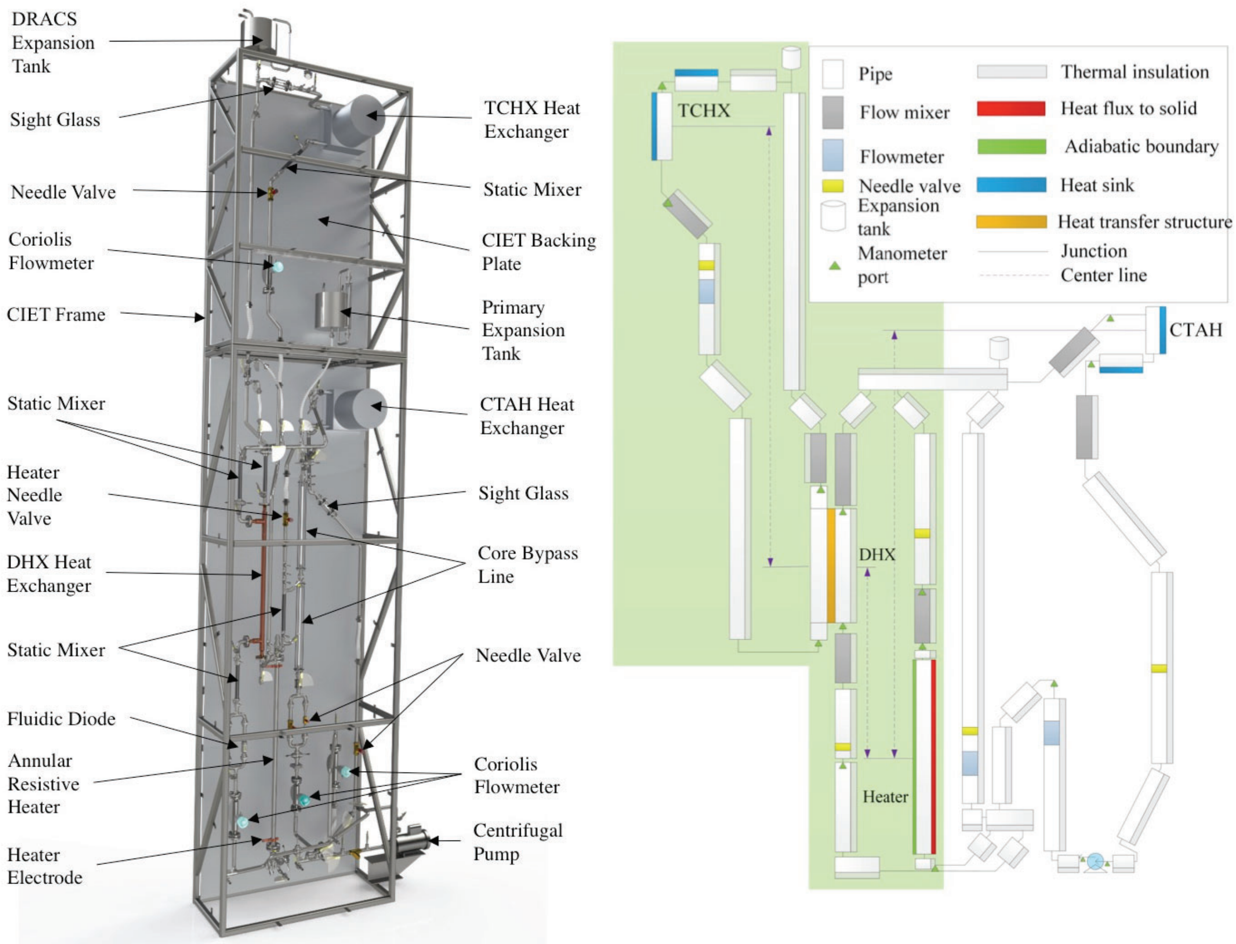


Figure 1. CIET 1.0 3-dimensional model, not showing insulation (left) and corresponding nodalization diagram for the RELAP5-3D and FANCY models (right).

