RERTR 2008 — 30th INTERNATIONAL MEETING ON REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

October 5-9, 2008
Hamilton Crowne Plaza Hotel
Washington, D.C. USA

NATURAL CIRCULATION FLOW RATE CALCULATION IN PLTEMP/ANL CODE

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ABSTRACT

PLTEMP/ANL is a single-phase thermal-hydraulic code used for the analysis of research reactors having fuel assemblies made of multiple fuel plates/tubes, with a coolant channel between each pair of fuel plates/tubes. A Bernoulli equation-based method of calculating natural circulation flow, up through the fuel assemblies and down through the flow area in the reactor pool/vessel outside the fuel assemblies, was recently implemented and verified in the PLTEMP/ANL V3.5 code. This paper describes the flow circuit modeled, the solution method, and the code verification. The method accounts for (i) the channel-to-channel variation of coolant temperature profiles in a fuel assembly, and (ii) the axial variation of coolant temperature, density, viscosity, Reynolds number, friction factor. The code was verified by comparing its solution to a natural circulation test problem with solutions obtained by hand calculation, the *Mathematica*, the NATCON code, and the RELAP5-3D code.

1. Introduction

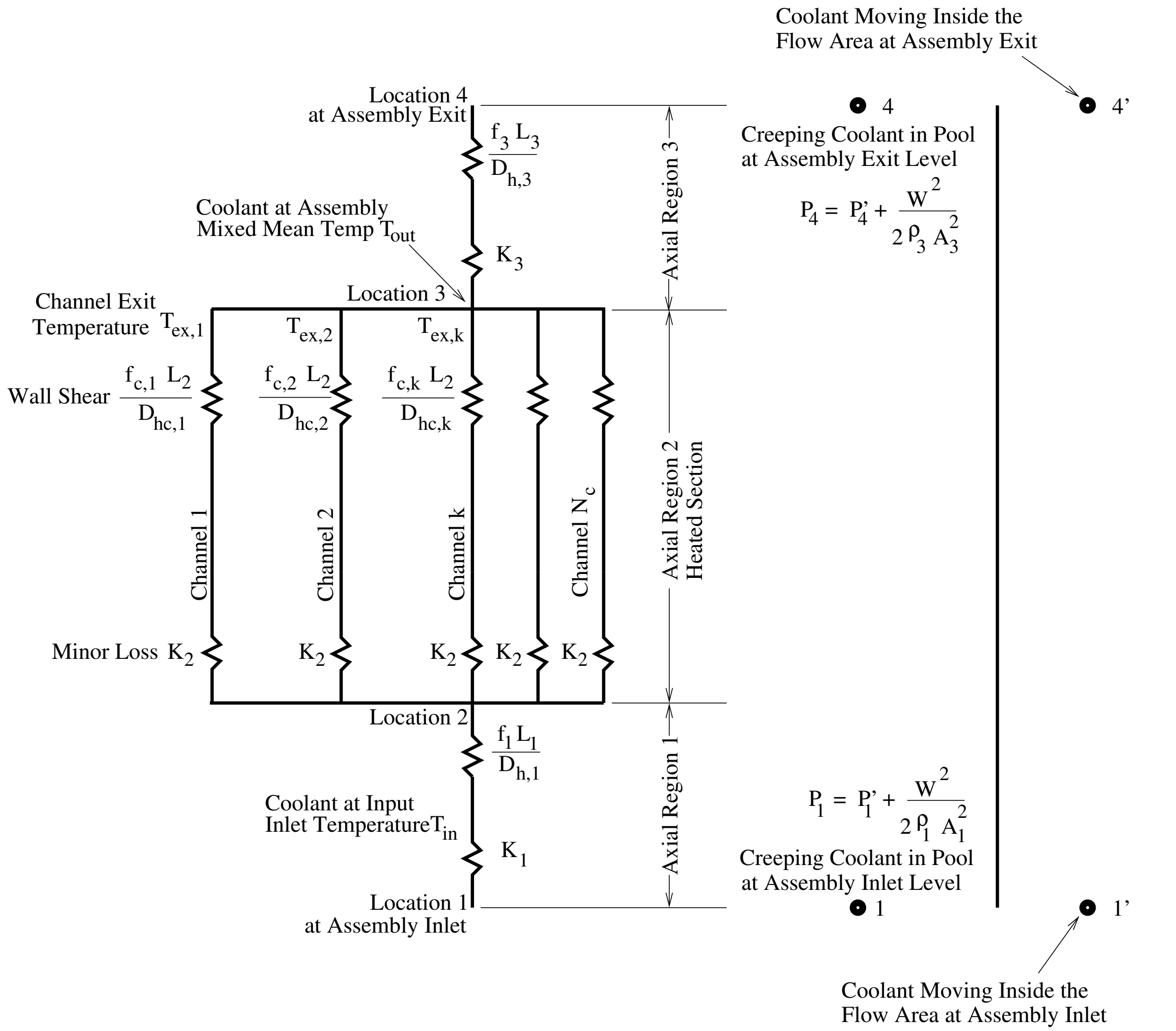
Some research reactors are cooled during steady-state operation by the natural circulation of the coolant (water), without a pump forcing the coolant flow. The coolant flows up through the fuel assemblies due to buoyancy, and down through the flow area in the reactor pool/vessel outside the fuel assemblies. The flow area outside the fuel assemblies is usually large, and the *frictional* pressure drop in the down-flow part of the flow circuit can be ignored. The bypass assemblies (that do not generate any power) play a minor role of simply providing an additional path of downward coolant flow. A method of calculating the flow rate in this circuit was implemented in the PLTEMP/ANL V3.5 code [1].

