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Design and modeling of the passive residual heat removal system for VVERs

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ABSTRACT

The results and effects of the Fukushima Daiichi accident show that the passive safety systems, which require no user input in order to operate, are very significant in nuclear industry. Even after stopping the reactor, heat dissipation remains a primary concern. If the reactor is not properly managed after shutdown, residual heat may cause catastrophic failures. The passive residual heat removal system (PRHRS) is designed to increase the inherent safety features of Nuclear Power Plants (NPP). In the present study, thermal hydraulic performance of the PRHRS of VVER type NPP is investigated using RELAP5 MOD3.4 (developed by Innovative Systems Software) system code. The PRHRS is designed to remove decay heat when normal heat removal system is not available and it consists of steam generator secondary side, a heat exchanger cooling by atmospheric air, and corresponding pipes, valves and air gates. In accident conditions, residual heat is transferred to the ambient air by natural circulation in both steam and air cycles of PRHRS. In the part which include analytical calculations of this study, geometric design parameters of PRHRS was investigated for 5.50 MW heat capacity. Selected system parameters, which are found by performing analytical modeling, are tested and analyzed with RELAP5 code and compared with the analytical results. Steady-state behavior of the system has been simulated, and cooling capacity of PRHRS has been investigated during station blackout scenario (including loss of coolant accident case). The results of steady-state behavior obtained by using RELAP5 code show that the PRHRS is able to take residual heat away from the primary coolant system.

1. Introduction

For the Nuclear Power Plants (NPPs), improvements in reliability, economics and safety are important. Passive safety concept was proposed to improve safety and reliability of NPPs and to ensure the integrity of reactors. Passive safety systems have become more important after the Fukushima Daiichi accident (Fu et al., 2015). Except the passive safety systems, all controls at NPP are power operated, and if a station blackout follows an initiating event, all power-operated systems would fail (Zubair et al., 2014).

The operational principle of passive safety system is based on natural forces, such as gravity. In passive safety systems, safety functions are less dependent on active components like pumps and diesel generators. It does not only simplify engineered safety features, but also improves the inherent safety of NPP, since it reduces possible malfunctions due to human intervention. However, the passive safety systems have lack of practical operating experience and their performance is heavily influenced by the other systems. A passive residual heat removal system requires large elevation difference between heat source and heat sink in order to improve the ability of natural circulation.

For the (beyond) design basis accidents, the (short or long term) station blackout accident has a great importance in the design of nuclear power plants. After reactor shutdown, decay heat generation continues and it has the possibility to cause a severe accident. Passive safety systems have to remove this residual heat sufficiently, since active cooling systems need the electric pumps, which are unavailable in case of station blackout accident.

In the Water–Water Energetic Reactor (WWER) or VVER design, passive systems are widely implemented to deal with design basis accidents and beyond design basis accidents. The passive residual heat removal system (PRHRS) is used to solve decay heat problem in VVERs. Based on the passive characteristics of the system, the PRHRS could remove the residual heat under natural convection conditions. The passive residual heat removal (PRHR) system is designed to provide cooling to reactor. The main system component is passive residual heat removal heat exchanger (HE), which uses atmospheric air as cooling fluid. With PRHR HE, residual heat

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is removed from the core to the atmosphere via the secondary side of steam generator (SG) at design basis accidents and beyond design basis accidents.

Similar heat removal systems are available in Chinese advance pressurized water reactor-CAPWR. By the way of PRHRS, residual heat is transferred to the cooling water pool, which is cooled by air natural circulation in the chimney. There are several numerical and experimental studies about CAPWR (Wenbin et al., 2014; Xinian et al., 2001; Zejun et al., 2003). Another natural draft air cooler system exists in high-temperature gas-cooled reactor (GTHTR300A) design (Yan et al., 2014).

According to the literature (IAEA, 2002, 2009, 2012), PRHRS, which is located in VVER type reactors, can remove up to 2% of reactor nominal power. However, there are no technical specifications about PRHRS of VVERs in the literature. The main purpose of this study is designing and modeling of PRHRS, which is able to remove residual heat from the reactor core, and examining the system whether it works naturally or not.

In the previous part of this study, an analytical model was developed to determine the geometrical specifications of PRHRS located in VVERs. With the help of this model, mass flow rate of primary (steam coming from SG) and secondary (ambient air) fluids and the heat capacity of PRHR HE can be determined under different geometrical design and boundary condition.

In the presented study, using outputs of analytical calculation, PRHRS which is able to reject residual heat (2% of nominal power) is modeled using RELAP5 MOD3.4 system code (developed by Innovative Systems Software). The results of this study give ideas about the capacity of passive heat removal system of VVERs. Results are significant since they contribute lots of informations to the literature.