Prior to the V&V effort described here, pressure drops were measured at various flow rates in each branch of the CIET 1.0 loop at room temperature. The flow rate ranges selected for this series of tests covered Reynolds numbers (Re) up to 1,600 in each branch, corresponding to expected regimes during forced and natural circulation operation of CIET 1.0. The goal of these tests was to generate CIET-specific component-scale friction number correlations in the following non-dimensional form, which were subsequently implemented in RELAP5-3D and FANCY:

$$K + f\frac{L}{D} = A + B\mathrm{Re}^{-C} \tag{1}$$

where K is the sum of form losses, f the friction factor, L the component length, D the component hydraulic diameter, and A, B and C empirically-derived coefficients. This series of tests validated the analytical correlation for laminar flow friction factor in straight, cylindrical pipes ($f = 64/\mathrm{Re}$) and its applicability to the CIET 1.0 annular heater, with an agreement within 10% between experimental data and the analytical correlation. Moreover, CIET-specific correlations were derived for static mixers, Coriolis flowmeters and fan-cooled heat exchangers, as listed in Table II. These correlations yield higher friction numbers than vendor-provided charts over the range of Re of interest, therefore confirming the value of performing such tests prior to any V&V effort.

Table II. CIET-specific friction number correlations for static mixers, Coriolis flowmeters and fan-cooled heat exchangers.

Component	Friction Number Correlation
Static Mixer	$K + f\frac{L}{D} = 21 + \frac{4{,}000}{\mathrm{Re}}$
Coriolis Flowmeter	$K + f\frac{L}{D} = 18 + \frac{93{,}000}{\mathrm{Re}^{1.35}}$
Fan-Cooled Heat Exchanger	$K + f\frac{L}{D} = 400 + \frac{52{,}000}{\mathrm{Re}}$

For this study, all calculations are run with RELAP5-3D/Ver. 4.0.3 and FANCY/Ver. 2.0 in transient mode until steady-state conditions are reached for fluid temperatures and mass flow rates in each loop.

3. SOLUTION AND CODE VERIFICATION FOR NATURAL CIRCULATION

Verification is "the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model" [5]. Verification efforts are divided between solution verification, assessing the numerical accuracy of the solution to a computational model, and code verification, assessing the reliability of the software coding. Such efforts are pursued here, to the extent made possible for end users of the executable version of the RELAP5-3D code.

3.1. Solution Verification

For solution verification purposes, sensitivity of the natural circulation mass flow rate to a set of initial and boundary conditions, as well as model discretization, is assessed in RELAP5-3D and FANCY. This sensitivity analysis is performed using models of the DRACS loop with 1 kW heat input. The results are summarized in Table III, where solutions are reported as *not sensitive* to a parameter when they vary by less than 1% for any value of the parameter in the range of interest.

Table III. Sensitivity of natural circulation mass flow rate calculated by RELAP5-3D and FANCY to a set of model parameters.

Model Input Parameter	Parameter Range	Sensitivity
Expansion Tank Temperature [°C]	25 – 185	Not sensitive
Loop Initial Temperature [°C]	25 – 185	Not sensitive
Loop Initial Pressure [kPa]	100 – 200	Not sensitive
Loop Initial Mass Flow Rate [kg/s]	0.01 – 1.0	Not sensitive
Wall Radial Discretization [meshes]	3 – 20	Not sensitive
Hot Leg and Cold Leg Axial Discretization [control volumes]	10 – 50	Not sensitive
Heater and Heat Exchangers Axial Discretization [control volumes]	5 – 55	Not sensitive
TCHX Outlet Temperature [°C]	35 – 70	Sensitive

