Development and Validation of a T-H Module for a Thermal Feedback in the CAPP Code

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1. Introduction

The effect of thermal feedback on a core neutronics analysis is important and it should be treated properly not only in a transient but also in a steady state analysis of pebble bed reactors. The temperatures from the thermal-hydraulic (T-H) analysis codes such as MARS-GCR [1] or GAMMA+ [2] can be used for thermal feedback in the neutronics calculation of the CAPP code [3] for both steady state and transient analyses by coupling the CAPP code and one of the T-H codes. However, it is very inefficient especially in a steady state analysis because the T-H codes obtain the steady state solution by performing a null transient calculation.

In this study, a simplified T-H analysis module for the CAPP code stand-alone steady state calculation was developed and it was verified and validated against a PBR-400 reactor [4] by comparing its results with those of the GAMMA+ code.

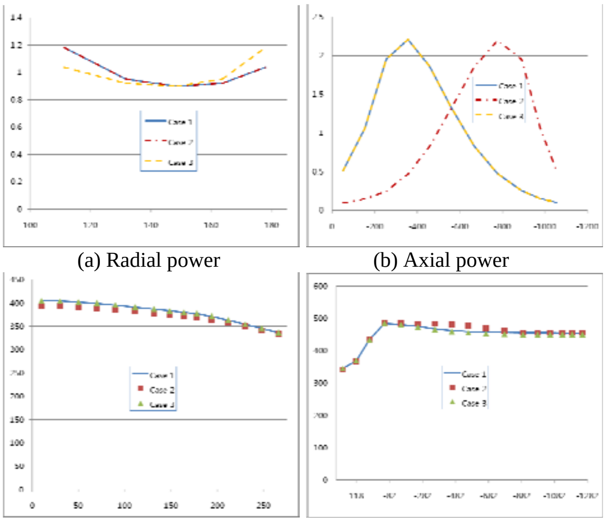
2. Methods and Results

2.1 Assumptions and Simplifications in T-H Model

For an efficient T-H analysis in the CAPP code steady state calculation, the following assumptions and simplifications were adopted:

1) The heat loss from the core through the conduction of the reflector is negligible.
2) The cross flow in radial and azimuthal direction is negligible.
3) The heat transfer by the conduction or radiation between the pebbles is very small compared to that by the helium coolant convection.
4) The coolant inlet flow portion is proportional to the flow area of each coolant channels.
5) The reflector region in which the coolant holes from the core to the lower plenum exist has the same temperature as the core outlet temperature.
6) The heat transfer between the coolant and the reflector at the riser holes is negligible.
7) Adiabatic condition at the bottom refl. surface.
8) The Zehner-Schlünder correlation is also valid for the pebbles near the core-reflector interface.
9) The radial/axial temperature distribution at the surface of the top/outer reflector is insensitive to the core power distribution.
10) No bypass flow was considered.

The assumptions and simplifications from1 to 7 are well known from the previous T-H analysis [4, 5]. Assumption 8 was adopted because it is also used in the GAMMA+ modeling. Figure 1 shows the core power distribution and the temperature distribution at the surface of the top reflector and the outer reflector for the three cases. We observe that the reflector surface temperature distribution is very insensitive to the core power distribution, which justifies assumption 9.

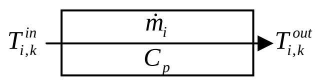


(a) Radial power (b) Axial power
(c) Temp. at top refl. surface (d) Temp. at outer refl. surface

Figure 1. Core power and reflector surface temperature distribution for the three cases.

2.2 Development of Simplified T-H Model

According to assumption 1, the temperature in the core region can be calculated without a coupling with the reflector region. The core can be divided into several closed coolant channels with axial channel cells and it can be assumed that all the heat generated in a channel cell is used to raise the temperature of the coolant by assumptions 2 and 3. The coolant inlet flow of each coolant channel is determined by assumption 4 and the outlet temperature of each channel cell can be determined as follows :



$$T_{i,k}^{out} = T_{i,k}^{in} + P_{i,k} / \left(\dot{m}_i C_p\right), \quad (1a)$$

$$T_{i,k}^{avg} = \left(T_{i,k}^{in} + T_{i,k}^{out}\right) / 2, \quad (1b)$$

$$T_{i,1}^{in} = T^{in}, \quad (1c)$$

where $T_{i,k}^{in}$, $P_{i,k}$, $\dot{m}_i$, C_p, $T_{i,k}^{out}$, and $T_{i,k}^{avg}$ are the coolant inlet temperature, reactor power, coolant flow rate, specific heat capacity of the coolant, outlet coolant temperature, and average coolant temperature at the k^{th} cell of the i^{th} channel, respectively.

