RELAP5/MOD3 Code
Quality Assurance Plan
for
ORNL ANS
Narrow Channel
Flow and Heat Transfer
Correlations

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ABSTRACT

This report summarizes modifications to RELAP5 to account for flow and heat transfer in narrow channels between fuel plates such as found in the cores of the Advanced Neutron Source (ANS) and High Flux Isotope Reactor (HFIR) reactors. These models were developed by Oak Ridge National Laboratory (ORNL) and the Idaho National Engineering Laboratory (INEL) and were adapted to and implemented into RELAP5 at INEL. The emphasis of this report is on the verification and validation of these models using the experimental data of Christensen and Marchaterre.

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NOMENCLATURE

(SI units)

ρ	=	density
σ	=	surface tension,
μ	=	viscosity
f	=	friction factor (Darcy)
g	=	gravity
h_{fg}	=	heat of vaporization
k	=	thermal conductivity
$\dot{q}''$	=	heat flux
r_f	=	junction fluid density
r_g	=	junction vapor density
A_{flow}	=	channel flow area
b	=	channel gap
C_p	=	specific heat
D	=	hydraulic diameter
H	=	height
Nu	=	Nusselt number $\frac{hD}{k}$
Pr	=	Prandtl number $\frac{\mu C_p}{k}$
Re	=	Reynolds number $\frac{\rho V D}{\mu}$
s	=	channel span
T	=	temperature
V	=	velocity
V_{gj}	=	vapor drift velocity

Subscripts

b	=	bulk
f	=	saturated liquid
g	=	saturated vapor
s	=	saturation
w	=	wall
ws	=	wall but not exceeding saturation

RELAP5/MOD3 Code Quality Assurance Plan for ORNL ANS Narrow Channel Flow and Heat Transfer Correlations

1 Introduction

Modifications have been made to RELAP5 to account for flow and heat transfer in narrow channels between fuel plates such as found in the cores of the Advanced Neutron Source (ANS) and High Flux Isotope Reactor (HFIR) reactors. These early models were supplied by Art Ruggles of Oak Ridge National Laboratory (ORNL) and Don Fletcher of the Idaho National Engineering Laboratory (INEL) and were adapted to and implemented into RELAP5 by Rich Riemke, Rex Shumway and Ken Katsma.

The purpose of this report is to document the current status of these special models in the standard version of RELAP5/MOD3 and describe the quality assurance procedures.

The model additions were described in the previous report but are repeated here to show what changes have been made and to document the current model forms. The remainder of the report describes the quality assurance (QA) verification and validation.

2 Models

Models and suggestions for models were supplied by ORNL to account for interphase friction flow and heat transfer effects in vertical narrow channels between fuel plates.

2.1 Flow Model Status

The interphase friction in bubbly and slug flow regimes depends heavily on a profile slip distribution factor, C_o , and the vapor drift velocity, V_{gj} . These variables are determined using the Griffith drift flux correlation^{1,2}. The vapor drift velocity, V_{gj} , has the form:

$$V_{gj} = (0.23 + 0.13 \times \frac{b}{s}) \sqrt{((r_b - r_g) \times g \times s / r_b)} \quad (1)$$

The profile slip distribution factor, C_o , is given by:

$$Co = 1.35 - 0.35 \times \sqrt{\frac{r_g}{r_b}} \quad (2)$$

The liquid density in the denominator of equation (1) was previously incorrectly given as a vapor density. This discrepancy was uncovered by ORNL and is corrected in the current version.

2.2 Heat Transfer Model Status

Models were provided for the heat transfer correlation for single phase liquid forced convection and modifications to the critical heat flux correlation. For single phase liquid forced convection in narrow channels, the Petukhov correlation is used. The Petukhov³ correlation has the form:

$$Nu_D = \frac{\left(\frac{f}{8} \times Re_b \times Pr\right) \times \left(\frac{\mu_b}{\mu_{ws}}\right)^{0.11}}{(1. + 3.4f) + \left(11.7 + \frac{1.8}{Pr_b^{\frac{1}{3}}}\right) \times \left(\frac{f}{8}\right)^{0.5} \times \left(Pr_b^{\frac{2}{3}} - 1.0\right)} \quad (3)$$

The numerator of the Filonenko⁴ correlation has been changed such that for flow in a rectangular channel the friction factor is:

$$f = \frac{1.0875 - 0.1125 \left(\frac{b}{s}\right)}{(1.82 \log_{10} Re_b - 1.64)^2} \quad (4)$$

where

f= friction factor (Darcy)

Re_b= Reynolds number based on bulk conditions

b= channel gap

s= channel span

For non-rectangular channels, when the channel span, s, is input as zero, the numerator of Equation 4 is protected by setting its value to one.