As expected, the steady-state natural circulation mass flow rate is not sensitive to the expansion tank fixed temperature, since at steady-state, there is no flow going in or out of the tank. It is not sensitive to initial conditions, which should not impact steady-state behavior of the loop. It is not sensitive to radial discretization of the walls, nor to axial discretization of the hot and cold legs, heater and heat exchangers, because temperature distributions are approximately linear. However, the natural circulation mass flow rate is sensitive to the TCHX outlet temperature boundary condition. Indeed, higher temperature boundary conditions lead to a higher average fluid temperature in the loop at steady-state. Because viscosity of the oil decreases at higher temperature, friction losses are reduced, which leads to higher natural circulation mass flow rates. This result is shown in Fig. 2, where mass flow rates in the DRACS loop are obtained with RELAP5-3D for TCHX outlet temperatures in the range of 35-70°C. This confirms the necessity to properly account for the impact of this boundary condition on natural circulation problems solved with RELAP5-3D and FANCY.

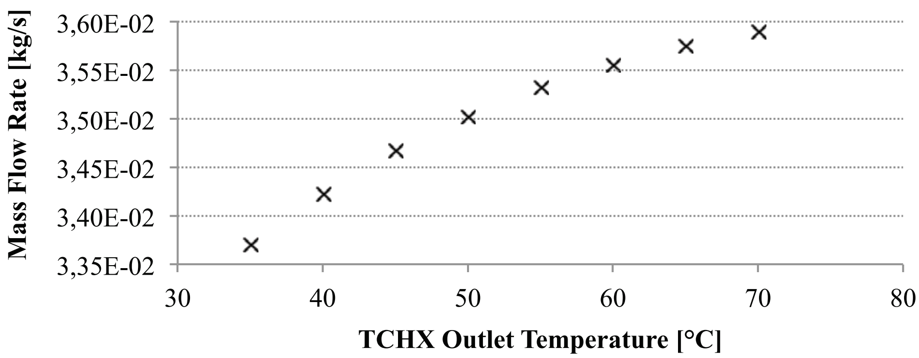


Figure 2. Sensitivity of DRACS natural circulation mass flow rate to TCHX outlet temperature.

3.2. Code Verification

For code verification, the following tests are performed at steady-state:

- Is the heat input to the fluid equal to the sum of the heat removed through the TCHX and parasitic heat losses along the loop?
- Is the mass flow rate uniform in each loop?
- Is the following equation verified in each loop:

$$Q_h = \dot{m} c_{p,av} \Delta T_h \tag{2}$$

where Q_h is the heat input from the heat source (i.e. the heater in the primary loop and the DHX in the DRACS loop), $\dot{m}$ the loop mass flow rate, $c_{p,av}$ the average specific heat capacity of the fluid in the heat source, and ΔT_h the temperature change of the fluid across the heat source. The code results have passed these tests, hence partly verifying proper solving of the fundamental conservation equations.

The CIET 1.0 models in RELAP5-3D and FANCY have therefore been developed to a point where they are only sensitive to relevant physical parameters for our application, such as heat input to the fluid and heat exchanger temperature boundary conditions. The next step of the V&V exercise is model validation.

4. MODEL VALIDATION

Validation is "the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model" [5]. The validation effort is performed here by comparing computational results from RELAP5-3D and FANCY to experimental data from CIET

1.0 for both single loop natural circulation in the DRACS, and coupled natural circulation in the primary loop and the DRACS loop.

4.1. Model Calibration

There is a distinction between model validation and calibration efforts, where validation is an assessment of the model in a "blind" test with experimental data, whereas the key issue in calibration is to adjust the physical modeling parameters to improve agreement with experimental data [5]. For this V&V study, four different sets of natural circulation data were collected on CIET 1.0. The first dataset is used for model calibration, while the three remaining datasets are used for model validation. In this case, the calibration effort consists in correcting for the overall heat transfer coefficient of the DHX and piping thermal insulation. It was observed that default heat transfer coefficient correlations in RELAP5-3D and FANCY systematically underestimate parasitic heat losses in the primary loop by ~75% and in the DRACS loop by ~50%, likely due to additional losses through metallic parts (e.g. TC ports and manometer valves) protruding from the thermal insulation, even after these protrusions were insulated based on image data from an infrared camera. Conversely, default heat transfer coefficient correlations overestimate overall heat transfer coefficient in the DHX by ~45%. These effects are easily corrected by using multiplication factors on heat transfer coefficients in each major section of the coupled loops.