PLTEMP/ANL V3.5 accounts for the effect of the shape of fuel plate power axial distribution. In computing the buoyancy head and frictional pressure drop, the code accounts for (i) the channel-to-channel variation of coolant temperature profiles, and (ii) the axial variation of coolant temperature, density, viscosity, Reynolds number, and friction factor.

The NATCON code [2] is capable of doing a similar calculation for a single coolant channel in a fuel assembly. When using NATCON, one selects the hottest coolant channel in the reactor core, and then *assumes that half* of the power generated by the two fuel plates that are adjacent to the selected hottest channel goes into the channel. This assumption is avoided when using PLTEMP/ANL to calculate the natural circulation flow rate in a fuel assembly because it determines (i) the coolant temperature profiles in all coolant channels of a fuel assembly, and (ii) the fraction of each fuel plate power that goes into an adjacent coolant channel by a multi-fuel-plate heat transfer calculation.

2. Hydraulic Equations for Modeling Natural Circulation

The hydraulic equations used to calculate the natural circulation flow rate in a fuel assembly are derived based on the modified Bernoulli equation in Shames [3]. Figure 1 shows the coolant flow paths and flow resistances in a fuel assembly as modeled in PLTEMP/ANL. Each fuel assembly consists of an unheated axial region (axial region 1) below the heated length (region 2) consisting of multiple parallel coolant channels, above which are several unheated axial regions (regions 3 to $N_f - 2$). In Fig. 1, point 1' is located inside the flow area at the assembly inlet; point 2 is located in axial region 1 *just before the inlet* to the heated length and is common to all coolant channels of the assembly; point 3 is located in axial region 3 *just after the exit* from the heated length and is common to all coolant channels; and point 4' is located inside the flow area at the assembly exit.



(i) **(ii)**

Fig. 1. Fuel Assembly Model in PLTEMP/ANL: (i) Coolant Flow Path, (ii) Details of Coolant Pressure at the Fuel Assembly Inlet and Outlet

The modified Bernoulli equation between points 2 and 3 in Fig. 1, for the flow path passing through the coolant channel k, can be written as:

$$P_2+\frac{W^2}{2\rho_1 A_1^2}=P_3+\frac{W^2}{2\rho_3 A_3^2}+g\int_{\text{Channel k}}\rho_{c,k}(z)\,dz+\frac{K_2\,W_{c,k}^{\;2}}{2\,\overline{\rho_{c,k}}\,A_{c,k}^2}+\frac{W_{c,k}^{\;2}}{2\,D_{hc,k}\,A_{c,k}^2}\int_{\text{Channel k}}\frac{f_{c,k}\,dz}{\rho_{c,k}(z)} \qquad (1)$$

All symbols are defined in the nomenclature at the end. In Eq. (1), the second term on the left hand side is the velocity head at point 2, and the second term on the right hand side is the velocity head at point 3. The third, fourth, and fifth terms on the right hand side of Eq. (1) are the gravity head, the minor loss, and the pressure drop due to wall shear for the k^{th} coolant channel. The gravity head is found by integrating the coolant density over the channel height because the density varies with coolant temperature in the channel. The gravity head varies from channel to channel in a fuel assembly (because the coolant temperature profile varies from channel to channel). The channel-to-channel variation of gravity head must be included in the model in order to account for the channel-to-channel variation of the natural circulation flow rate, since the gravity head determines the buoyancy head which drives the natural circulation.

The mean coolant density of the channel, $\overline{\rho_{c,k}} = [\rho_1 + \rho(T_{ex,k})]/2$, is used in the minor loss term because the coefficient K_2 for the channel is the sum of losses at the channel entrance and exit. The frictional pressure drop due to wall shear is calculated by integration over the channel length because the coolant (water) viscosity, density, Reynolds number, and Moody friction factor all vary with temperature. The dependence of the friction factor on flow regime (laminar, transition, or turbulent), and on the aspect ratio of channel cross section in laminar flow [4], is accounted for in the method.

Collecting the channel-independent terms in Eq. (1) on the left hand side, we get Eq. (2) for any coolant channel k (k = 1, 2, 3 … N_c) in the heated length of the fuel assembly.

$$P_2 - P_3 + \frac{W^2}{2\,\rho_1\,A_1^2} - \frac{W^2}{2\,\rho_3\,A_3^2} = g \int_{\text{Channel k}} \rho_{c,k}(z)\,dz + \frac{K_2\,W_{c,k}^{\;\;2}}{2\,\overline{\rho_{c,k}}\,A_{c,k}^2} + \frac{W_{c,k}^{\;\;2}}{2\,D_{hc,k}\,A_{c,k}^2} \int_{\text{Channel k}} \frac{f_{c,k}\,dz}{\rho_{c,k}(z)} \qquad (2)$$