Note that a term previously in equation (3) involving the ratio of heated diameter to heated length has been removed upon the recommendation of ORNL. This was a modeling choice rather than a programing error.

The normal RELAP5 critical heat flux (CHF) calculation using the Groeneveld⁵ correlation was modified for plate type fuel adjacent to narrow channels by adding the Gambill/Weatherhead model. This model^{6,7} makes use of the following equations:

$$\dot{q}''_{CHF} = \dot{q}''_{POOL} + \dot{q}''_{CONV} \quad (5)$$

$$\dot{q}''_{POOL} = 0.18 h_{fg} \rho_v \times \left(\sigma g \times \frac{\Delta \rho}{\rho_v^2} \right)^{0.25} \times \left(1. + \left(\left(\frac{\rho_l}{\rho_v} \right)^{0.75} \times C_p \left(\frac{T_{sat} - T_b}{9.8 h_{fg}} \right) \right) \right) \quad (6)$$

$$\dot{q}''_{CONV} = \frac{\frac{k}{D} \times \frac{f}{8} \times Re Pr \left(\frac{\mu_b}{\mu_{ws}} \right)^{0.11}}{(1. + 3.4f) + \left(11.7 + \frac{1.8}{Pr^{\frac{1}{3}}} \right) \times \left(\frac{f}{8} \right)^{0.5} \times \left(Pr^{\frac{2}{3}} - 1.0 \right)} \times (T_w - T_b) \quad (7)$$

$$f = \frac{1.0875 - 0.1125 \left(\frac{b}{s} \right)}{(1.82 \log_{10} Re_b - 1.64)^2} \quad (8)$$

$$T_w = (47.7 - 0.127 \times (T_{sat} - 273.16)) \times \left(\frac{\dot{q}''_{CHF}}{3154.6} \right)^{0.25} + T_{sat} \quad (9)$$

Again, note that in equation (6) a term involving the ratio of heated diameter to heated length has been removed upon the recommendation of ORNL. This again was a modeling choice rather than a programing error

The set of equations (5) through (9), is solved iteratively for Gambill CHF if the mass flux is greater than 7500 kg/m²-s. For mass flux between 7500 and 10000 kg/m²-s, a linear interpolation for CHF based on flow is made between the Gambill model and the normal RELAP5 CHF model. If the mass flux is less than 7500, the

normal RELAP5 CHF calculation is used, and if the mass flux is greater than 10000, the Gambill CHF is used.

The ORNL data base and Gambill-Weatherhead correlation are designed to be used under subcooled conditions. Therefore, ORNL decided to have RELAP5 print a warning message when the subcooling is less than 8 degrees Kelvin. The message says "Blue Flag from CHF CAL Subroutine" and the value of the subcooling and mass flux are printed. If the quality is positive, the message says "Red Flag from CHF CAL Subroutine" and the value of the quality and mass flux are printed⁸

Figure 1 demonstrates the regions where warning messages appear. The highest mass flux in the Groeneveld table is 7500 kg/s-m². Between 7500 and 10,000 linear interpolation is used between the Groeneveld and the Gambill-Weatherhead correlation.

3 Verification

Verification is defined as the process that demonstrates that the software correctly performs its intended function. A simplification of this is:- "Was the model or correlation programed into RELAP5 correctly?"

Verification in RELAP5 is handled by an independent line-by-line check of modified portions of modified subroutines. This is generally done by one of the code developers or someone familiar with the specific part of the coding.

Simple problems are also run to check input, output and whether the modified code portion is functioning as intended.

3.1 Verification for Flow Models

The flow model modification for ANS consisted of adding the Griffith drift flux correlation to select a relative velocity between vapor and liquid and a consistent shape factor that goes into the interfacial drag model. The coding to determine the drift velocity and distribution factor was added as a new subroutine, GRIFTJ. The coding to set up the call to GRIFTJ and the logic to determine when to execute that call was added to subroutine FIDISJ.