4.2. Model Validation

For model validation, computational results from RELAP5-3D and FANCY are compared to experimental data from CIET 1.0. This is first done for single loop natural circulation in the DRACS, where analytical solutions for mass flow rate in a loop with no parasitic heat losses exist. Then, model validation is performed for coupled natural circulation in the primary loop and the DRACS loop.

4.2.1 DRACS loop natural circulation model validation

Three sets of experimental data have been collected for model validation at various heat input levels and TCHX outlet temperatures. Corresponding boundary conditions have been reproduced in RELAP5-3D and FANCY.

For single-phase natural circulation loops with no parasitic heat losses, Scarlat has derived the following expression from the mass, momentum and energy conservation equations for mass flow rate, based on fluid average thermophysical properties and loop geometry [6]:

$$\dot{m}^3 = \frac{2\rho_{av}{}^2 g\beta_{av}}{c_{p,av}} \cdot \frac{\Delta z_{NC} Q_h}{F'} \tag{3}$$

$$F' = \sum_{i=1}^{N} \left(\frac{1}{A_i{}^2} \cdot \frac{L_i}{D_i}\right) f_i \tag{4}$$

where ρ_{av} is the average density of the fluid, g the gravity constant, β_{av} the average volumetric expansion coefficient of the fluid, Δz_{NC} the buoyancy head, defined as the elevation difference between the centerlines of the heated and cooled sections, A_i the cross-sectional area of section i, L_i the length of section i, D_i the hydraulic diameter of section i, f_i the friction factor in section i, and N the total number of sections in the loop.

Equation 3 is implicit since f_i depends on Re_i, the Reynolds number in section i, which in turns depends on $\dot{m}$ through:

$$Re_i = \frac{1}{\mu_i} \dot{m} \frac{D_i}{A_i} \tag{5}$$

where μ_i is the dynamic viscosity of the fluid in section i. However, using the analytical correlation for laminar flow friction factor in straight, cylindrical pipes ($f = 64/\mathrm{Re}$), Eq. 3 can be solved. This correlation is valid here. Indeed, the DRACS loop always operates in the laminar regime, and it has been measured that friction losses make up to 98% of total losses in the loop, while form losses only contribute to 2% of total losses. Therefore, the analytical solution is expected to be close to the correct solution.

Figure 3 shows the comparison of experimental data, RELAP5-3D and FANCY results, and analytical solutions for various heat inputs and two different TCHX outlet temperatures. Since Eq. 3 uses average fluid thermophysical properties, analytical results are calculated at the average fluid temperatures obtained from RELAP5-3D. All analytical solutions use the following temperature-dependent thermophysical properties for Dowtherm A, based on data in the 20-180°C range [7]:

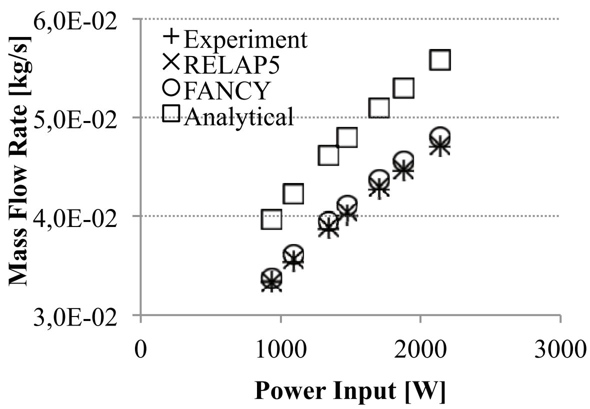
$$\mu = \frac{0.130}{T^{1.072}} \tag{6}$$