Equation set (2) shows that the sum of the gravity head and the frictional pressure drop due to minor loss and wall shear is the same for each coolant channel. The frictional pressure drop alone is *not the same* for each channel. Equation (2) is a set of equations for the channel flow rates $W_{c,k}$. The assembly flow rate W is the sum of all the channel flow rates $W_{c,k}$ in the heated length.

$$W = \sum_{k=1}^{N_c} W_{c,k} \qquad (3)$$

In steady-state natural circulation, the difference between the absolute pressures at points 1 and 4 equals the static head of the coolant in the pool. This assumes that the frictional pressure drop due to the creeping flow of coolant in the pool is negligible, and that the coolant temperature in the pool is uniformly equal to the inlet temperature over the assembly height.

$$P_1 - P_4 = g\rho_1 (L_1 + L_2 + L_3) \qquad (4)$$

It is assumed that the velocity head exiting from the assembly is fully converted into pressure head. If the reactor analyst believes that the exiting velocity head is lost (converted into heat), then the analyst should increase the minor loss coefficient K_3 by 1.0, to account for it with the minor loss in axial region 3. The Bernoulli equation between points 1 and 2 can be written as Eq. (5), and the Bernoulli equation between points 3 and 4 (see Fig. 1) can be written as Eq. (6).

$$P_2 = P_1 - \frac{W^2}{2\,\rho_1\,A_1^2} - g\,\rho_1\,L_1 - \left(K_1 + \frac{f_1\,L_1}{D_{h,1}}\right)\frac{W^2}{2\,\rho_1\,A_1^2} \qquad (5)$$

$$P_3 = P_4 - \frac{W^2}{2\,\rho_3\,A_3^2} + g\,\rho_3\,L_3 + \left(K_3 + \frac{f_3\,L_3}{D_{h,3}}\right)\frac{W^2}{2\,\rho_3\,A_3^2} \qquad (6)$$

Collectively, Eqs. (2) to (6) are a set of N_c+4 simultaneous equations in N_c+4 unknown variables P_2, P_3, P_4, W, and $W_{c,k}$. The following solution strategy is used to solve these equations to find the flow rates.

3. Solution Strategy to Find Natural Circulation Flow Rates

The solution strategy uses (i) inner iterations performed *at a fixed set of coolant channel temperature profiles*, to find a consistent set of channel flow rates $W_{c,k}$ and assembly flow rate W that satisfy Eqs. (2) to (6), and (ii) outer iterations in which a *new multi-fuel-plate heat transfer calculation* is done using the consistent set of channel flow rates $W_{c,k}$ last found. After each heat transfer calculation, the inner iterations are performed again, using a new set of coolant channel temperature profiles, obtaining another consistent set of channel flow rates $W_{c,k}$ and assembly flow rate W. The problem is solved when the consistent set of channel flow rates and assembly flow rate change by a negligible amount, from an outer iteration to the next.

In order to assure convergence, only a fraction ε (e.g., 0.6) of the coolant temperature change from the previous outer iteration is used to find the temperature-dependent coolant properties and friction factor during the inner iterations. The coolant properties and friction factor are evaluated at the temperature $T_{c,k,used}(z)$ defined by Eq. (7) and used to calculate the integrals in Eq. (2) for each channel. In Eq. (7), L is outer iteration counter, and $T_{c,k,L}(z)$ is coolant temperature profile calculated *just before* outer iteration L. Equation (2) is then solved to find the channel flow rate $W_{c,k}$, as shown by Eq. (8).

$$T_{c,k,used}(z) = T_{c,k,L-1}(z) + \varepsilon\left[T_{c,k,L}(z) - T_{c,k,L-1}(z)\right] \tag{7}$$

$$I_{g,k} = g \int_{\text{Channel } k} \rho_{c,k}(z)\, dz \;;\; I_{f,k} = \int_{\text{Channel } k} \frac{f_{c,k}\, dz}{\rho_{c,k}(z)} \;;\; W_{c,k} = \left[\frac{P_2 - P_3 + \dfrac{W^2}{2\,\rho_1\, A_1^2} - \dfrac{W^2}{2\,\rho_3\, A_3^2} - I_{g,k}}{\dfrac{K_2}{2\,\overline{\rho_{c,k}}\, A_{c,k}^2} + \dfrac{I_{f,k}}{2\, D_{hc,k}\, A_{c,k}^2}} \right]^{0.5} \tag{8}$$

Since the sum of all channel flow rates, $\sum W_{c,k}$, may not equal the assembly flow rate with which the inner iteration was started, a new guess for the assembly flow rate is defined as $0.5(W_{guess}+\sum W_{c,k})$. The calculation of Eq. (8) is repeated until the assembly flow rate converges. This completes the inner iterations in an outer iteration, and the resulting flow rates are stored for checking the convergence of outer iterations. A multi-fuel-plate heat transfer calculation is then performed using the flow rates found after the inner iteration convergence, and this completes an outer iteration. The convergence of outer iterations is checked in outer iteration 2 and later. When the channel flow rates have converged from an outer iteration to the next, the natural circulation problem is solved.

