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Performance Optimization and Validation for the PRHRS of VVERs with RELAP5 Code

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Abstract. Passive safety systems are considered as the systems which improve safety and reliability of the Nuclear Power Plants (NPP). Although they seem helpful, for the nuclear technology, passive systems require special attention, because of the disadvantages for their use due to the large difficulties in the thermal-hydraulic design compared with the active systems. One of the important dynamics of the operational principle of passive systems is natural circulation. Natural circulation phenomenon plays an important role in energy transfer from hot zones to the cold zones without using a mechanical pump. In all light water reactors, natural circulation is an important passive heat removal mechanism. In this study, the natural circulation phenomenon was studied with reference station blackout scenario in VVER type NPP. Thermal-hydraulic calculations of Passive Residual Heat Removal System (PRHRS) were performed using RELAP5 system code. This study was performed to evaluate the natural circulation performance of PRHRS for the VVER type NPP.

Keywords: Natural Circulation, PRHR Systems, RELAP5, VVER 1200

1 Introduction

For the nuclear technology, passive systems require special attention, because the thermal-hydraulic design of passive systems is more complicated and difficult compared to active systems. Natural Circulation (NC) is one of the important working principle of passive systems.

For the new generation nuclear technology, extended use of the NC principles is seen. This includes, in some cases, the nominal operation of the reactors and, in all cases, the reactor cooling by passive systems. Passive systems have several advantages, for example simplifying the systems, reducing the costs and increasing the safety level.

The NC, in phenomenological terms, is at the basis of the design of the majority of the passive systems that are of interest in the nuclear technology and is considered for the system analyzed in the present framework.

NC phenomenon plays an important role in energy extraction from hot zones and rejection to the cold zones without using a mechanical pump in several engineering systems, such as reactor core cooling. The density difference between fluid leaving the heat source at one elevation and the heat sink at a higher elevation induces flow and provides a passive means of core cooling. The circulating fluid removes heat from source and transports it to the sink. The flow can be single phase or two phase wherein vapor flows alongside the liquid.

These NC loops are widely used in energy conversion systems. Naturally driven systems have been used in the VVER type nuclear reactors to remove the core heat (through the steam generator (SG)) under station blackout conditions.

2 Passive Residual Heat Removal System

The amount of decay heat is dependent on the preceding operation time and on the period after the shutdown. It is approximately 7% of operating power at shutdown, 2% at 1 hour, 1% at 5 hours, 0.5% at 1 day and 0.1% at 10 days [1].

Although the residual heat generation rate of a reactor is only about 1% (after a couple hours) of the nominal reactor power and it decreases with time, heat generation continues for a very long period even after the reactor has been stopped. If the reliability and continuity of cooling cannot be guaranteed, a reactor accident could occur. So the residual heat removal system (RHRS) is considered as an important safety system.

RHRS is designed for the decay heat removal and reactor plant cool-down during a normal Nuclear Power Plant (NPP) trip, under the conditions of anticipated operational occurrences and under design basis accidents on condition of retaining the primary-side integrity together with the low pressure emergency injection system. Passive Residual Heat Removal (PRHR) via steam generators is designed for long-time residual heat removal from the core to the ultimate heat sink via the secondary side at beyond design basis accidents.

Passive cooling relies on the efficient energy transfer of the steam produced by decay heat in the core of the reactor to a number of large heat sinks utilizing inherent mechanisms such as buoyancy, gravity-driven flow, evaporation and condensation.

A schematic representation of typical PRHRS is presented in Figure 1. For VVER type NPPs PRHRS is designed to

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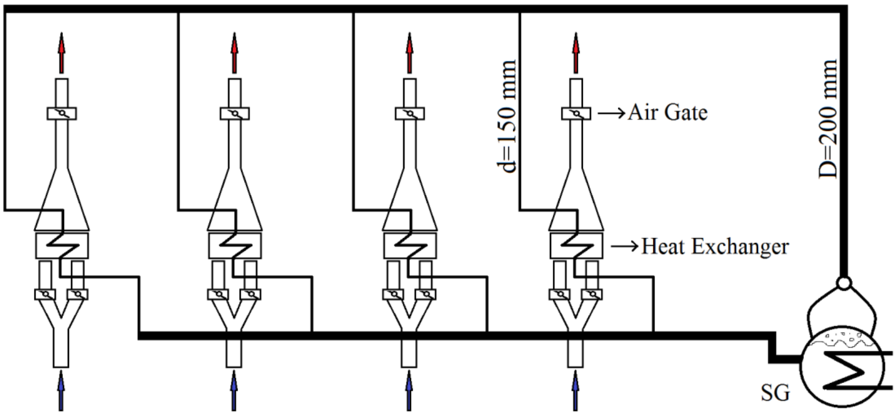