Coding was added in input subroutines RPIPE, RBRNCH and RSNGLV to allow flags to be set so that the Griffith drift flux contribution to interfacial drag will be used with pipe, branch or single volume components

Simple problems using these components while RELAP5 was run with a DEC window debugger, DXDB, showed that the flag concept worked correctly, the logic in FIDISJ correctly called GRIFTJ, and the drift velocity and distribution factor were returned.

Subsequently, more complex problems run at ORNL showed that a variable argument used as a pointer was wrong in FIDISJ. Also, an inspection of the coding at ORNL of the Griffith drift flux model showed that a wrong density was being used in one place. When these errors were corrected, the code performed satisfactorily.

A final line-by-line reading of the modified portions of FIDISJ, RPIPE, RBRNCH, RSNGLV and of the whole of GRIFTJ was made.

3.2 Verification for Heat Transfer Models

The heat transfer model modification for ANS consisted of adding the Petukhov forced convection correlation and the Gambill-Weatherhead critical heat flux (CHF) correlation. The coding for the Petukhov correlation was added as a new subroutine, PETUKV. The coding to set up the call to PETUKV and the logic to determine when to execute that call was added to subroutine HTRC1. The CHF subroutine, CHFCAL, was modified to add the Gambill-Weatherhead correlation.

Coding was added in input subroutine IHTCMP to allow flags to be set so that the Petukhov correlation and the Gambill-Weatherhead CHF models can be selected for heat structures representing ANS type plate fuel.

Simple problems using these components while RELAP5 was run with a DEC window debugger, DXDB, showed that the flag concept worked correctly, the logic in HTRC1 correctly called PETUKV, and the heat transfer coefficient was returned.

Similar simple problems, run with the window debugger, showed that the flag also sent the code through the Gambill-Weatherhead correlation logic in subroutine CHFCAL.

The CHFCAL coding has undergone a close inspection at INEL and ORNL and some modifications have been made to the interpolations between the original RELAP5/MOD3 Groeneveld CHF correlation and Gambill-Weatherhead and also to add warning messages when the fluid state is such that the correlations may be being used in a manner unsupported by data.

A final line by line reading of the modified portions of CHFCAL, HTRC1, IHTCMP, and of the whole of PETUKV was made.

4 Validation

Validation is defined as the process that demonstrates that algorithms and mathematical models embodied in the software are an acceptable representation of the phenomena, processes, and/or systems for which it is intended. In simpler terms: "Was the correct correlation selected to model ANS with RELAP5?"

A formal validation of the physics and "first principles" of the new models in the code, or test of whether the correct models were chosen for the intended use, has not

been done. It was assumed that the correct models were selected by Ruggles of ORNL and Fletcher of INEL.

For the RELAP5 code, validation has been shown by running a range of sample calculations that simulate actual experiments with good data. These range from simple separate effects experiments to test individual models or correlations to complex integral tests to test the interrelationships between models.

4.1 Validation for Flow Model

The validation of the Griffith drift flux model working within the existing interfacial drag model was made with data from Christensen⁹ and Marchaterre¹⁰. The Christensen experiment was an electrically-heated, rectangular cross section, 1.11 by 4.44 by 127 cm, tube for obtaining subcooled boiling data. The Marchaterre experiment was again a electrically heated, rectangular cross section for natural and forced convection boiling. It used two test configurations, .635 by 5.08 and 1.27 by 5.08 cm. cross sections Both were 152.4 cm. long. All of the data for all of these tests were for light water only. It is realized that the geometry and the working fluid aren't exactly that of the ANS reactor design, but data from these experiments are the best currently available to us.

RELAP5 runs, using the ANS models, simulating the Christensen experiment are reported in section 4.1.1 while those simulating the Marchaterre experiments with the narrowest cross section are reported in section 4.2.1.

4.1.1 Christensen Experiment Simulations

The Christensen subcooled nucleate boiling experiment has been used for assessment of the interphase mass transfer, interphase friction and wall heat flux partitioning models. The test section was, as mentioned above, a rectangular channel, 1.11 by 4.44 by 127 cm. The channel was heated by passing ac current through the tube walls. The void fraction along the channel was measured by a gamma densitometer.

The test section was simulated for RELAP5 as a 20 cell pipe with time dependent source and sink volumes at the bottom and top. A heat structure was provided for each cell of the test section to model the heat addition. Test conditions for test 15 are given in **TABLE 1**.