4. Testing and Verification

PLTEMP/ANL V3.5 was verified by comparing its solution to a natural circulation test problem for a four-plate fuel assembly (defined below) with the solutions found by hand calculation, *Mathematica* [5], the NATCON code, and the RELAP5-3D code [6]. The solutions by codes/methods other than PLTEMP/ANL were obtained for a single coolant channel, whereas the PLTEMP/ANL solution was obtained for the four-plate assembly. The *Mathematica* solution was performed three times, using the different sets of coolant properties built in the three codes, i.e., the NATCON code, the PLTEMP/ANL code, and the RELAP5-3D code. These seven solutions are summarized in Table 1. Four of these solutions agree well with the PLTEMP/ANL solution, and this provides a verification of the natural circulation calculation of PLTEMP/ANL. The RELAP5-3D solution is found to be slightly inaccurate because the coolant temperatures calculated at node exit are treated by the code as node-centered temperatures in calculating buoyancy and frictional pressure drop, as discussed in Section 4.4. That is why the RELAP5-3D-calculated flow rate is about 5% higher than the PLTEMP/ANL-calculated flow rate.

Table 1. Solution of the Test Problem by Different Codes Used to Verify the Natural Circulation Option of the PLTEMP/ANL V3.5 Code*

Input or Calculated Quantity	Hand Calculation Using NATCON Properties	*Mathematica* Calculation			NATCON Code Solution	RELAP5 Code Solution **	PLTEMP/ANL V3.5 Solution	
		Using NATCON Coolant Properties	Using PLTEMP Coolant Properties	Using RELAP5 Coolant Properties			General Method, Friction Factor = 96/Re	General Method, Friction Factor = 94.717/Re
Inlet Temp, °C	25	25	25	25	25	25	25	25
Power per Channel, W	25000	25000	25000	25000	25000	25000	25000	25000
Loss Coeff. at Inlet	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Loss Coeff. at Exit	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CALCULATED QUANTITIES								
Flow per Channel, kg/s	0.1086	0.1088	0.1088	0.1113	0.1087	0.1140	0.1088	0.1093
Exit Temp, °C	79.967	79.900	79.891	78.727	79.970	77.432	79.891	79.646
BUOYANCY ΔP_{buoy}, Pa								
Axial Region 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Axial Region 2	75.716	75.761	75.793	79.094	75.783	82.591	75.786	75.342
Axial Region 3	36.040	36.001	36.009	36.334	36.034	35.157	36.015	35.785
Channel ΔP_{buoy}	111.756	111.762	111.802	115.428	111.817	117.748	111.801	111.127
FRICTIONAL PRESSURE DROP ΔP_f, Pa								
Inlet Loss	3.652	3.664	3.667	3.830	3.659	4.022	3.667	3.700
Axial Region 1	22.268	22.307	22.300	22.514	22.348	23.074	22.300	22.101
Axial Region 2	68.970	69.239	69.276	71.500	69.275	71.385	69.275	68.758
Axial Region 3	9.015	9.037	9.041	9.340	9.033	9.630	9.042	8.894
Exit Loss	7.487	7.513	7.518	7.855	7.503	8.243	7.518	7.585
Momentum Flux Term	0.368	0.0	0.0	0.389	0.0	0.395	0.0	0.0
Channel ΔP_f	111.760	111.761	111.802	115.428	111.817	116.749	111.803	111.126

* Laminar friction factor = 96/Re, except as noted in the last column.

** The RELAP5-3D solution is not accurate because the nodal coolant temperatures at node exit are treated by the code as node-centered temperatures in calculating buoyancy and frictional pressure drop.

<u>Test Problem Definition</u>: Calculate the coolant flow rate caused by natural circulation in a 1.05 m long vertical coolant channel in a 4-plate MTR-type fuel assembly with a 0.75 m long heated length, as shown in Fig. 2. The lower unheated length is 0.15 m, and the upper unheated length is 0.15 m. The heated length has a power of 25 kW per fuel plate distributed uniformly over the 0.75 m length, with an inlet temperature of 25 °C. Each channel has a rectangular cross section of thickness 3 mm, width 0.3 m, inlet pressure loss coefficient 0.5, and exit pressure loss coefficient 1.0. The absolute pressure at the channel inlet is 5 bar, corresponding to the channel inlet being 40.81 m below the free surface of water in the reactor pool.