Figure 1. PRHR system for VVER type reactors: cooling by atmospheric air.

remove heat from the reactor plant in case of a long term station blackout, and also to depressurize the Reactor Circulation System (RCS) under a small break Loss of Coolant Accident (LOCA) [2]. The removal of residual heat should be provided without damage to the reactor core and the primary system boundary for an unlimited time.

The PHRS consists of four independent trains, each of them is connected to the respective loop of the reactor plant via the secondary side of the SG. Each train has pipelines for steam supply and removal of condensate, valves, and four air-cooled heat exchanger modules outside the containment. The steam that is generated in the steam generators due to the heat released in the reactor, condenses and rejects its heat to the ambient air in the PRHRS. The condensed liquid is returned back to the SG. The motion of the cooling medium takes place as NC. Heat removal capacity through three channels under the worst external conditions (temperature of ambient air is $+50^{\circ}$C) amounts to not less than 2% of nominal reactor power [3].

The heat exchanger of PRHRS depends on reliable passive components and processes such as gravity effect and NC rather than the active equipment such as pumps and AC power sources. It is the main component of PRHRS. In literature it is said that the PRHRS for VVER can safely remove the decay heat in case of the extended station blackout accident and enhance the inherent safety of the plant.

3 Problem Description and Boundary Conditions

In this study, we assume that the plant goes into a station black-out condition. Since there is no electric power source, the desired decay heat removal must be based on NC. The heat removal system should not require any operator actions. There are no pump(s) in the coolant loop or blower(s) in the air cooler. The cooling system consists of the SG, a closed water circuit and an air cooler. One loop of the train is illustrated in Figure 2.

3.1 Steam generator side: Condensation in helical pipe

Steam generator connected to a large-diameter pipe ($D = 0.2$ m) (see Figure 1). This pipe goes to the air cooler, where the cooling water is distributed over four small-diameter pipes ($d = 0.15$ m). At the outlet of the air cooler the coolant is collected again into one big pipe and then

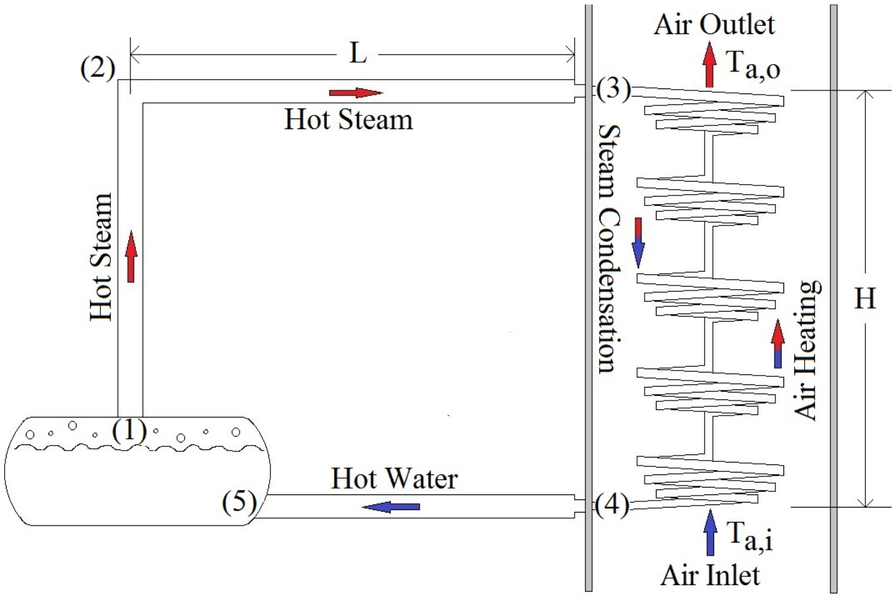

Figure 2. Simple representation of the computational domain.

circulates back to the SG [4,5]. In this study, one of the four loops is investigated. Operating and boundary conditions are adjusted for this model geometry.

