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Review of the nuclear reactor thermal hydraulic research in ocean motions

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ABSTRACT

The research and development of small modular reactor in floating platform has been strongly supported by Chinese government and enterprises. Due to the effect of ocean waves, the thermal hydraulic behavior and safety characteristics of floating reactor are different from that of land-based reactor. Many scholars including the author have published their research and results in open literatures. Much of these literatures are valuable but there are also some contradictory conclusions. In this wok, the nuclear reactor thermal hydraulic research in ocean motions was systematically summarized. Valuable results and experimental data were analyzed and classified. Inherent mechanism for controversial issues in different experiments was explained. Necessary work needed in the future was suggested. Through this work, we attempt to find as many valuable results as possible for the designing and subsequent research.

Contents

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In 20th century, many countries have accelerated the development of advanced small modular reactor (SMR). According to the classification adopted by the IAEA, "'SMRs' are reactors with equivalent electric power less than 300 MW (IAEA-TECDOC-1451, 2005)". Compared with the third generation nuclear power plant, the SMR of modular design is more flexible and of higher passive safety According to the report (IAEA-TECDOC-1451, 2005), several countries have launched their development program of SMRs, including America (SMR, mPower, and NuScale), Russia (KLT-40S, ABV, VK-300 and VBER-300), India (AHWR), Argentina (CAREM), Korea (SMART), France (NP-300), Japan (MRX and HTTR), China (HTR-PM, ACP100 and ACPR50S), etc. Until now, there are 26 SMRs under operation in the world. Besides that, there are also 4 SMRs under construction (Li et al., 2013a[1]).

SMRs are of particular interest for both near-term, e.g. seawater desalination, and advanced future non-electrical applications, such as hydrogen production and coal liquefaction. In China, the resources of oil and natural gas are in rich deposits in coastal region. The existing energy supply method is of high cost and pollution, resulting in a large emission reduction pressure. The SMR is an effective way to solve this problem and could fulfill the requirement of electrical energy supplying in oceans.

The SMR could be built on land or on a floating platform. Lee et al. (2013) presented a new concept for offshore nuclear power plants (ONPP) with enhanced safety features. The design concept of a nuclear power plant was mounted on gravity-based structures. A new emergency passive containment cooling system and emergency passive reactor-vessel cooling system were proposed. The seawater was used as coolant against earthquakes, Tsunamis, storms, and marine collisions. Buongiorno and his team proposed a new offshore floating nuclear plant (OFNP) concept with high potential for attractive economics and an unprecedented level of safety (Jurewicz, 2015). OFNP creatively combined state-of-the-art light water reactors and floating platforms similar to those used in offshore oil/gas operations. It eliminated earthquakes and tsunamis as accident precursors; its ocean-based passive safety systems eliminate the loss of ultimate heat sink accident by design. The OFNP crews operated in monthly or semimonthly shifts with onboard living quarters, like on oil/gas platforms. OFNP was a reactor for the global market which can be constructed in one country and exported internationally.

In China, several SMRs built on a floating platform are being designed (Li et al., 2013a). In ocean motions, the designing and operation of nuclear reactor is not exactly the same with that on land. Due to the action of waves, the coolant flow in primary loop and secondary loop is affected by additional forces. The gravitational pressure drop might also be changed due to the height variation between the reactor core and steam generator. The earliest open literature about the designing floating nuclear reactor was published by Isshiki (1966), Hiroshi and Kazuo (1969). They suggested that the guarantee of safety in nuclear ship is a dominant design criterion. From then on, more and more scholars have participated in the designing of nuclear reactor in ocean motions. Most of them were devoted in nuclear reactor thermal hydraulic analysis.

In recent years, the SMRs ACP100 and ACPR50S are being designed and are going to be built in China. Until now, much work including mathematical models for single phase and two phase flow and heat transfer in ocean motions, developing of thermal hydraulic code and sub-channel analysis code in ocean motions have been carried out. Although many analysis results and theoretical models have been published in open literatures, there are still plenty of numerical and experimental researches need to be finished.

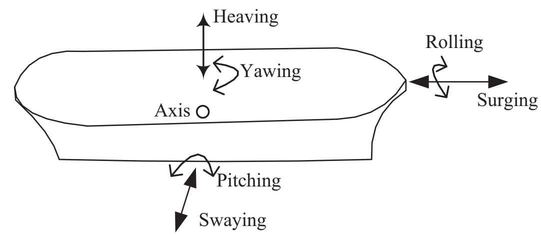

Fig. 1. Ship motions.

In this work, the investigation about nuclear reactor thermal hydraulic is systematically summarized. From mathematical models to the sub-channel analysis code and two phase flow experiments, most papers published in open literatures in this field are classified and evaluated. Through this work, we wish to find as many valuable results as possible for future work.

1. Description of ocean motions

The ocean motions that contributing to the nuclear reactor thermal hydraulic characteristics are usually caused by the ocean surface waves that occur in the upper layer of the ocean. They usually result from wind or geologic effects and range in size from small ripples to huge waves. Then the ocean motions affect on the ships or floating platforms and then result in difficult ship motions, as shown in Fig. 1. The ship motions are determined by ocean motions and ship parameters, like weight, length, height, etc. The law of ocean waves is complex, which one sees on an ocean beach usually result from winds. The wind usually changes with space and time. Therefore, the ocean motions and ship motions change with space and time, just like the wind waves. Due to the complexity of ocean motions, the real time simulation with high accuracy of nuclear power system on a floating platform is unrealizable. The research of seakeeping theory reveals that the complex ship motions are equivalent to the superposition of several single sinusoidal motions, approximately (Lewis, 1967). Ishida et al. (1990) investigated the thermal hydraulic behavior of a reactor with RETRAN code by assuming the ship motions to be a sinusoidal function. This method has been followed by nearly all scholars.

The ship motions mainly include heeling, heaving, rolling, pitching, yawing, swaying and surging motions (Ishida et al., 1990). In heeling or inclination motion, there is only height difference change but no additional force, which is different form the other six motions. The amplitudes of yawing, surging and swaying motions are usually very small, since the ship and floating platforms are long and narrow designed. Compared with these three motions, the heeling, heaving, rolling and pitching motions are more frequent.

In heeling motion, neither additional acceleration nor inertial force exists. Only the relative height difference between reactor core and steam generator is changed. That is the simplest motion and closest to the stationary state. In heaving motion, contrast to the heeling motion, there is no spatial distance variation, only an additional gravitational acceleration affects on the coolant flow. It was expressed by Ishida et al. (1990) as:

$$g(t) = g_0 + g_a \sin(nt) \tag{1}$$

where g_0 is gravitational acceleration in stationary state, g_a and n are the amplitude and frequency of the heaving motion, respectively. t is time.

[1] In order to distinguish the references from different authors with the same first name and the same publication year, the abbreviation of their second names is added in the citation. For example, the reference authored by Li et al. in 2013 is cited as Li et al. (2013a), rather Li et al. (2013). The reference authored by Li et al. in 2013 is cited as Li et al. (2013d), rather Li et al. (2013). This kind of citation is introduced in the subsequent section.