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Nuclear Power Plants: Recent Advances Towards to Safety

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1. Introduction

The demand for energy in the world is continuously growing. Electricity is one of the most common types of energy in the daily life and human development is directly related to the energy consumption [1]. Then, the question is how to generate increasing amounts of energy preserving the environment? Certainly, fossil fuels are not the solution. Solar, biomass, nuclear, hydroelectric, and wind energy have low emission of greenhouse gases, and each one of them has specific characteristics which shall be considered to choose the best alternative. Any power technology has advantages and disadvantages.

Solar energy has always been considered a clean energy, free of carbon emissions. Its maintenance cost is lower than other sources of renewable energy and provides service for a long time. However, the installation of photovoltaic panels requires large areas [2].

Wind energy is considered clean and ecological. It can be easily placed in terrestrial and aquatic environments. It uses wind speed to generate electricity. The major problem reported by the wind turbine is the noise caused, which disturbs flora and fauna, besides altering the aesthetics of the site, impairing tourism [2].

Biomass is one of the oldest sources of energy. Traditional charcoal power plants can be used to burn biomass for electricity production. However, research shows that biomass power plants are responsible for some environmental impacts [2].

Hydroelectricity is produced by the construction of a dam in a river. The water in higher altitude is released and falls into the blades of a hydroelectric turbine that produces electricity. Apparently, hydroelectric plants do not emit greenhouse gases during operation. However, environmental effects have been reported in some studies [2].

Considering this, nuclear energy emerges as an important alternative to promote the energy transition.

Besides of the kind of power generation, it is important to consider the best technology of power distribution, particularly in continental countries like Brazil. In this sense, large power plants require long distribution networks. Small power plants could meet distant locations, reducing distribution costs.

This paper aims to discuss the possible contribution of nuclear energy to compose the energy matrix using Small Modular Reactors (SMRs) technology, and some challenges to improve safety in this kind of reactor design.

2. Small Modular Reactors

Small Modular Reactors (SMRs) are seen as the technological way to overcome high costs and delays in building a large Nuclear Power Plant (NPP). Some SMRs design can help relieve the problem of nuclear waste disposal by using spent fuel and nuclear waste, helping the safeguard and nuclear weapon proliferation; moreover, they can offer inherent and passive safety capabilities, reducing the risk of severe accidents. In this sense, SMRs can play a significant role in facing the challenge of climate change, providing a reliable source of low carbon emission for electricity production [3].

Most of SMR design introduces simplifications by modularization, as well as system integration to increase safety using passively cooled containment, residual heat removal system, passive autocatalytic recombiners (PARs), and Accident Tolerant Fuels (ATF). However, the small free volume inside the containment can be one of the major challenges for SMRs design in order to keep the safety under severe accident conditions.

3. Nuclear Power Plant Safety System

The licensing process of NPP for the generation of electricity in the world was deeply affected by the Fukushima Daiichi accident in 2011 [3], where due to the loss of cooling in the fuel cladding there was the generation of a high amount of hydrogen resulting from exothermic reaction between water/steam and fuel rod cladding material (zirconium-based alloy). From then on, in the licensing process for a new facilities management of combustible gas inside the containment became a main safety concern.

3.1. Combustible Gas Management

Combustible gas, such as hydrogen, can be generated in a NPP during design basis accident and severe accidents. Hydrogen is generated due to the metal oxidation, especially for fuel systems which are based on zirconium alloys as cladding material; also from others material, such as boron carbide and stainless steel of reactor pressure vessel internal. Moreover, hydrogen can also be generated in later phases of severe accidents due to the interaction core-molted concrete [4]. The presence of combustible gas, particularly hydrogen, is recognized as a safety problem in water cooled reactors and combustion processes may represent a threat to containment integrity, among other safety concerns [4].

To ensure the effectiveness of mitigation systems, their performance shall be evaluated under a wide range of design and beyond design basis accident scenarios. In addition, in the light of the Fukushima Daiichi accident [3], additional experimental and analytical needs were identified for issues associated with hydrogen generation and fission products, together with the development of mitigation systems inside the NPP containment, using PARs and ventilation systems, which shall be investigated in an integrated and optimized approach [4].

To limit the concentration of combustible gas inside the containment, the strategies usually adopted are based on the following approaches: recombination of hydrogen generated under accident conditions using the PARs; deliberate and controlled ignition to consume flammable gas by combustion at low concentrations; forced ventilation of the containment atmosphere, ensuring the removal of the hydrogen present in the gaseous mixture; inertization by means of inert gas injection (nitrogen); mixing of the gas atmosphere to ensure homogenization avoiding the local accumulation of flammable gases mixtures [4].

The management of combustible gas (hydrogen) strategy in nuclear power plants can be implemented by one or a combination of previous methods. PARs have been developed and become commercially available in the last decade. The PARs are simple devices, consisting of catalyst surfaces arranged in an open-end enclosure [5]. In the presence of hydrogen (with available oxygen), a catalytic reaction occurs spontaneously on the surface of the catalyst and the heat of the reaction promotes a natural convection flow, exhausting the hot and damp hydrogen moist air from the upper part of the equipment and allowing the entry of fresh gas from the bottom.

PARs do not require any external power supply or reactor operator action; the installation requires only appropriate positioning of PARs units within the containment considering the volume of containment and the required recombination efficiency. The analysis of the performance of the PARs has shown that its performance has negligible dependence on its location within a particular compartment due to the very vigorous natural mixture process during the operation. The performance of the PARs is subject to mass transfer limitations and may not track the high hydrogen release rates in small volumes, for example, as in the vicinity of hydrogen source release [6].

PARs usually use the catalysts based on platinum and/or palladium to oxidize (recombine) hydrogen at low temperatures, in a wider range of hydrogen/oxygen concentration, and even under steam environment conditions [7].

3.2. Accident Tolerant Fuel

Under loss of coolant conditions, the cladding materials based in zirconium alloy are rapidly heated due to nuclear decay heat and rapid exothermic oxidation in water steam environment occurs and generate large amounts of hydrogen gas. The ATF technology aim to improve existing cladding technology in order increase resistance to oxidation reaction and reduce hydrogen generation, as well as improve the mechanical resistance, consequently, to keep the cooling geometry of the reactor core.

Several studies with alternative materials are under assessment and one of the most promising candidates for ATF cladding is the zirconium alloy coated with chromium, which can increase tolerance of zirconium-based alloys and can be deployed without significant changes in existing fuel technology. Another promising candidate is based on iron alloy, named FeCrAl alloy, which can endure during 24 hours under high temperature (1,200^{o}C) [8].

4. Conclusions

The generation and distribution of energy in continental size countries must have a diverse matrix in order to supply energy in remote areas. In this sense, various available sources should be considered, according to the size of cities and their distances from power generation, environmental, economic and social impact.

Among the different energy sources, nuclear energy is an excellent option to produce electricity free of carbon emission; and the technology of SMRs presents characteristics which enable to produce energy in compact power plants in remote areas with safety. However, for the implementation of SMRs with different designs, it will be necessary to overcome some challenges, such as to demonstrate the effectiveness of combustible gases management system inside small free volume containment and complying with the safety requirements, as well as development of ATF capable to improve the performance of fuel system under severe accident conditions. Many efforts are being carried out to overcome these challenges and to show the important contribution of nuclear energy, and specifically the technology of SMRs to promote an efficient energy transition.

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