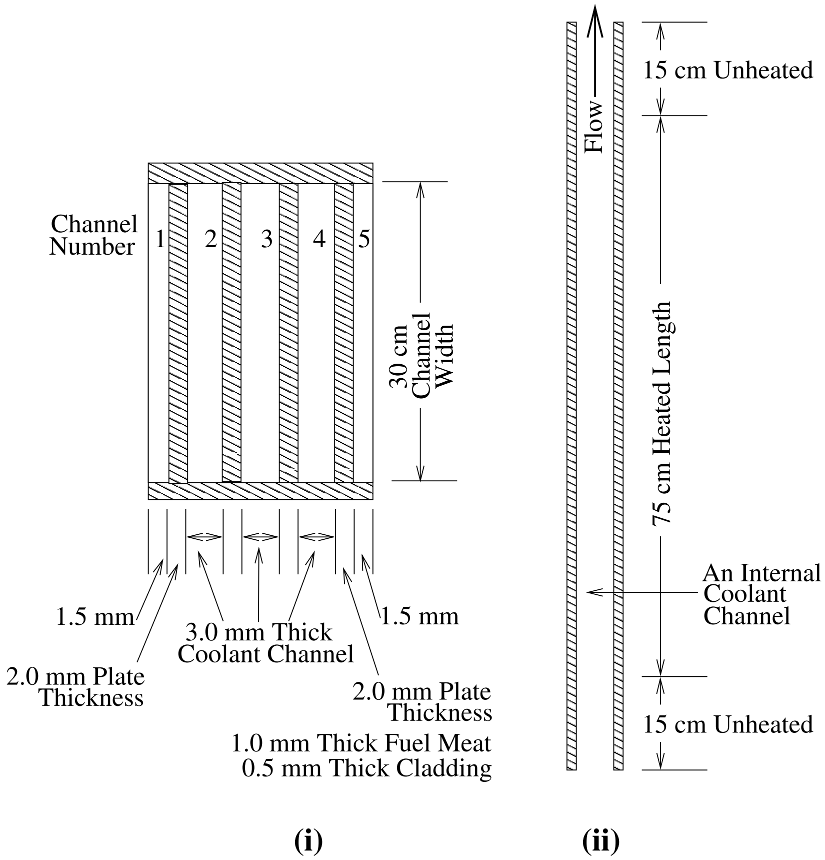


Fig. 2. (i) Fuel Assembly Cross Section and (ii) an Internal Coolant Channel Used in the Test Problem

4.1. Solution of the Test Problem by Hand Calculation

Based on symmetry in the problem, exactly half of each fuel plate's power goes to each channel adjacent to the plate. Hence, a single internal channel is modeled in the hand calculation and in the codes/methods except the PLTEMP/ANL code. An assumed flow rate was adjusted in the hand calculation so that the total buoyancy equals the total frictional pressure drop plus the momentum flux term. The calculation for the finally obtained flow rate of 0.1086 kg/s is shown below, and is summarized in Table 1.

Coolant Exit Temperature: For the above flow rate, the exit temperature T_{out} is calculated as $T_{in}+Q/(W\ C_p) = 79.967$ °C, using a specific heat C_p of 4188 J/kg-°C obtained by averaging the temperature-dependent water specific heat over the expected temperature range 25 to 80 °C.

Total Buoyancy: Only axial regions 2 and 3 have coolant densities lower than the density in the reactor pool at the inlet temperature 25 °C and therefore contribute to the buoyancy. Axial region 1 does not contribute. The density averaged over the heated region 2 is found by numerically integrating the temperature-dependent density data of the NATCON code (Table 2), using Eq. (9) in *Mathematica*. The density in axial region 3 uniformly equals the density at the exit temperature 79.967 °C. Then the buoyancy is calculated using Eq. (10).

$$\rho_{ave} = \frac{1}{(T_{ex}-T_{in})}\int_{T_{in}}^{T_{ex}} \rho(T)\,dT = \frac{1}{(79.967-25)}\int_{T=25}^{79.967} \rho(T)\,dT = 986.541\ \text{kg/m}^3 \qquad (9)$$

$$\Delta P_{buoyancy} = g\left[(\rho_1 - \rho_{ave})\,L_2 + (\rho_1 - \rho_3)\,L_3\right] = 111.756 \text{ Pa} \qquad (10)$$

Total Frictional Pressure Drop: The frictional pressure drop was calculated by summing the frictional drops $\Delta P_{f,1}$, $\Delta P_{f,2}$ and $\Delta P_{f,3}$ in axial regions 1, 2 and 3. $\Delta P_{f,1}$ consists of a pressure drop due to the inlet loss coefficient 0.5 and a drop due to wall shear over the length 0.15 m. $\Delta P_{f,3}$ consists of a pressure drop due to the exit loss coefficient 1.0 and a drop due to wall shear over the length 0.15 m. The pressure drop $\Delta P_{f,2}$ over the heated region 2 was calculated by dividing its length into 5 equal sub-regions (each 0.15 m long) to account for the temperature dependence of coolant viscosity (Table 3). The sub-regions are numbered i = 1 to 5, starting from

Table 2. Water Properties Used in the NATCON Code, RELAP5-3D Code, and PLTEMP/ANL Code

Water Properties Used in NATCON Code and Hand Calculation				Water Properties Used in in RELAP5-3D Code at 5.0 bar				Water Properties Used in in PLTEMP/ANL Code at 5.0 bar			
Temp °C	Specific Heat kJ/kg-°C	Water Density kg/m^3	Dynamic Viscosity µ Pa-s	Temp °C	Enthalpy kJ/kg	Water Density kg/m^3	Dynamic Viscosity µ Pa-s	Temp °C	Enthalpy kJ/kg	Water Density kg/m^3	Dynamic Viscosity µ Pa-s
21.718	4.165	997.54	974	20	84.33	998.505	1001.8	20	83.952	997.988	1014.5
32.879	4.171	994.81	755	30	126.12	995.930	797.6	30	125.608	995.759	804.50
44.022	4.179	991.06	604	40	167.89	992.466	653.3	40	167.327	992.672	652.48
55.144	4.187	986.30	499	50	209.68	988.244	547.1	50	209.116	988.754	542.91
66.239	4.196	980.62	422	60	251.49	983.357	466.6	60	250.973	984.042	462.93
77.311	4.206	974.00	367	70	293.36	977.871	404.1	70	292.915	978.583	401.28
88.356	4.217	966.66	326	80	335.28	971.843	354.5	80	334.946	972.432	355.98
99.370	4.230	958.67	292	90	377.27	965.313	314.5	90	377.075	965.655	320.63
110.356	4.244	950.09	263	100	419.36	958.315	281.8	100	419.314	958.326	290.21
121.294	4.259	941.16	238	110	461.57	950.869	254.7	110	461.672	950.532	263.52
132.340	4.276	931.85	216	120	503.93	942.990	232.0	120	504.162	942.367	240.27
				130	546.46	934.684	212.9	130	546.797	933.940	220.10