$$c_p = 1518 + 2.82 \cdot T \tag{7}$$

$$k = 0.142 - 0.00016 \cdot T \tag{8}$$

$$\rho = 1078 - 0.85 \cdot T \tag{9}$$

where T $[°C]$ is the fluid temperature, μ $[Pa \cdot s]$ the fluid dynamic viscosity, c_p $[J/kg°C]$ the fluid specific heat capacity, k $[W/m°C]$ the fluid thermal conductivity, and ρ $[kg/m^3]$ the fluid density. It has been verified that Dowtherm A thermophysical properties at atmospheric pressure, implemented in RELAP5-3D, lie within ±0.4% of the values obtained with Eq. 6-9 in the 20-180°C temperature range [4]. Moreover, the oil used in CIET 1.0 was sent to the manufacturer for analysis prior to filling the loop.



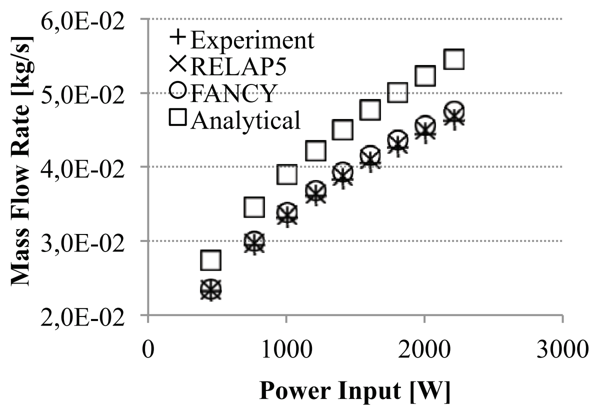


Figure 3. Comparison of experimental, RELAP5-3D, FANCY and analytical natural circulation mass flow rates for various heat inputs and TCHX outlet temperatures of 46°C (left) and 35°C (right).

At all power input levels and TCHX outlet temperatures, the agreement between RELAP5-3D and experimental data is within 1% and the agreement between FANCY and experimental data is within 3%. Figure 3 also shows that analytical solutions overestimate natural circulation mass flow rates in the

DRACS loop by ~18%. Indeed, analytical solutions are only valid for ideal loops with no parasitic heat losses from the hot and cold legs, while for these tests, parasitic heat losses ranging from ~50% at a power input of 450 W to ~5% at a power input of 2,200 W result in reduced natural circulation mass flow rates in the DRACS. The parasitic heat loss effect, typical of scaled IETs with reduced flow area, is properly taken into account by the RELAP5-3D and FANCY models, where properties of the fiberglass thermal insulation and ambient temperatures are included, and overall heat transfer coefficients of piping thermal insulation have been calibrated.

The direct comparisons shown in Fig. 3 are not optimal since a new graph must be generated when experimental boundary conditions are varied. Vijayan proposes a non-dimensional, generalized correlation of the following form for steady flow in a fully laminar or fully turbulent natural circulation loop [8]:

$$Re = C\left[\frac{(Gr_m)_{\Delta z_{NC}}}{N_G}\right]^r \tag{10}$$

$$Re = \frac{D_r \dot{m}}{A_r \mu_{av}} \tag{11}$$

$$(Gr_m)_{\Delta z_{NC}} = \frac{{D_r}^3 {\rho_{av}}^2 \beta_{av} g Q_h \Delta z_{NC}}{A_r {\mu_{av}}^3 c_{p,av}} \tag{12}$$

$$N_G = \frac{L_t}{D_r}\sum_{i=1}^{N}\left(\frac{l_{eff}}{d^{1+b}a^{2-b}}\right)_i \tag{13}$$