Even though Eq. (1) is a more accurate expression for the coolant temperature and it is used in the actual calculation, the following equation based on an up-wind scheme was used in comparison with the GAMMA+ results because GAMMA+ uses the up-wind scheme for the sake of stability in a transient calculation.

$$T_{i,k}^{avg} = T_{i,k-1}^{avg} + P_{i,k} \Big/ \left(\dot{m}_i C_p\right), \quad T_{i,0}^{avg} = T^{in} \,. \qquad (2)$$

Once the coolant temperature is determined for each coolant channel cell, the temperature distribution in the pebbles can be determined by solving the following conduction equation over a 1-D spherical pebble.

$$-\nabla \cdot k\nabla T = q \,, \qquad (3a)$$

$$-k\nabla T = h(T_s - T_b) \,, \qquad (3b)$$

where h, T_s, and T_b are the heat transfer coefficient at the pebble surface, pebble surface temperature, and coolant bulk temperature, respectively.

The temperature distribution in the reflector region is determined by solving a 3-D conduction equation over the reflector region with the following internal and external boundary conditions: 1) adiabatic condition at the bottom reflector surface, 2) temperature distribution at the top/outer reflector surface, 3) convection from the coolant at the upper cavity, 4) conduction from the pebble bed, 5) internal temperature distribution in the bottom reflector region. They are shown in Figure 2.

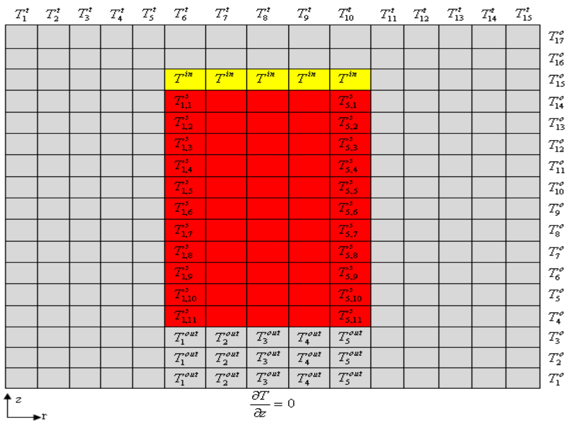


Figure 2. The internal and external boundary conditions.

2.3 Results and Discussion

The T-H module developed for the CAPP code was verified and validated against a PBR-400 reactor. A typical (Case 1) power distribution and reflector surface temperature distribution were used. The h in Eq. (3) is known to vary about by 10% throughout the core and the core-average value is used for this calculation.

Figure 3 shows the coolant temperature distribution. The maximum error is about 8.5°C. Figure 4 shows the reflector and the pebble average temperature. The maximum error is about 24 °C.

590.6 1.4	572.7 1.5	568.3 1.9	570.2 1.9	582.0 -0.8
718.9 2.6	676.8 2.4	666.3 2.6	670.6 2.7	694.1 0.6
926.1 3.8	846.2 3.5	826.7 4.1	835.4 4.2	878.7 2.8
1055.1 3.7	952.9 4.3	927.2 5.6	937.9 5.5	991.6 4.4
1101.3 2.1	988.3 4.0	959.3 6.4	971.1 6.0	1029.0 5.3
1103.8 -0.4	987.2 2.9	956.9 6.1	969.0 5.7	1027.2 5.4
1092.1 -3.0	975.0 1.4	944.2 5.4	956.4 4.7	1013.0 5.5
1076.4 -4.8	960.7 0.0	929.8 4.6	941.9 3.8	996.1 6.0
1064.9 -5.7	950.8 -1.0	920.0 3.8	932.0 2.9	983.7 6.8
1057.3 -6.0	944.5 -1.6	913.8 3.4	925.8 2.4	975.9 7.4
1055.3 -6.1	943.8 -2.5	912.7 3.0	924.3 2.2	972.5 8.5
xxxx.x x.x	GAMMA+(°C) CAPP Error (°C)			