Table 3. Hand Calculation of Channel Frictional Pressure Drop

Region Or Heated Sub-region	Average Coolant Temp, °C	Length m	Dynamic Viscosity Pa-s	Reynolds Number	Friction Factor	Coolant Density kg/m^3	Frictional Pressure Drop, Pa
Region 1	25.000	0.15	9.0170×10^{-4}	794.980	0.120758	996.842	**25.920**
Sub-region 1	30.497	0.15	7.9546×10^{-4}	901.154	0.10653	995.48	19.672
Sub-region 2	41.490	0.15	6.3381×10^{-4}	1130.99	0.084882	992.01	15.729
Sub-region 3	52.484	0.15	5.2097×10^{-4}	1375.95	0.069770	987.52	12.988
Sub-region 4	63.477	0.15	4.3925×10^{-4}	1631.95	0.058825	982.12	11.010
Sub-region 5	74.470	0.15	3.7934×10^{-4}	1889.70	0.050802	975.76	9.571
Region 2		0.75				986.541	**68.970**
Region 3	79.967	0.15	3.5606×10^{-4}	2013.24	0.047684	972.325	**16.502**

The total frictional pressure drop is 25.920 + 16.502 + 68.970 + 0.3683 = 111.760 Pa

the lower end of the heated length. The coolant temperature rises linearly with axial position in the heated length, and the average temperature in the i^{th} sub-region is $T_{in} + (T_{out} - T_{in})(i - 0.5) / 5$. The coolant density and dynamic viscosity are interpolated from the NATCON data given in Table 2. The coolant density, viscosity, Reynolds number, laminar friction factor (96/Re), and the frictional pressure drop of each region or sub-region is given in Table 3. The pressure drop due to momentum flux from the channel inlet to the exit is $\Delta P_{mom} = \rho_1 V_1^2(\rho_1/\rho_3 - 1) = 0.3683$ Pa.

4.2. *Mathematica* Calculations Using Three Sets of Coolant Properties

The codes NATCON, RELAP5-3D, and PLTEMP/ANL have different built-in coolant properties shown in Table 2. To account for the effect of the difference in coolant properties, solutions to the test problem were obtained by *Mathematica* calculations, using the coolant properties built in each code. A *Mathematica* program was written in which any set of coolant properties could be inserted. The program uses 21 axial nodes (mesh intervals) of equal length in the total channel length of 1.05 m, with three each in the lower and upper unheated lengths of the channel, and 15 in the heated length. The program uses coolant enthalpy as a function of temperature. Since the NATCON code uses built-in coolant specific heat rather than enthalpy (see Table 2), some additional statements were added to the program when using the NATCON code properties, to find the corresponding enthalpy by integrating the specific heat.

Starting from a guess flow rate, the program calculates the coolant enthalpy at each node exit, the coolant temperature at the node exit, and the temperature at the node-center. Using the node-center temperatures, the program finds the nodal Reynolds number, friction factor, nodal frictional pressure drop, and the nodal contribution to buoyancy. It finds the inlet and outlet pressure losses. The calculation ends after printing the total buoyancy and the total frictional pressure drop in the channel. The steady-state natural circulation flow rate was found by running the program several times, each time using a more improved guess of the flow rate, in order to make the total buoyancy equal to the total frictional pressure drop.

Three *Mathematica* solutions to the test problem were obtained using the coolant properties of (1) the NATCON code, (2) the RELAP5-3D code, and (3) the PLTEMP/ANL code. These solutions are summarized in columns 3 to 5 of Table 1. It is noted that the flow rate of 0.1114 kg/s per channel, calculated using the coolant properties of RELAP5-3D, is 2.4 % higher than the flow rate based on the coolant properties of NATCON and PLTEMP/ANL. By doubling the number of node many times (from 21 to 16128), it was found that the flow rates change by ~$3x10^{-6}$ kg/s only.

4.3. NATCON Code Calculation

In the NATCON calculation [2], the heated length was divided into 20 axial mesh intervals (or nodes). The code computes the coolant temperature, density, viscosity, Reynolds number, friction factor, buoyancy head, and frictional pressure drop for each axial node, for a guessed value of channel flow rate. The code finds the total buoyancy head and frictional pressure drop, and then adjusts the channel flow rate to make the total buoyancy head equal to the total frictional pressure drop. The momentum flux term is ignored in the code because it is small. The results obtained are summarized in Table 1.

