Determining Coolant Flow Rate Distribution In The Fuel-Modified TRIGA Plate Reactor

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Abstract. TRIGA 2000 reactor in Bandung is planned to have the fuel element replaced, from cylindrical uranium and zirconium-hydride (U-ZrH) alloy to U₃Si₂-Al plate type of low enriched uranium of 19.75% with uranium density of 2.96 gU/cm³, while the reactor power is maintained at 2 MW. This change is planned to anticipate the discontinuity of TRIGA fuel element production. The selection of this plate-type fuel element is supported by the fact that such fuel type has been produced in Indonesia and used in MPR-30 safely since 2000. The core configuration of plate-type-fuelled TRIGA reactor requires coolant flow rate through each fuel element channel in order to meet its safety function. This paper is aimed to describe the results of coolant flow rate distribution in the TRIGA core that meets the safety function at normal operation condition, physical test, shutdown, and at initial event of loss of coolant flow due power supply interruption. The design analysis to determine coolant flow rate in this paper employs CAUDVAP and COOLODN computation code. The designed coolant flow rate that meets the safety criteria of departure from nucleate boiling ratio (DNBR), onset of flow instability ratio (OFIR), and ΔT onset of nucleate boiling (ONB), indicates that the minimum flow rate required to cool the plate-type fuelled TRIGA core at 2 MW is 80 kg/s. Therefore, it can be concluded that the operating limitation condition (OLC) for the minimum flow rate is 80 kg/s; the 72 kg/s is to cool the active core; while the minimum flow rate for coolant flow rate drop is limited to 68 kg/s with the coolant inlet temperature 35°C. This thermohydraulic design also provides cooling for 4 positions irradiation position (IP) utilization and 1 central irradiation position (CIP) with end fitting inner diameter (ID) of 10 mm and 20 mm, respectively.

Keywords: CAUDVAP code, COOLODN code, flow distribution, modified reactor, TRIGA plate

1. Introduction

TRIGA 2000 reactor in Bandung is planned to have its fuel element replaced, from cylindrical uranium and zirconium-hydride (U-ZrH) alloy to U₃Si₂-Al plate type of low enriched uranium of 19.75% with uranium density of 2.96 gU/cm³. Its reactor power is maintained at 2 MW. This change is planned to anticipate the discontinuity of TRIGA fuel element production by CERCA, which is a joint venture company with CERCA of France, as the supplier of international TRIGA fuel element. The selection of this plate-type fuel element is supported by the fact that such fuel type has been produced...
in Indonesia and used in MPR-30 safely since 2000 [1]. It is not the first time that TRIGA fuel element experienced modification. Previously, TRIGA reactor in Dalat, Vietnam converted its fuel element into cylindrical plate type [2].

The fuel element conversion of TRIGA reactor from cylindrical into plate type has consequences in cooling mode in its reactor core, which is initially based on natural circulation cooling mode and changed into forced circulation at normal condition, and natural circulation during physical test; and changed a transition from forced circulation to natural circulation mode when its cooling pump stops. Moreover, the plate-type-fuelled core configuration that is completed with parallel coolant channel requires cooling flow rate through each fuel element plate channel in order to meet safety requirement. Determination of flow distribution in the plate-type-fuelled TRIGA reactor core has to fulfill safety feature design, which supports the basic safety functions of the reactor facility. The safety functions include that the reactor core should be able to be shut down and maintained at safe conditions, either at operational condition or during accident. Therefore, the reactor core should be equipped with sufficient heat removal system, either after shutdown or during accident to minimize radioactive material releases into environment.

To meet this safety requirement, flow distribution for heat removal of the primary cooling system pump that supplies coolant flow into each position of 5x5 grid in accordance with the specified design configuration [3]. In addition, the flow distribution is designed so that operational safety and cooling availability for reactor utilization is fulfilled. The utilization meant here is cooling availability at irradiation position INPUT located at the most outer angles (4 positions) and central irradiation position CIP at the center of the core (1 position).