where $L_t = \sum_{i=1}^{N} L_i$ is the total length of the loop, $D_r = \frac{1}{L_t}\sum_{i=1}^{N} D_i L_i$ the reference hydraulic diameter of the loop, $A_r = \frac{1}{L_t}\sum_{i=1}^{N} A_i L_i$ the reference flow area of the loop, $d_i = \frac{D_i}{D_r}$ the relative hydraulic diameter of section i, $a_i = \frac{A_i}{A_r}$ the relative flow area of section i, $\left(l_{eff}\right)_i = \left(L_{eff}\right)_i / L_t$ the relative effective length of section i, $\left(L_{eff}\right)_i = L_i + Le_i$ the effective length of section i, and $Le_i = \frac{K_i D_i}{f_i}$ with K_i the sum of form loss coefficients in section i. The correlation is applicable if a friction law of the form $f = \frac{p}{Re^b}$ is valid throughout the loop with the same values of p and b. Then, Vijayan shows that:

$$C = \left(\frac{2}{p}\right)^r \tag{14}$$

$$r = \frac{1}{3-b} \tag{15}$$

For fully laminar flow ($p = 64$, $b = 1$), as in the DRACS loop, $C = 0.1768$ and $r = 0.5$.

Figure 4 shows results of the comparison between RELAP5-3D and FANCY calculations, experimental data, and the correlation proposed by Vijayan (Eq. 10) in the non-dimensional space. Because of the high accuracy of instrumentation used on CIET 1.0, specified in Section 2.1, error bars are included but not visible on Fig. 4, which uses a logarithmic scale to exemplify the linear trend predicted by Eq. 10. Throughout the range of interest, Fig. 4 shows an excellent agreement between RELAP5-3D and FANCY solutions, experimental data, and the correlation proposed by Vijayan with $C = 0.1768$ and $r = 0.5$.

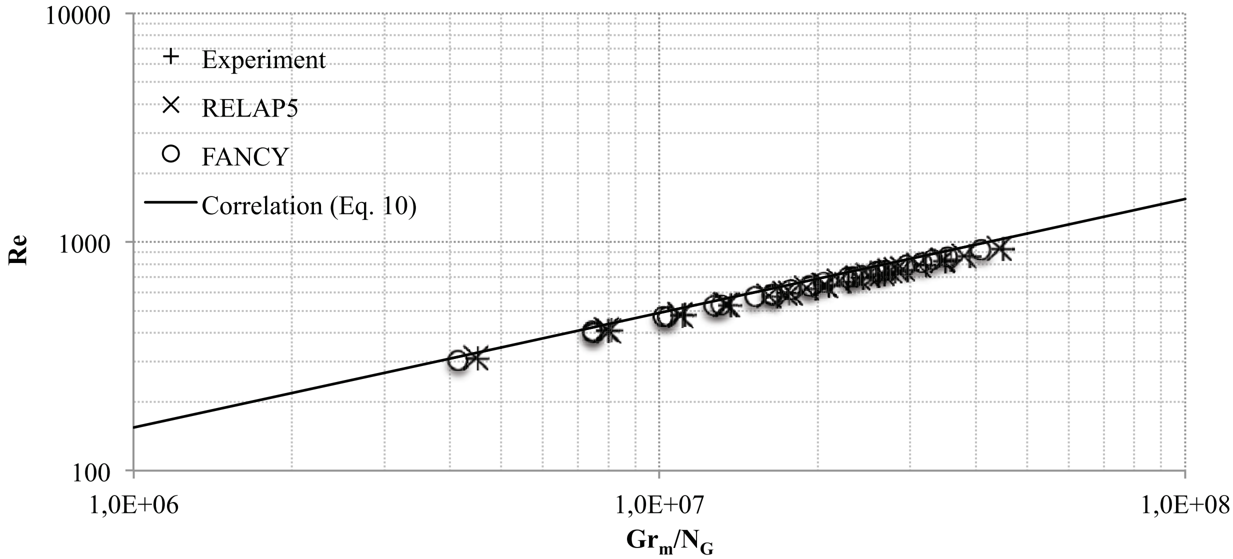


Figure 4. CIET 1.0 experimental data, RELAP5-3D and FANCY natural circulation models.