Figure 3. Coolant temperature distribution

418.0 -3.0	417.4 -3.2	416.0 -3.3	413.9 -3.2	410.9 -2.8	407.5 -2.9	403.5 -3.4	399.3 -3.7	395.1 -4.1	391.1 -4.9	384.8 -4.6	376.2 -3.4	367.4 -2.4	358.4 -1.5	349.3 -0.5
444.4 3.9	444.2 4.0	443.6 4.5	442.8 5.0	441.6 5.7	440.3 6.4	436.3 7.3	431.2 8.1	425.4 8.5	419.2 8.1	411.2 6.8	402.3 5.1	393.3 3.5	383.9 2.1	374.1 0.7
479.1 4.5	479.1 4.9	478.7 6.2	478.0 8.4	476.9 11.6						457.7 21.8	450.6 14.3	444.6 8.8	439.7 4.4	435.7 1.0
532.3 3.1	532.3 2.8	532.0 2.7	531.5 2.5	530.8 2.3	551.5 1.6	540.3 1.6	537.5 1.9	538.5 2.1	547.0 -0.7	505.3 1.6	498.2 1.6	492.8 0.9	488.8 0.0	486.1 -0.6
608.7 0.5	608.3 0.5	607.5 0.5	606.0 0.7	603.8 1.0	642.2 3.0	613.6 2.6	606.4 2.9	609.3 3.0	626.0 0.8	546.3 1.9	529.5 1.2	514.7 -0.1	501.1 -1.4	487.3 -1.2
718.1 2.0	718.2 2.0	718.3 2.2	718.5 2.4	718.7 2.8	797.9 4.5	739.3 4.1	724.9 4.7	731.2 4.7	763.3 3.2	617.5 6.0	578.9 3.3	546.1 0.1	517.1 -2.5	488.6 -2.0
829.4 2.0	829.7 2.3	830.6 2.4	832.0 2.7	834.0 3.0	920.7 4.3	838.9 4.9	818.3 6.3	826.8 6.2	869.7 5.0	692.3 8.5	630.9 4.2	578.7 -0.5	533.3 -4.1	489.8 -2.8
915.7 0.6	916.1 0.7	917.0 1.0	918.5 1.2	920.6 1.4	991.6 2.4	894.7 4.5	869.8 6.9	879.8 6.6	929.2 5.8	749.9 7.7	671.8 2.5	604.3 -2.5	545.9 -6.5	490.7 -4.1
973.0 -1.4	973.3 -1.3	974.0 -1.2	975.2 -1.2	976.8 -1.1	1026.4 -0.2	921.1 3.2	893.6 6.5	904.5 6.0	956.7 5.8	787.3 5.9	699.0 0.4	621.3 -4.4	554.2 -8.0	491.3 -4.8
1009.9 -3.8	1010.2 -3.8	1010.7 -3.8	1011.5 -3.7	1012.7 -3.7	1043.7 -2.9	933.7 1.5	904.6 5.6	916.0 4.9	968.9 5.8	810.9 4.2	716.3 -1.4	632.2 -6.0	559.5 -9.2	491.7 -5.3
1030.0 -5.7	1030.1 -5.6	1030.4 -5.6	1030.8 -5.4	1031.5 -5.4	1048.9 -4.7	937.3 0.0	907.4 4.6	919.0 3.9	971.1 6.1	822.5 3.4	725.0 -2.4	637.7 -6.8	562.2 -9.8	491.8 -5.6
1039.8 -8.5	1039.9 -8.4	1040.1 -8.3	1040.3 -7.8	1040.7 -7.1	1050.2 -5.7	938.2 -1.0	907.9 3.9	919.7 3.0	970.3 6.9	827.7 3.3	728.8 -2.8	640.1 -7.3	563.3 -10.4	491.8 -6.1
1042.8 -10.5	1042.9 -10.5	1043.0 -10.1	1043.1 -9.3	1043.3 -8.2	1048.7 -6.1	937.1 -1.6	906.7 3.5	918.6 2.5	968.0 7.4	828.8 3.7	729.8 -2.4	640.8 -7.0	563.6 -10.0	491.7 -5.8
1043.8 -13.4	1043.9 -13.1	1044.2 -12.3	1044.5 -10.8	1045.1 -8.9	1049.7 -6.1	938.9 -2.5	908.0 3.0	919.6 2.2	967.5 8.5	830.4 5.4	731.2 -0.9	641.7 -5.8	564.1 -9.4	491.7 -5.5
1040.8 -13.2	1040.8 -12.8	1040.7 -11.4	1040.6 -9.1	1040.3 -6.0	1039.6 -2.1	936.8 -5.5	906.0 0.1	917.0 -0.1	950.0 20.8	840.8 19.2	737.5 8.4	645.4 -0.6	565.7 -6.9	491.8 -5.1
1039.1 -13.3	1039.1 -12.3	1039.2 -10.5	1039.2 -7.9	1039.2 -4.9	1039.2 -1.7	937.1 -5.8	906.3 -0.2	917.2 -0.3	949.8 21.0	841.2 20.6	738.1 10.0	645.8 0.8	566.0 -6.2	491.8 -4.8
1036.9 -9.3	1037.1 -8.4	1037.5 -7.0	1038.0 -5.2	1038.6 -3.4	1039.3 -1.8	937.0 -5.7	906.1 0.0	917.1 -0.2	949.6 21.2	838.0 24.0	736.6 11.8	645.4 1.4	565.9 -6.0	491.8 -4.8
xxxx.x x.x	GAMMA+ (°C) CAPP Error (°C)													

Figure 4. Reflector (pebble) temperature distribution

3. Conclusions

A T-H module was developed for the thermal feedback in the CAPP code based on a simplified T-H model and it was verified and validated against a PBR-400 reactor. It showed a good agreement with the GAMMA+ code results. Even though the bypass flow is not negligible in a pebble bed reactor, it was not modeled in this study because the bypass phenomena are not clearly known and no accurate bypass model is developed yet. It should be modeled in the CAPP code when an accurate model is developed in the future.

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