Some researches that address coolant flow distribution in plate-fuelled TRIGA reactor include Anwar Ilmar Ramadhan et al. (2017) who carried about a preliminary design on the use of MTR-type fuel element using Computational fluid dynamic (CFD) performed calculation on flow distribution in the plate fuel element, in which the flow in the core configuration was modeled without considering both power peak factor and technical factor of nuclear fuel fabrication [4]. Research on the performance of the flow rate in the plate-type fuel by using CFD has also been conducted by several researchers [5,6,7]. Meanwhile research on reactor design and safety, is also being conducted [8,9,10]. This paper aimed to complete the design before, is describe the result of the design of coolant flow distribution in the reactor core that meets the safety function at normal operation, physical test, shut down and during an accident of loss of coolant flow due to power supply interruption. The primary cooling system that cools the fuel element should fulfill the safety margin in the forced convection cooling mode in spite of free convection. The computation codes used to determine this coolant flow distribution are CAUDVAP and COOLODN.

2. Theory

2.1. Primary Cooling System of Plate-Type-Fuelled TRIGA Reactor

The reactor cooling system has a function to remove fission product heat generated at full load using downward forced cooling circulation mode and transfer the heat to secondary cooling system. The primary cooling system in the reactor core is also used to remove decay heat by natural circulation, when the primary cooling system pump experiences failure. The reactor primary cooling system is connected to the reactor pool water, primary piping circuit, decay tank, primary cooling pumps, heat exchanger, valves, and pipe fitting components. This primary cooling system functions to remove heat from the core at operational condition and during accident while maintaining the reactor in safe condition. Heat is removed by coolant water flow through the core by forced circulation at normal power or by natural circulation when the core is used for physical test, shutdown, or refueling. The heat removed from the core is then transferred to the secondary cooling system and released to environment. The primary cooling system section located in the reactor core has a function to cool the core at normal operation and at free convection cooling condition, which is defined as Safety Category 1 of engineered safety feature. Meanwhile, the primary cooling system section located outside of the reactor pool that is not directly needed to cool the core using natural circulation mode is classified as
Safety Category 2 system. The cooling flow in the reactor core is directly responsible for heat removal in the fuel element as defined as Safety Category 1 of engineered safety feature.

This plate-type-fuelled TRIGA reactor utilizes demineralized water as coolant and moderator. Its reactor core consists of 5×5 lattices. The reactor pool is 8.5 cm deep, while the core is 5.5 m under water. The coolant water flows downward through fuel element gaps to remove 2 MW heat generated by the fuel element and makes N-16 decayed into a delay chamber, and then transfers the heat to a heat exchanger. The reactor core lattice comprise 25 identical holes to hold 16 fuel element, 4 control element, 1 irradiation position at the center and 4 irradiation positions at the core edge, as shown in figure 1. The element ends are inserted to the lattice holes. Additional smaller holes are provided between the main lattice holes in order to fuel element surface.

![Figure 1. Core configuration of modified TRIGA plate reactor [2]](image)

The fuel elements used are made based on MTR technology, as shown in figure 2. Each standard fuel element consists of a handle at the upper part, two side plates and 21 fuel element plates, and end fitting at the bottom part. Each fuel plate comprises AlMg2 frame and cover plates, which enclose $U_3Si_2$-Al dispersion fuel element. The control elements are designed to be inserted by fork-type absorber. The sections containing fuel element in the control element is similar to those of the fuel element. As many as 15 fuel element plates are supported by two side plates. Three fuel element plates are taken out at each end of the section containing fuel element in order to provide space for inserting absorber blade. Aluminum plates replace two out of three fuel element plate taken out. The absorber component consists of two Ag-In-Cd blades coated by stainless steel (1.4541, similar to SS321) as shown in figure 3.
2.2. Safety criteria
The primary cooling system is designed to meet design basis accident, which includes:

a) To provide cooling flow to remove heat from the core at power condition. Distribution of the coolant flow is determined by thermal hydraulic design.

b) To maintain inlet coolant temperature not exceeding normal operation condition.

c) To remove decay heat when primary cooling system pump does not operate at natural circulation.

d) To ensure thermal margin availability of fuel cladding during postulated transient.

e) To maintain the reactor core integrity during accident occurring in abnormal condition.
In order to fulfill this safety design basis, safety margin for the plate-type fuelled TRIGA reactor should be determined. The safety criteria implemented to the plate-type fuelled core are as follows [2]:
1. There is no occurrence of onset of nucleate boiling (ONB), as indicated by the safety margin for the initial nucleate boiling, where ΔT ONB ≥ 0 °C;
2. There is no occurrence of onset of flow instability (OFIR), OFIR ≥ 1;
3. There is no occurrence of departure from nucleate boiling (DNBR), as indicated by DNBR value at all points along the fuel element, DNBR ≥ 1.5.