The coolant takes heat from the SG, and the heat is emitted into the atmosphere through the air cooler. The SG is assumed to be insulated from reactor building. The present study is the design analysis for the SG. The implications of the passive system with respect to design of equipment should be carefully analyzed.

3.2 Heat exchanger side: Specifications for VVERs

Dimensions of reactor building for typical VVER nuclear power plants are about 70 m in height and 45 m in diameter. So available elevation for HE must be smaller than 45 m because of the form of dome. The perimeter of the reactor building is about 140 m. This information is significant for the cross-sectional area of air-side of the HE. The initial conditions for the temperature and pressure of the air coolant are atmospheric conditions.

3.3 Boundary conditions

In normal operation, secondary cycle (steam cycle) pressure is 7.84 MPa and steam temperature is 300°C (superheated steam). In this study, SG outlet temperature is assumed to be 293.6°C (saturated steam, quality equals to 1.0), since in an earlier study geometric parameters were determined for these conditions [6]. Several values for temperature of ambient air are tested and the effect of this temperature is investigated.

In this study heat exchanger optimization for 2 MW capacity is examined using RELAP5 code. Calculation is provided by analytical calculation. According to the analytical calculations, there are several system combinations for 2 MW capacity. Also analytical calculations show that PRHRS can reject greater than 4 MW heat amount from SG. To obtain this capacity performance, elevation (H) between SG outlet and air cooler inlet is considered as 7 m and horizontal pipe length (L) is considered as 10 m for this calculations.

4 RELAP5 Nodalization

In the previous study [6], optimization analysis is performed to make a decision on the geometrical parameters. This is an analytical solution for this system. After deciding geometrical dimensions and parameters, RELAP analysis is performed. And also analytic and RELAP results are compared and some improvements are done coordinately.

According to analytical calculation, system height (H) is adopted as 7 m, pipe length (L) is adopted as 10 m and the heat exchanger tube length is adopted as 2394 m. Nodalization of the system is shown in Figure 3. Primary side (secondary cycle of reactor) has water-steam and secondary side (PRHRS heat exchanger side) has ambient air for working fluid.

SG is modeled as two separate volumes, one for steam side and the other one is for water side in the SG. This is a reasonable assumption, since there is a heat source in SG (primary side of the reactor still working) and water level of the SG almost constant during the process. So boundary conditions and thermodynamic properties of steam and water are almost constant for SG inside.

All loss terms are determined in the analytical calculation. Using system height, heat exchanger area and tube length values, the number of coils are determined. Coils are modeled as inclined pipes and the loss terms for helical geometry are included to the system.

Heat structures are included and the data obtained from analytical study (previous study) are used for its initial values. There is no time dependent junction in the nodalization. So both cycles are circulate naturally.

5 Results

In analytical calculations, for 2 MW capacity of PRHR heat exchanger, geometrical parameters are obtained as 7 m in height, 10 m in horizontal length, 2394 m in tube length (heat exchanger) and boundary conditions are used as 7.84 MW in steam pressure, 298 K in air temperature and operation conditions are found as zero exit quality, 373 K in air outlet temperature, 1.377 kg/s in steam mass flow