A comparison of the RELAP5/MOD3 ANS model axial void fractions with measured data from Christensen test 15 is shown in **Figure 2**. The calculated void fraction up the test section is slightly under-predicted for this test.

4.2 Validation for Heat Transfer Models

The Petukhov forced convection heat transfer coefficient was validated by comparing it with a calculation which used the DITTUS subroutine instead of the PETUKV subroutine. This was done by taking a Marchaterre input deck and increasing the flow by a factor of 10 and running the deck in both the PETUKV and DITTUS mode by changing the 501 heat structure card. The ratio of the heat transfer coefficient axial variation is shown in **Figure 3**. The Petukhov correlation gave results slightly larger than the Dittus-Boelter correlation for these particular conditions.

The validation of the Gambill-Weatherhead CHF model and its interpolated use with the current Groeneveld CHF model has been done by Rex Shumway^{8,11}. He ran a driver program to exercise the CHF subroutine from RELAP5 with the ANS changes included in it. These runs compared the ANS model, Gambill-Weatherhead interpolated with Groeneveld, to an ORNL data base. This data base included heavy water.

4.2.1 Marchaterre Experiment Simulations

The Marchaterre experiment has been used for assessment of the interphase mass transfer, interphase friction and wall heat flux partitioning models. The test section was, as mentioned above, a rectangular channel, 1/4 by 2 by 60 inches. The channel was heated by passing ac current through the channel walls. The void fraction along the channel was measured by a gamma densitometer.

The test section was simulated for RELAP5 as a 20-cell pipe with time dependent source and sink volumes at the bottom and top. A heat structure was provided for each cell of the test section to model the heat addition. Experiment characteristics and operating parameters for six tests are given in **TABLE 2** and **TABLE 3**.

Results for the six test calculations, seen in **Figure 4** through **Figure 9**, show that calculated axial void profile is slightly under-predicted for first part of the channel and slightly over-predicted at the channel end. RELAP5 tends to under predict more at the lower pressures. In general, the agreement is better in the midsection of the channel. The axial location where the fluid temperature is calculated by RELAP5 to reach the saturation temperature is marked on the figures.

4.2.2 CHF Comparisons

ORNL sent 1274 sets of measured data to INEL. The ratio of the measured critical heat flux to the predicted heat flux from the "driver" program is shown in **Figure 10** through **Figure 12** for varying mass flux, quality and pressure, respectively. The "driver" program is a FORTRAN main program which reads a file containing the geometry and heat transfer parameters for each data point. The driver makes "calls" to the RELAP5 heat transfer subroutines to obtain the predicted CHF. The largest errors occur in the data points taken at a mass flux of 20,000 kg/s-m² over a wide range of quality at a pressure of 3.254 MPa. An electronic copy of the results has been transmitted to ORNL for statistical analyses.

A RELAP5/MOD3 input deck was developed which modeled the CHF test section and conditions. Simulation of only a few of the CHF data points was performed. The results of these runs are shown in **TABLE 4**.

Differences were noticed between the "driver" CHF results and those from RELAP5. The difference was traced to the surface tension in the pool boiling part of the Gambill correlation. The "driver" evaluated the surface tension at the bulk fluid temperature and RELAP5 used the saturation temperature. Both methods evaluated the liquid and gas density and liquid specific heat at the bulk temperature. After consulting with ORNL it was concluded that the proper method is to evaluate the specific heat at the average of the bulk and saturation temperature and evaluate the remaining properties at the bulk temperature. This property change resulted in a only a small change in the results.

5 Summary

The current status of the ORNL ANS changes to RELAP5/MOD3 version 7AC are reviewed in this report.

The changes for ORNL ANS narrow channel flow and heat transfer that modify RELAP5/MOD3 Version 7AC were verified by: (1) a hand check of the coding to verify that the equations shown previously were correctly implemented; and (2) running the test problems mentioned in the previous section to assure that the options function in the manner intended.

A formal validation of the physics and "first principles" of the new models in the code, or test of whether the correct models were chosen for the intended use, has not been performed. It was assumed that the correct models were selected by Ruggles of ORNL and Fletcher of INEL.

A validation of the performance of the flow models against data has been performed to compare the models with data for narrow channel and plate type heat structures. A simulation of subcooled boiling tests of Christensen was done and simulations of natural and forced convection boiling tests of Marchaterre were also performed.