4.2.2 Coupled loops natural circulation model validation

The same three sets of experimental data are used to validate RELAP5-3D and FANCY models of coupled natural circulation in the primary loop and the DRACS loop. At all power input levels and TCHX outlet temperatures, the agreement between RELAP5-3D and experimental data is within 8% in both loops and the agreement between FANCY and experimental data is within 13% in both loops. Figure 5 and Fig. 6 show results of the comparison between RELAP5-3D and FANCY calculations, experimental data, and the correlation proposed by Vijayan (Eq. 10) in the non-dimensional space for the primary loop and the DRACS loop, respectively. Throughout the ranges of interest, Fig. 5 and Fig. 6 show excellent agreements between RELAP5-3D and FANCY solutions, experimental data, and the correlation proposed by Vijayan with $C = 0.1768$ and $r = 0.5$.

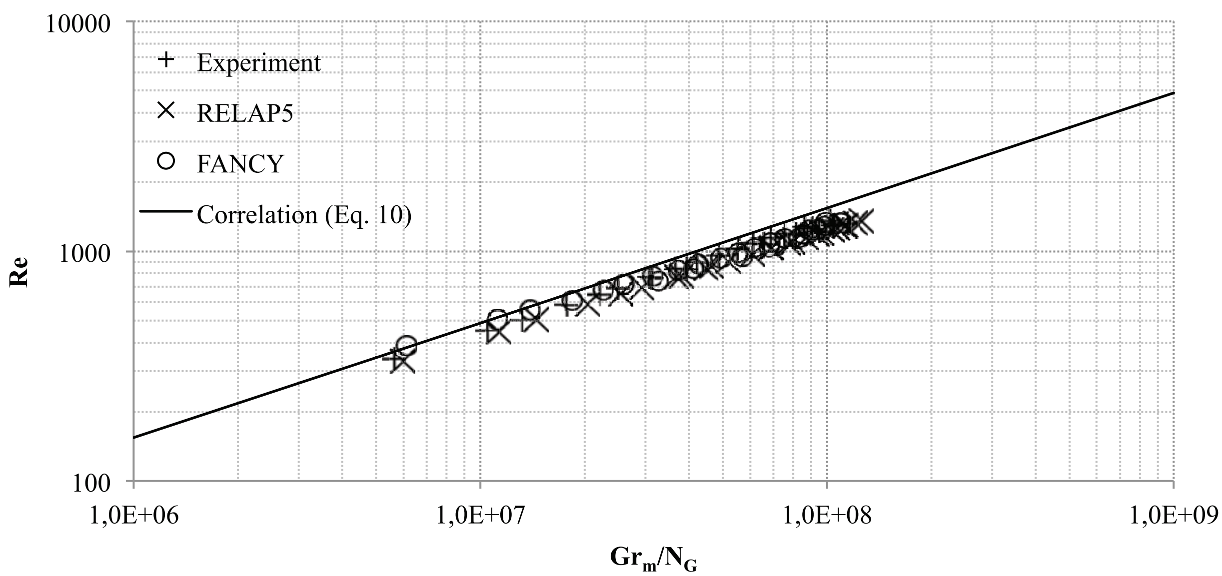


Figure 5. Primary loop experimental data, RELAP5-3D and FANCY natural circulation models.