4.4. RELAP5-3D Code Calculation

The test problem was solved by running a thermal-hydraulic transient model of a single coolant channel for 1000 s to reach a steady-state, using a fixed channel inlet pressure of 5.0 bar and a fixed channel exit pressure of 4.897305 bar. This exit pressure equals the inlet pressure minus the gravity head of water at the pool temperature of 25 °C. The channel length of 1.05 m was divided into 21 axial nodes (mesh intervals) of equal length, with three each in the lower and upper unheated lengths of the channel, and 15 in the heated length.

The code finds a natural circulation flow rate of 0.11401 kg/s per channel and an exit temperature of 77.432 °C but there is a discrepancy in these results. The discrepancy is that the code computes coolant temperatures at the node exit, but uses these nodal temperatures as node-centered values in computing nodal gravity head, nodal buoyancy and nodal frictional pressure drop, as discussed below. The printed solution is shown in Table 4, with two analyses of the solution (done on a Microsoft Spreadsheet) for the purpose of pointing out the discrepancy.

Table 4. RELAP5-3D Solution of the Test Problem and Two Analyses of the Solution

Flow rate per coolant channel = 0.11401 kg/s (practically constant at 1000 s into the transient)

	RELAP5-3D Printed Output					Output Densities and Re Treated as Node-exit Values			Output Densities and Re Treated as Node-center Values		
1	2	3	4	5	6	7	8	9	10	11	12
Axial Node Number	P_n Pressure at Node Center, Pa	Coolant Temp at Node Exit, K	Reynolds Number at Node Exit	Density at Node Exit kg/m^3	P_{n-1} - P_n Pressure Drop Pa	Nodal Gravity Head Pa	Buoyancy Due to the Node Pa	Frictional Pressure Drop in the Node Pa	Nodal Gravity Head Pa	Buoyancy Due to the Node Pa	Frictional Pressure Drop in the Node Pa
inlet	500000.0	298.150	845.17	997.34				4.0225			4.0225
1	499747.0	298.150	845.17	997.34	253.00	489.028	0.0000	7.6912	489.028	0.0000	7.6912
2	499251.0	298.150	845.17	997.34	496.00	489.028	0.0000	7.6912	489.028	0.0000	7.6912
3	498754.0	298.150	845.17	997.34	497.00	489.028	0.0000	7.6912	489.028	0.0000	7.6912
4	498258.0	301.649	913.8	996.38	496.00	488.793	0.2354	7.3947	488.557	0.4707	7.1204
5	497762.0	305.148	984.75	995.30	496.00	488.293	0.7355	6.8581	488.028	1.0003	6.6146
6	497268.0	308.648	1057.9	994.12	494.00	487.739	1.2896	6.3815	487.449	1.5789	6.1645
7	496775.0	312.148	1133.2	992.85	493.00	487.138	1.8902	5.9565	486.827	2.2016	5.7623
8	496283.0	315.647	1210.5	991.48	492.00	486.491	2.5375	5.5760	486.155	2.8733	5.4017
9	495792.0	319.145	1289.8	990.02	491.00	485.797	3.2313	5.2343	485.439	3.5892	5.0771
10	495302.0	322.643	1370.9	988.47	490.00	485.059	3.9692	4.9262	484.679	4.3492	4.7842
11	494813.0	326.140	1453.7	986.85	489.00	484.282	4.7464	4.6478	483.885	5.1436	4.5191
12	494325.0	329.636	1538.2	985.14	488.00	483.465	5.5628	4.3953	483.046	5.9821	4.2783
13	493838.0	333.130	1624.3	983.36	487.00	482.610	6.4185	4.1656	482.173	6.8548	4.0589
14	493353.0	336.624	1711.8	981.51	485.00	481.720	7.3084	3.9561	481.266	7.7620	3.8586
15	492868.0	340.116	1800.7	979.59	485.00	480.796	8.2327	3.7647	480.325	8.7034	3.6753
16	492385.0	343.606	1890.8	977.60	483.00	479.837	9.1913	3.5893	479.349	9.6792	3.5073
17	491902.0	347.095	1982.2	975.55	483.00	478.846	10.1818	3.4281	478.344	10.6843	3.3526
18	491421.0	350.582	2074.7	973.44	481.00	477.827	11.2016	3.2797	477.309	11.7189	3.2101
19	490941.0	350.582	2074.7	973.44	480.00	477.309	11.7189	3.2101	477.309	11.7189	3.2101
20	490460.0	350.582	2074.7	973.44	481.00	477.309	11.7189	3.2101	477.309	11.7189	3.2101
21	489980.0	350.582	2074.7	973.44	480.00	477.309	11.7189	3.2101	477.309	11.7189	3.2101
Exit	489731.0				249.00			8.2426			8.2426
Pressure Drop due to Momentum Flux								0.3950			0.3950
Total					10269.59	10157.704	111.889	118.918	10151.844	117.748	116.749

<u>RELAP5-3D-Printed Results</u>: Since the printed temperature (column 3) for the last node (node 18) in the heated length is equal to the temperature of nodes 19, 20 and 21 in the unheated length, the printed nodal temperatures are inferred to be *node-exit* values. If the temperature for node 18 were *node-centered*, it would be less than the nodal temperatures in the unheated length. Based on similar observations in columns 4 and 5 of Table 4, the nodal Reynolds numbers and coolant densities are inferred to be *node-exit* values.