2.3. CAUDVAP Computation Code
CAUDVAP v2.60 is a computation code developed by Nuclear Engineering Division, INVAP SE, Argentine. This code is used to calculate flow distribution and pressure drop in reactor core. CAUDVAP v2.60 is developed for research reactor core hydraulics. This code computes distribution of flow rate for steady state condition through various cooling channels, inter-connected in parallel, between plenum inlet and outlet. The calculation parameters include total pressure drop of reactor core with input of total flow, flow distribution at various cooling channel, and friction, as well as flow loss at each flow section [5].

2.4. COOLODN Computation Code
COOLODN is a thermal hydraulic computation code developed by JAERI (Japan Atomic Energy Research Institute). This code has been well verified and used to analyze thermal hydraulic characteristics of JRR-4 reactor core of Japan and RSG-GAS in Serpong. Meanwhile, COOLODN-N has capability to calculate thermal hydraulic characteristics of research reactor with plate-type or rod-type fuel element with either forced or natural convection cooling mode [12].

3. Methodology
To fulfill the safety criteria of plate-type fuelled TRIGA reactor, distribution of coolant flow rate is calculated by knowing the effect of flow rate to safety factor using computation code COOLODN. Meanwhile, primary coolant flow fraction through active core fuel element is computed using CAUDVAP. The calculation results are then input to COOLODN code. The minimum coolant flow through fuel element is calculated by considering minimum flow rate condition as operation condition limit that will make the reactor scram if this value is exceeded. In addition, flow rate that cools the reactor core should also take into account a condition in which the reactor operates at full power.

3.1. Core geometry and fuel element
The geometry of TRIGA reactor pool does not change even though there is fuel element conversion from cylindrical to plate-type. In accordance with the modified core configuration as shown in figure 1. Table 1 gives core geometry and channel geometry that will be passed by primary coolant flow.

| No. | Parameter                              | Value       |
|-----|----------------------------------------|-------------|
| 1.  | Reactor Pool                           |             |
|     | Pool height, m                         | 8.5         |
|     | Reactor core position under the pool water level, m | 5.5     |
|     | Reactor pool diameter, m               | 1.9812      |
| 2.  | Reactor core                           |             |
|     | Matrix grid                            | 5 x 5       |
|     | Geometry grid, mm                      | 81x77.1     |
| 3.  | Standard fuel element                  |             |
|     | Number of standard fuel element        | 16          |
| No. | Parameter                                           | Value                        |
|-----|----------------------------------------------------|------------------------------|
|     | Number of plate                                    | 21                           |
|     | Number of coolant channel                          | 20                           |
|     | Fuel element cross section geometry, mm            | 75.7x67.1x51.5               |
|     | Coolant channel gap, mm                            | 2.55                         |
|     | Channel geometry between 2 fuel elements, mm       | 2.70x57.1                    |
|     | Channel geometry between plate and core shroud, mm | 2.85x67.1                    |
|     | Plate geometry, length x width x thick, mm         | 625x70.75x1.3                |
|     | Meat geometry, length x width x thick, mm          | 600x62.75x0.54               |

3. Control Element
- Number of control elements: 4
- Number of plate: 15
- Number of coolant channel: 14

4. Irradiation Position (IP),
- Number of IP: 4
- ID end fitting, mm: 10

5. Central Irradiation Position (CIP)
- Number of CIP: 1
- ID end fitting, mm: 20

3.2. Coolant flow division in the reactor core for CAUDVAP modeling
Distribution of coolant flow in the reactor core is shown in figure 4. It shows many kinds of coolant flow related to sub-channel geometry. Primary coolant system flows to cool fuel element and control element, including the most outer fuel element plate through bypass flow and irradiation target by providing holes at the end fitting target, either in CIP or IP.