The Petuhkov forced convection heat transfer coefficient was compared with output from the DITTUS subroutine.

A CHF validation check of the Gambell/Weatherhead and interpolation with Groeneveld was made by Rex Shumway of INEL. Shumway did a comparison of ORNL CHF data with of calculations with both the normal Groeneveld CHF model and the new CHF subroutine using Groeneveld, Gambill/Weatherhead or the interpolation between them. This has been reported^{6,9} in letter reports.

The Version 7AC of RELAP5/MOD3, used for this study, is maintained under EG&G configuration control. The official master source is in UPDATE form on the INEL Cray. The same source in non-UPDATE form is stored on the code architect's workstation. The single source is used for installation on a wide range of platforms. This is done by means of a installation script which calls several preprocessors that modify the installation and parts of the source to make the code compatible with the target computer or workstation.

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- 11 Rex Shumway(INEL), letter report to Moshe Siman-Tov of ORNL, dated 2/92.

TABLE 1 Christensen Test 15

Parameter	Value
Pressure	5.512 MPa
Mass Flux	907.3 kg/s-m ²
Inlet Subcooling	12.5 Deg. K.
Heat Flux	0.65 MW/m ²

TABLE 2 Marchaterre Test Section Characteristics

Parameter	Value
Flow Channel	0.00635 x 0.0508 x 1.524 m
Wall Thickness	0.00254 m
20 vertical RELAP5 cells	each 0.0762 m
Flow Area	3.2256e-4 m ²
Hydraulic Dia.	4.4089e-5 m
Heat Trans. Area Total	0.17422 m ²
Heat Trans. Area per Cell	8.7115e-3 m ²
Metal Volume Total	5.2070e-3 m ³

TABLE 3 Marchaterre Test Parameters

Run	Press.	Subcooling	Velocity	Power Density	Heat Flux
	MPa	Deg. K.	m/s	kW/liter	kW/m ²
155	1.124	6.94	0.9418	56.6	143.76
165	4.221	12.06	1.0363	84.9	215.65
194	2.848	9.33	0.9997	65.8	167.16
237	1.821	9.22	0.9053	66.1	167.95
296	4.230	6.64	1.8105	75.14	190.89
316	1.127	9.74	0.5700	47.03	119.46

TABLE 4 CHF Comparisons with ORNL Database

Run	Pressure	Mass Flux	Quality	Q measured	Q driver	Q RELAP5
	MPa.	kg/m ² -s		MW/m ² -s	MW/m ² -s	MW/m ² -s
1	0.38349	1.0443e4	-0.154	16.2966	12.537	12.476
2	0.38319	1.0512e4	-0.163	16.4102	12.979	12.907
4	3.79212	1.1509e4	-0.0549	13.6909	10.241	10.297
5	3.90743	0.7791e4	-0.082	9.5900	11.872	11.879
25	0.34819	0.5614e4	-0.143	7.6657	5.2180	5.3140
184	0.44609	0.4424e4	-0.079	6.3029	5.6460	5.6350
188	0.44609	0.8819e4	-0.059	7.0978	6.8720	6.6940

Figure 1 Illustration of zones where warning Flags are printed

Christensen Test 15

Figure 2 Christensen Test 15 Void Profile

Forced Convection Comparison

$P=1.2$ MPa, $G=2718$ kg/m²-s, Qual=0

Figure 3 Comparison of PETUKV and DITTUS

Marchaterre Test 155

Figure 4 Marchaterre Test 155 Void Profile

Marchaterre Test 165

RELAP5 vs Data

Figure 5 Marchaterre Test 165 Void Profile

Marchaterre Test 194

Figure 6 Marchaterre Test 194 Void Profile

Marchaterre Test 237

RELAP5 vs Data

Figure 7 Marchaterre Test 237 Void Profile

Marchaterre Test 296

RELAP5 vs Data

Figure 8 Marchaterre Test 296 Void Profile

Marchaterre Test 316

RELAP5 vs Data

Figure 9 Marchaterre Test 316 Void Profile

ORNL CHF Comparison With Data

new; Filonenko, Petukhov, Props

Figure 10 Critical Heat Flux Ratio vs. Mass Flux

Figure 11 Critical Heat Flux Ratio vs. Quality

ORNL CHF Comparison With Data

new; Filonenko, Petukhov, Props

Figure 12 Critical Heat Flux Ratio vs. Pressure

END

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