2. Passive residual heat removal system of VVER

The PRHRS consists of four independent trains, each of them is connected to the respective loop of the reactor plant via the secondary side of the steam generator. 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 by the PRHRS. The condensed liquid returns back to the SG. The motion of the cooling medium takes place as natural circulation (IAEA, 2009).

Steam generator is connected to a large-diameter pipe ($D = 0.2$ m) which is going through the air cooler (HE) of the PRHRS. Before reaching the air cooler units (four units), this large pipe is divided into four small-diameter pipe ($d_i = 0.15$ m). At the outlet of the air cooler the coolant is collected again into one big pipe and then circulates back to the SG (IAEA, 2009).

Fig. 1 presents one of the four heat exchanger units of the PRHRS. 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 the reactor building.

The heat exchanger is the main component of PRHRS and is located outside the containment acting as heat sink. The PRHR HE consists of ribbed and coiled tube bundle which removes core decay heat from the Reactor Cooling System (RCS) for certain postulated accident events where loss of cooling capacity via the steam generators occur.

Whenever the normal heat removal paths are unavailable, the PRHRS will be actuated by density difference between cold water in HE tubes cooled by ambient air and hot steam in SG. The core decay heat is removed continuously by natural circulation in the PRHRS and transferred to the atmosphere via PRHR HE. Natural

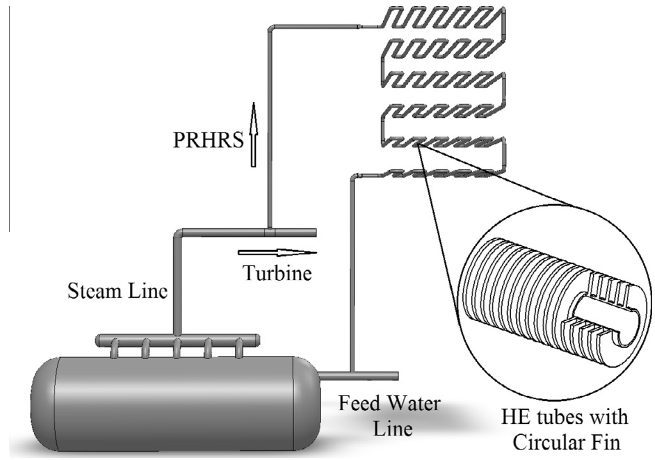

Fig. 1. Unit heat exchanger of the passive residual heat removal system connected to the secondary side of steam generator.

circulation within the PRHRS is provided by the appropriate placements of the steam generator, heat exchanger and draught air duct, which has the common outlet collector–deflector.

During normal operation, the PRHRS is in standby mode, and all the PRHRS circuits are in the warmed-up state. In case of plant blackout, the PRHRS state changes from the standby to the operating condition. In addition to its main purpose (core decay heat removal in case of complete loss of AC power), the PRHRS can maintain the hot standby conditions of the reactor plant; for this purpose the PRHRS has a special controller and air gates. Inlet and outlet gates and controller are installed on the air side of each heat exchanging module (IAEA, 2012).

Under standby condition the air gates are closed, but the heat exchangers are in the hot state due to air leakage through air gates and heat transfer through the building constructions. These thermal losses are estimated in the design to be less than 0.1% of reactor rated power (IAEA, 2002). The PRHRS is actuated by loss of power supply at electric magnets holding air lock in a closed position in about 30 s after the loss of all alternate current supply sources.

The PRHRS has 16 air cooled heat exchangers (each steam generator has four ones). The design basis of the PRHRS is the removal of up to 2% of nominal reactor power at the maximum design temperature of the external air (plus 50 °C) by taking into account failure of one train, so approximate power of the twelve heat exchangers is 64 MW for VVER-1200. The air flow rate is controlled by partial opening of the air gates to ensure that the power of the heat exchanger does not exceed the limit set for minimum design temperature of external air (minus 40 °C) (IAEA, 2002).

2.1. Passive residual heat removal system response during a station blackout

The initial state of NPP is the operation at rated power. As a result of an initial event, loss of all sources of alternating current electrical power, all main coolant pumps (MCP) are tripped, stop valves of the turbine generator are closed, the primary circuit makeup-blowdown system is disconnected, the power supply to pressurizer is disconnected, steam dump valves (to turbine) are disconnected, and the main and auxiliary feedwater systems of secondary circuit are stopped.

Besides, as the result of diesel generators failure to start, all active safety systems do not function. After scram, the reactor power reduces down to residual heat level. After the ending of MCPs coastdown the natural circulation of the primary coolant is