Distribution of primary coolant flow in the plate-type-fuelled TRIGA reactor is divided into active core, bypass, and reflector. Flow division through coolant channel is modeled in more detailed, as shown in figure 4.

![Coolant flow distribution model in modified TRIGA reactor core](image)

**Figure 4.** Coolant flow distribution model in modified TRIGA reactor core

Remarks:

- **Flow in the active core**
  1. Coolant channel in the fuel elements
  2. Coolant channel in the fuel control
  3. Outer channel of fuel element
  4. Channel in side blade of control element

- **Bypass flow**
  5. Coolant channel between 2 fuel element
  6. Coolant channel in the end fitting of IP
  7. Coolant channel in the end fitting of CIP

- **Reflector**
  8. Coolant channel in reflector

4. Results and Discussion
To identify the effect of the flow rate of primary cooling system to changes of reactor safety margin, initial estimation is first performed. This initial estimation is selected below and above the debit of the
existing pump available in plate-type-fuelled TRIGA reactor in Bandung. The assumption used is 90% of the flow rate of the primary cooling system will cool the active core, consisting of fuel element and control element. It is assumed that the coolant inlet temperature is 35°C, while the power peak factor distribution is obtained from neutronic calculation, where criticality is achieved when the control element is withdrawn as high as 30 cm. The calculation results based on coolant flow rate of 40 – 400 kg/s are shown in table 2 and figure 5.

Table 2. Precalculation results of primary coolant system flow

| Flowrate (kg/s) | T coolant outlet (°C) | T clad (°C) | T meat (°C) | ΔT ONB (°C) | T sat (°C) | OFIR  | DNBR |
|----------------|-----------------------|------------|------------|-------------|-----------|-------|------|
| 40             | 78.64                 | 122.74     | 123.66     | -5.07       | 113.45    | 0.82  | 1.01 |
| 50             | 69.93                 | 118.57     | 119.48     | -1.44       | 113.37    | 1.03  | 1.26 |
| 60             | 64.12                 | 111.53     | 112.45     | 3.06        | 113.26    | 1.23  | 1.51 |
| 70             | 59.96                 | 103.05     | 103.97     | 10.16       | 113.14    | 1.44  | 1.76 |
| 80             | 56.84                 | 96.46      | 97.39      | 17.1        | 113       | 1.64  | 2.02 |
| 90             | 54.42                 | 91.1       | 92.03      | 22.73       | 112.85    | 1.85  | 2.27 |
| 100            | 52.48                 | 86.65      | 87.59      | 27.39       | 112.68    | 2.05  | 2.52 |
| 200            | 43.74                 | 64.84      | 65.79      | 49.57       | 110.1     | 4.1   | 5.04 |
| 300            | 40.83                 | 56.45      | 57.41      | 55.57       | 105.71    | 6.16  | 7.56 |
| 400            | 39.37                 | 51.94      | 52.9       | 54.84       | 98.85     | 8.21  | 9.09 |

Figure 5. Thermal hydraulic characteristic base on primary coolant flowrate

It is shown in table 2 that at reactor power of 2 MW the primary coolant flow rate meets the safety criteria if it is ≥ 60 kg/s. The safety margin for nucleate boiling and DNBR is exceeded if coolant flow rate is less than that figure. The safety margin for OFIR and DNBR increases significantly for coolant flow rate in the core ≥ 200 kg/s. Moreover, plate and coolant channel temperatures drop significantly. However, this coolant flow is not necessary since it will give an over design figure. Estimation of
primary coolant flow rate needed is in the range of 60 - 100 kg/s at 2 MW power when the reactor operates at steady state condition.

To fulfill the minimum flow rate criteria that will trigger reactor protection system if loss of coolant flow accident occurs, a percentage of minimum flow rate used as a limit of operation condition needs to be determined. Taking into account RSG GAS experience, safety margin due to a decrease in flow rate is limited to 85%, under which reactor protection system will make the reactor scram so that the reactor is put in safe condition.

To anticipate primary cooling system disturbance causing loss of coolant flow accident, flow rate that cools the active core of only 85% is calculated. When the flow rate achieves this limit, reactor protection system starts to function and the reactor is protected by reactor scram. This figure is expected to be able to remove residual heat due to loss of coolant flow accident. The postulated worst case condition is that loss of primary coolant flow accident when the reactor operates at nominal power of 2 MW.