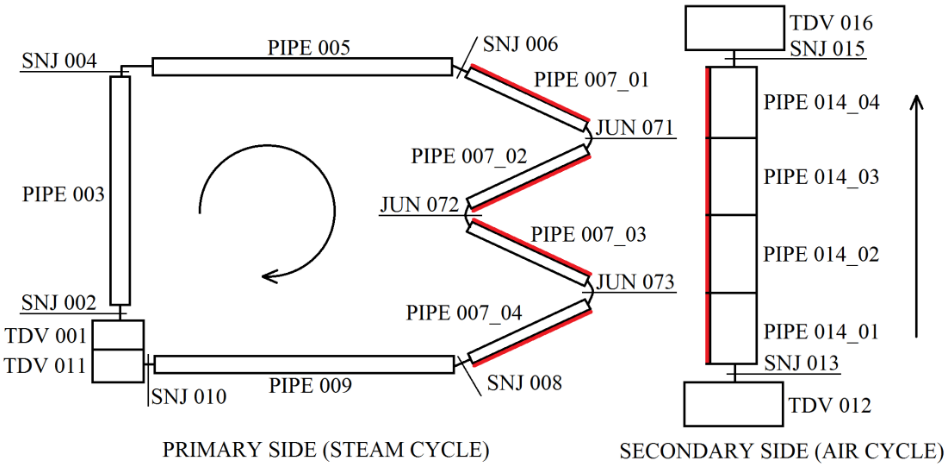

Figure 3. RELAP5 nodalization for the system.

rate and 26.126 kg/s in air mass flow rate. Same geometrical parameters are adopted in RELAP analysis.

Figure 4 shows time dependent rejected heat amount from the system. Steady state condition is reached and natural circulation mechanism started to work properly. Rejected amount is 1.88 MW. This geometrical configuration is designed for 2 MW capacity in analytical calculation. There is about 6% deviation between analytical and RELAP calculations. Several assumptions were adopted in analytical calculation. The reason of these deviations come from this acceptances and correlations applied.

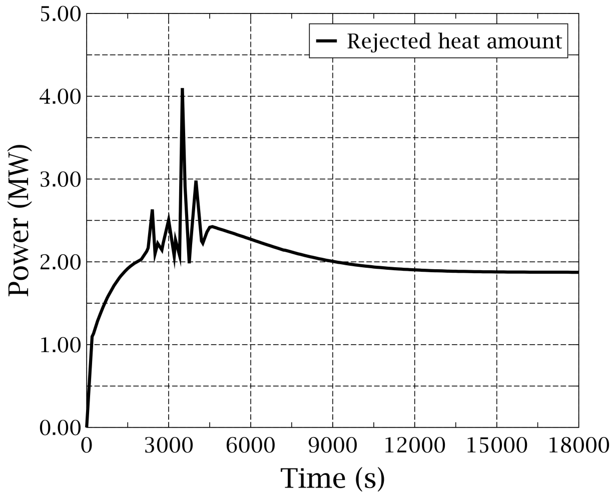

Figure 4. Rejected heat amount by air heat exchanger.

In Figure 5, void fractions at inlet and outlet section of heat exchanger tube are illustrated. Void fraction is 1.0 at the beginning part of heat exchanger and 0.0 at the outlet section of heat exchanger. Steam condenses completely while flowing through the helical tube of heat exchanger.

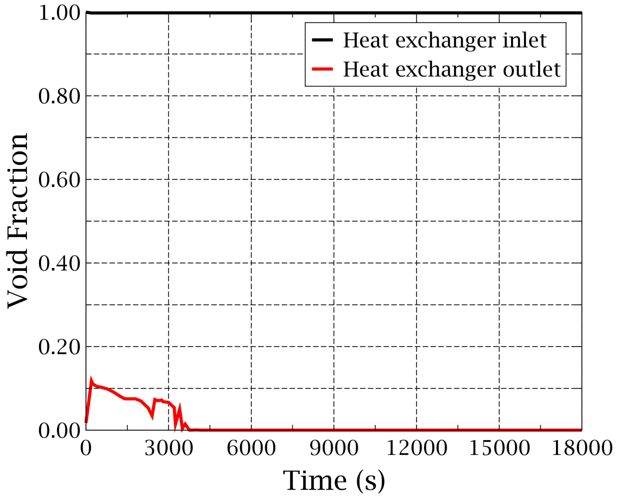

Figure 5. Void fraction profiles at inlet and outlet section of heat exchanger.

Figure 6 presents the temperature profiles for air side of the heat exchanger. The temperature of the ambient air is 298.0 K at the inlet, and the outlet temperature is calculated as 369.5 K. There is about 72 K increase in ambient air temperature. This heated air is released from the top section of reactor building after passing through the filtering plant and deflector, respectively.