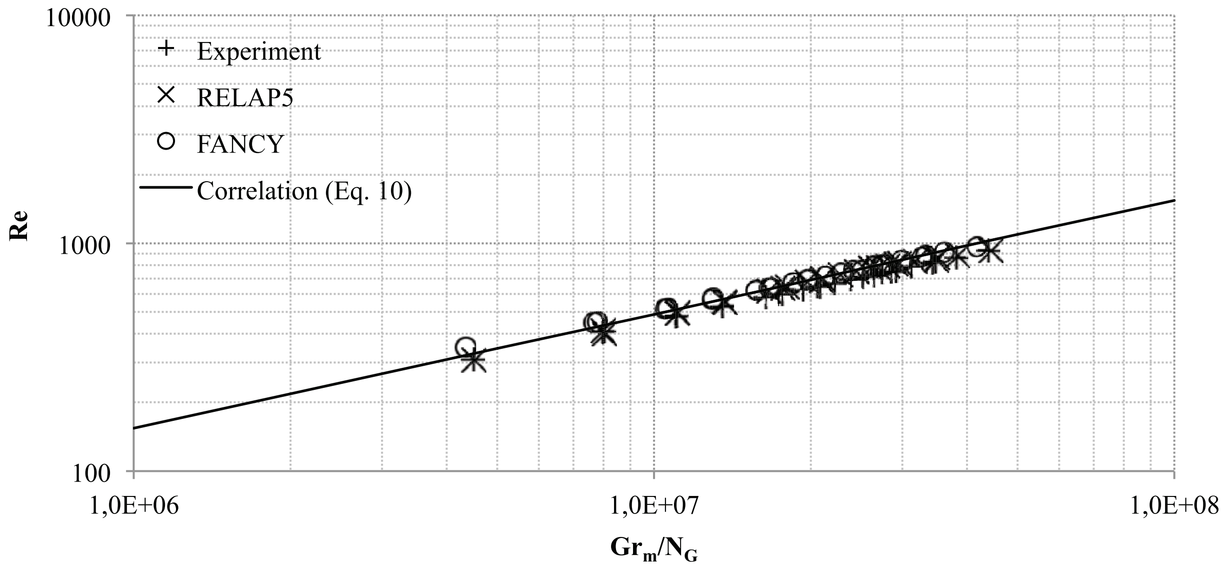


Figure 6. DRACS loop experimental data, RELAP5-3D and FANCY natural circulation models.

4.3. Conclusions of the Validation Effort

For single natural circulation loops, at all power input levels and TCHX outlet temperatures tested for this study, the agreement between RELAP5-3D and experimental data for the loop mass flow is within 1% and the agreement between FANCY and experimental data is within 3%. For coupled natural circulation between the primary loop and the DRACS loop, the agreement between RELAP5-3D and experimental data remains within 8% and the agreement between FANCY and experimental data remains within 13% in both loops. Equation 10 provides a means to properly compare best estimate code solutions to experimental data in the non-dimensional space. This comparison shows an excellent agreement between both code calculations and experimental data in the coupled loops, where flow is in the fully laminar regime. The results also show remarkable agreement with the correlation proposed by Vijayan for steady flow in a fully laminar natural circulation loop, which is the case here.

5. CONCLUSIONS AND FUTURE WORK

This V&V study shows that both RELAP5-3D and FANCY are appropriate tools to model single loop and coupled natural circulation in the primary loop and the DRACS loop of CIET 1.0, as a first step towards predicting the performance of passive decay heat removal systems in FHRs. RELAP5-3D shows agreement within 1% and 8% with experimental data in the DRACS loop alone and coupled loops, respectively, and FANCY shows agreement within 3% and 13% with experimental data in the DRACS loop alone and coupled loops, respectively. This performance remains valid across the whole range of power inputs and temperature boundary conditions investigated for this study, which covers the range of values expected for natural circulation in CIET 1.0.

This study is the first iteration of a series of benchmarking thermal hydraulic exercises in support of FHR technology development. The extensive modularity of the CIET 1.0 facility makes it a test rig of choice for a variety of FHR benchmarking exercises, and future work will involve similar validation efforts using other best estimate codes, as well as comparisons of code results with experimental data from transient tests, including loss of forced cooling and loss of heat sink.

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