Table 3 and figure 6 indicate the calculation results of reactor safety margin of plate-type-fuelled TRIGA reactor based on 85% and the flow rate is in a range of 60 – 100 kg/s at operating power of 2 MW at steady state condition. The calculation results show that there is a shift of minimum flow rate needed so that the minimum safety criteria, which is 70 kg/s, achieved.

**Table 3.** Thermalhydraulics characteristic base on minimal flowrate

| Flowrate (kg/s) | Nom. Flow (kg/s) | T Coolant outlet (°C) | T Clad (°C) | T Meat (°C) | ΔT ONB (°C) | T Sat (°C) | OFIR | DNBR |
|----------------|-----------------|-----------------------|-------------|-------------|-------------|-----------|------|------|
| 51             | 60              | 69.25                 | 118.07      | 118.99      | -1.04       | 113.36    | 1.05 | 1.29 |
| 59.5           | 70              | 64.36                 | 112.01      | 112.93      | 2.8         | 113.27    | 1.22 | 1.5  |
| 68             | 80              | 60.69                 | 104.58      | 105.51      | 8.58        | 113.17    | 1.4  | 1.71 |
| 76.5           | 90              | 57.84                 | 98.61       | 99.54       | 14.84       | 113.05    | 1.57 | 1.93 |
| 85             | 100             | 55.56                 | 93.65       | 94.58       | 20.05       | 112.93    | 1.74 | 2.14 |

**Figure 6.** Thermal hydraulic characteristic of 85% primary coolant flowrate
The reactor power will possibly rise during an accident. To anticipate this event, the reactor will be initiated by protection system to scram. Therefore, to specify the setting point for the protection system at accident condition, over-power based calculation should be conducted, where safety margin is still met.

Table 4 shows parameters of over-power-based thermal hydraulics that might occur early during loss of flow accident (LOFA). This calculation results in safety margin in severe accident. The assumptions used include that the flow rate achieves 85% of the minimum flow rate specified as high as 68 kg/s, the inlet temperature is 35°C, the accident occurs at initial cycle, where peak factor of axial and radial power has the highest value. Figure 7 shows characteristics of over-power-based safety margin. The analysis results indicate that over-power-based operation condition, where DNBR margin not exceeded is 110% of the nominal power or 2.2 MW.

| Power (MW) | Flowrate (kg/s) | T Coolant outlet (°C) | T Cladding (°C) | T Meat (°C) | ΔT ONB (°C) | T Sat (°C) | OFIR | DNBR |
|------------|-----------------|----------------------|----------------|-------------|-------------|------------|------|------|
| 2          | 68              | 60.69                | 104.58         | 105.51      | 8.58        | 113.17     | 1.4  | 1.71 |
| 2.1        | 68              | 61.98                | 107.67         | 108.64      | 5.62        | 113.17     | 1.33 | 1.63 |
| 2.2        | 68              | 63.26                | 110.72         | 111.73      | 3.57        | 113.17     | 1.27 | 1.56 |
| 2.4        | 68              | 65.83                | 115.86         | 116.96      | 0.6         | 113.17     | 1.16 | 1.43 |

Figure 7. Characteristic of thermalhydraulic and safety margins at over power

The calculation results of plate-type-fuelled TRIGA core using COOLODN has been compared with those of flow rate distribution calculation using CAUDVAP code, as shown in table 5. The calculation results of benchmarking between COOLODN and CAUDVAP indicate that there is an agreement of the two codes in a range of 2 – 8.7%. CAUDVAP is used to compute flow distribution in each sub-channel of the plate-type-fuelled TRIGA, as shown in figure 6. The calculation results of flow distribution show that coolant flow through the reactor core is divided to 88.2%, 4.8%, and 7%, respectively for cooling the active core, bypass, and reflector. In addition, in order to manage the largest coolant percentage flowing through the active core, this design also provides cooling for
reactor utilization. For the purpose of target irradiation in the core, cooling for 4 IPs with inner diameter (ID) of 10 mm each, which is located at end fitting irradiation target, is provided. Meanwhile, for CIP position, ID 20 mm is used.