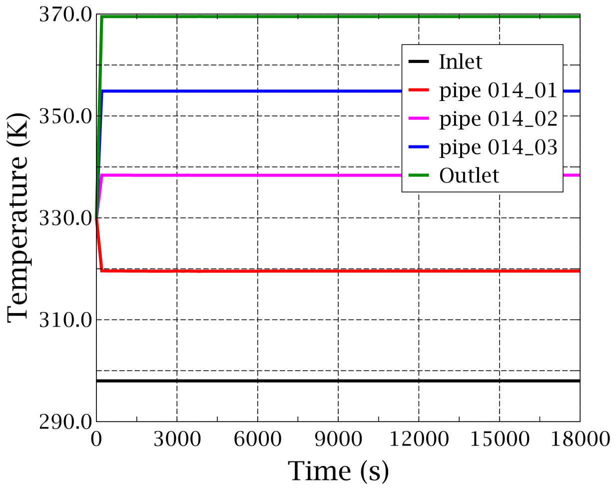

Figure 6. Temperature profiles at air side of the heat exchanger.

Flow rates of both steam and air are illustrated in Figure 7. These are mass flows of natural circulating fluids. Both steam and air circulate without any equipment such as pumps. Mass flow rates of steam and air are 1.291 kg/s and 25.48 kg/s, respectively.

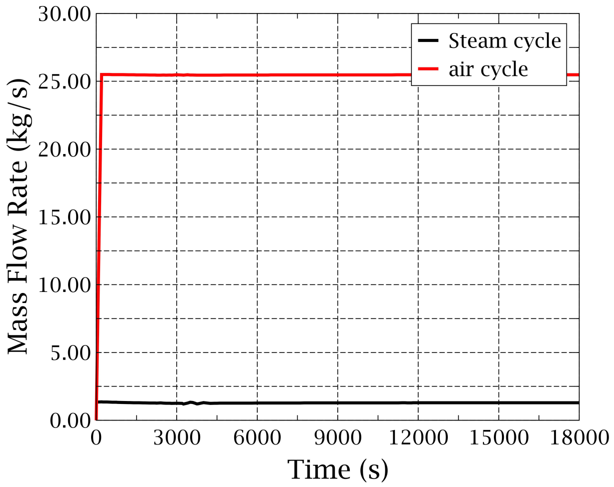

Figure 7. Mass flow rates for steam and air cycles (natural circulation).

Comparisons between the RELAP calculations and analytical results are listed in Table 1. All results are in good agreement with each other. These results also show that the performance of PRHRS is in the order of MW. In addition, at least 2 MW heat can be rejected in one unit of trains (there are 16 units in VVERs).

Table 1.

	Analytical	RELAP
System height H [m]	7.0	7.0
Pipe length L [m]	10.0	10.0
Heat exchanger tube length [m]	2394	2394
Steam flow rate [kg/s]	1.377	1.291
Air flow rate [kg/s]	26.13	25.48
Air heat transfer coefficient [W/m^{2}K]	7.396	7.226
Air outlet temperature [K]	373.0	369.5
Void fraction of condensed steam	0.0	0.0
Heat rejection amount [MW]	2.00	1.88

6 Conclusions

In previous study the new geometrical configuration of heat exchanger was designed analytically. Using this configuration, thermal-hydraulic calculations of Passive Residual Heat Removal System (PRHRS) were performed in this study. As it is stated in the literature, the achievable heat rejection by the PRHRS is in the order of MW in VVER type nuclear reactors. This is tested in present study with the RELAP5 code simulations.

This study shows that natural circulation problems having both air and water cycle can be simulated using RELAP code. There are some acceptable differences between analytical and RELAP calculations. In previous study [6] several assumptions were made to perform analytical calculation. And several correlations were used for friction factor and heat transfer coefficients. The reason of these discrepancies come from this acceptances and correlations applied. However the order of rejected heat amount is same for these calculations in the case of same geometrical and boundary conditions.

The residual heat generation rate of a reactor is about 1% of the nominal reactor power after a couple hours. For VVER-1200 type NPPs, thermal power is 3200 MW, and 1% of the nominal power is 32 MW. There are 16 small PRHR units in this type reactors. So, in one unit, heat rejected amount is about 2 MW. In this study, calculations with adopted parameters show that this heat amount can be rejected from the system.

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