<u>Analyses of Printed Results</u>: The first analysis (shown in columns 7 to 9 of Table 4) was done to calculate the nodal buoyancy and frictional pressure drop by treating the code-printed nodal densities and Reynolds numbers as node-exit values, as they actually are. The second analysis (shown in columns 10 to 12) was done by treating the code-printed nodal densities and

Reynolds numbers as node-centered values. In each analysis, the channel gravity head and buoyancy were found by summing the nodal values. The channel frictional pressure drop was determined by summing the nodal frictional pressure drops, the inlet and outlet losses, and the momentum flux term. In the first analysis, the channel buoyancy (111.889 Pa) and the channel frictional pressure drop (118.918 Pa) are not equal but they should be equal in the steady state. If the assumptions of the first analysis were used by RELAP5-3D in calculating channel buoyancy and frictional pressure drop, the code could not achieve the steady state. Hence it is inferred that the code does not treat the printed nodal densities and Reynolds numbers as node-exit values which is a discrepancy of the code.

In the second analysis, the channel buoyancy (117.748 Pa) and the channel frictional pressure drop (117.746 Pa) are nearly equal as they should be in the steady state. Hence it is inferred that RELAP5-3D uses the assumption of the second analysis, i.e., *treats the node-exit densities and Reynolds numbers as node-center values* in calculating the buoyancy and the frictional pressure drop. This assumption artificially increases the buoyancy (by ~5 %) which causes a higher flow rate. Hence, the RELAP5-3D solution can be used for only an approximate verification of the PLTEMP/ANL V3.5 calculation.

4.5. PLTEMP/ANL V3.5 Code Calculation

In the 4-plate fuel assembly test problem (see Fig. 2), each fuel plate produces 25 kW, and the fuel assembly produces 100 kW. The PLTEMP/ANL problem modeled two identical fuel assemblies, and a total power of 0.2 MW. The internal channels (channels 2, 3, and 4) have a thickness 3 mm. The first and the last channels are of half thickness (1.5 mm), resulting in identical axial profiles of coolant temperature in each channel. Due to symmetry, exactly half of each fuel plate's power goes to each coolant channel adjacent to the plate. For comparison purposes, the calculation was done using a friction factor of 96/Re that was used in all the other calculations shown in Table 1. The results of this PLTEMP/ANL calculation are shown in column 8 of Table 1. This calculation agrees well with the *Mathematica* solution obtained using the coolant properties of PLTEMP/ANL given in column 4 of Table 1, providing a verification of the PLTEMP/ANL V3.5 code.

The PLTEMP/ANL calculation in column 9 of Table 1 was done using the friction factor C/Re where C is 94.7174 based on the thickness-to-width ratio of the coolant channel [4]. The only difference between the two PLTEMP/ANL V3.5 code solutions by is in the value of the constant C in the laminar friction factor C/Re. This causes a difference of 0.5 % in the flow rate.

5. Conclusion

A good agreement among the solution of the test problem by hand calculation, the two *Mathematica* solutions using the coolant properties of NATCON and the coolant properties of PLTEMP/ANL, the NATCON code solution, and the PLTEMP/ANL V3.5 code solution using the frictional factor 96/Re, provides a verification of the natural circulation method implemented in the PLTEMP/ANL V3.5 code.

NOMENCLATURE

A_n = Flow area of the n^{th} axial region of the assembly, m^2
$A_{c,k}$ = Flow area of coolant channel k in the heated length (axial region 2) of the assembly, m^2
$D_{h,n}$ = Hydraulic diameter of the n^{th} axial region, m. It is an input data.
$D_{hc,k}$ = Hydraulic diameter of the k^{th} coolant channel in the heated length, m. It is an input data.
f(z) = Moody friction factor as a function of axial position z
K_n = Sum of minor loss coefficients at inlet and exit of the n^{th} axial region n. It is an input data.
L_n = Length of the n^{th} axial region, m. It is an input data.
n = Axial region index.
N_c = Number of coolant channels in the assembly
N_f = Total number of axial regions in the assembly
P_1 = Pressure of the creeping coolant in the pool at the assembly inlet level, Pa
P_2 = Coolant pressure just before the inlet to the heated length, Pa
P_3 = Coolant pressure just after the exit from the heated length, Pa
P_4 = Pressure of the creeping coolant in the pool at the assembly exit level, Pa
$\Delta P_{f,n}$ = Frictional pressure drop (minor loss + wall shear) in the n^{th} axial region, Pa
Q = Power produced in the assembly, W
$T_{c,k}(z)$ = Coolant temperature in channel k, °C
T_{in} = Coolant temperature at the assembly inlet, °C
T_{out} = Coolant temperature at the assembly outlet, °C
$T_{ex,k}$ = Coolant temperature at the exit of the k^{th} channel, °C
W = Flow rate in the assembly (total flow in all coolant channels), kg/s
$W_{c,k}$ = Flow rate in the k^{th} coolant channel, kg/s
$\rho(z)$ = Coolant density as a function of axial position z, kg/m^3
$\mu(z)$ = Coolant dynamic viscosity as a function of axial position z, Pa-s

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