Table 5. Comparison result between Coolodn and Caudvap

| Parameter                          | CoolodN | Caudvap | Deviation (%) |
|-----------------------------------|---------|---------|---------------|
| Primary coolant flow, kg/s        | 80      | 80      | -             |
| Flow through active core, kg/s    | 90% = 72| 88.2% = 70.56 | 2             |
| Coolant velocity in fuel element, m/s | 1.123  | 1.085   | 3.38          |
| Total loss through fuel element, kg/cm² | 0.06134| 0.0561  | 8.57          |

Table 6. Flow distribution in TRIGA plate core elements by Caudvap

| No. | Channel Type                  | Flow Distribution Kg/s | %    |
|-----|--------------------------------|------------------------|------|
| 1.  | Active core                   | 73.57                  | 88.20|
|     | Fuel element                  | 51.58                  | 64.47|
|     | Fuel Plate in control element | 12.86                  | 16.07|
|     | Outer channel of fuel plate   | 6.13                   | 7.66 |
|     | Blade in control element      | 3.84                   | 4.80 |
| 2.  | By Pass                       |                        |      |
|     | Between fuel element and others | 3.19                  | 3.99 |
|     | Irradiation positions, IP     | 0.55                   | 0.68 |
|     | Central irradiation position, CIP | 0.11                 | 0.13 |
| 3.  | Reflector                     | 5.60                   | 7.00 |

Table 7. Comparison between TRIGA Plate Innovation and similar reactor

| Parameter                          | JRTR [13] | JRR-4 [14] | MNR [14] | TRIGA Plate Modified |
|-----------------------------------|------------|------------|----------|----------------------|
| Power (MW)                        | 5          | 3.5        | 2        | 2                    |
| Site                              | Jordanian  | Japan      | Canada   | Indonesia            |
| Reactor Type                      | Open pool  | Open pool  | Open pool| Open pool            |
| Fuel Type                         | Plate      | Plate      | Curve plate | Plate               |
| Fuel Material                     | U₃Si₂      | U₃Si₂      | U₃Si₂    | U₃Si₂                |
| Fuel Enrichment , %-U235          | 19.75      | 19.75      | 19.75    | 19.75                |
| Fuel Density, g/cm³               | 4.8        | 3.8        | 0.74     | 2.96                 |
| No of FE/CE                       | 18/-       | 20/-       | 28/6     | 16/4                 |
| Average heat flux, kW/m²          | 173        | 150        | 45       | 72.5                 |
| Coolant                           | H₂O        | H₂O        | H₂O      | H₂O                  |
| Total flow rate, kg/s             | 170        | 135        | 75       | 80                   |
| Flow Direction                    | Downward   | Downward   | Downward | Downward             |
| Coolant velocity in core, m/s     | 2.5        | 1.45       | 0.69     | 1.123                |
| Inlet coolant temperature, °C     | 37         | 35         | 30       | 35                   |
| Average core ΔT, °C               | 9.2        | -          | 6.4      | 7.0                  |

Comparison of flow rate needed to cool down plate-type-fuelled TRIGA and similar reactor is shown in table 7. Compared with thermal hydraulic parameters of plate-type fuelled research reactor at 2 – 5 MW, total flow rate through plate-type-fuelled TRIGA reactor seems in agreement. It is shown by coolant flow rate and inlet-outlet temperature difference. Therefore, it can be concluded that determination of coolant flow rate in plate-type-fuelled TRIGA reactor has been verified.
**Conclusion**

Design and analysis have been performed to determine coolant flow rate in innovated plate-type fuelled TRIGA reactor core that meets the safety criteria of reactor operation at steady state condition and initial transient, as well as over power. The design of flow rate that fulfils safety criteria of DNBR, OFIR, and ΔT ONB indicates that minimum flow rate required to cool plate-type-fuelled TRIGA reactor at 2 MW power is 80 kg/s. Therefore, it can be concluded that operating limitation condition (OLC) for minimum flow rate is 80 kg/s; 72 kg/s is to cool the active core; while the minimum flow rate for coolant flow rate drop is limited to 68 kg/s with the coolant inlet temperature 35 °C. This thermohydraulic design provides cooling for IP utilization as many as 4 positions and 1 CIP with end fitting ID of 10 mm and 20 mm, respectively.

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