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Heat and mass transfer aspects in nuclear power generation

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Abstract

This paper addresses specific heat and mass transfer aspects linked to nuclear power generation safety analysis. Nuclear power plants design and licensing depends on safety analysis performed using dedicated computer codes for heat and mass transfer, thermal-hydraulics, neutron calculations in order to anticipate and address transient and any unwanted operating regimes. Fission produced or residual heat present at all times in the core of a nuclear power plant demands special systems for heat removal and the heat and mass transfer aspects are the most important nuclear systems design criteria.

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Keywords: nuclear safety analysis, fission and residual heat removal, design criteria

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1. Introduction

Nomenclature

PHWR	Pressurized Heavy Water Reactor
PWR	Pressurized Water Reactor
BWR	Boiling Water Reactor
CANDU	Canadian Deuterium Uranium
LOCA	Loss of Coolant Accident

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Nuclear power plants operate at steady state conditions, transient conditions being demanded only during start-up/shut-down or power maneuvers. The most common reactors are the ones that use pressurized water as a cooling agent due to the high thermodynamic potential given by this fluid.

Transient states behavior for nuclear systems has represented a serious problem for the safely functioning analysis of nuclear power plants. Computer codes where initially developed to analyze the behavior of the reactors and the plant in accident conditions, under conservative hypothesis. In this manner, the qualitative and quantitative developments during an accident where not taken into account. Specialists working on safety analysis for nuclear power plants aim to reproduce as realistic as possible the power plant behavior during an accident scenario and to study the action of emergency safety systems such as the control and shutdown system, decay heat removal systems which put the plant in an safe state in which repairs can be done or no radioactive release occurs.

In an accident scenario, as shown by the Three Mile Island and Fukushima accidents, hydrogen is generated due to high temperature metal oxidation in accident condition after failure to extract decay heat. Heat transferred from the fuel to adjacent structures increases temperatures in the metal alloys and an oxidation reaction produces more heat and hydrogen if coolant in liquid or vapour form is present. These phenomena are important for future accident development and are the subject of this paper, from the heat and mass transfer problems point of view.

2. CANDU pressure tube oxidation modeling mathematical relations

A feature of the structure of the core for PHWR (Pressurized Heavy Water Reactor) type reactor is dividing coolant flow in channels. This division brings additional structures to cores typical for PWR (Pressurized Water Reactor) / BWR (Boiling Water Reactor) and with them the possibility of oxidation of these structures where significant increases in temperature in the course of an LOCA (Loss of Coolant Accident) type accident due to excess metal at high temperatures existing in the later-stage accident. The SCDAP / RELAP5 computer code had a gap in what concerns modelling these systems in CANDU (Canadian Deuterium Uranium PHWR reactor, with no SCDAP or RELAP component to simulate zirconium alloy pipes surrounding the CANDU channel fuel bundles.

This was compensated with the introduction of the shroud component in SCDAP/RELAP5 family models [1]. The shroud component [2] can simulate the pressure tube and Calandria tube type structures in an LOCA accident, analyzing the contribution of heat of oxidation of these structures in addition to oxidation of the fuel elements. Below we present a study of the pressure tube oxidation in an LOCA type accident.

Metal alloy oxidation is modeled using parabolic rate equations and take into account material propreties listed in libraryes developed allong with the code [3][4]. The SCDAP/RELAP5 code was initialy developed for PWR and BWR reactors that have light water as a coolant but incorporates heavy water proprieties that enables it to model CANDU type reactors

The material oxidation model calculates heat generation, hydrogen production and the amount of steam reduction due to oxidation reactions. This model uses equations for calculating the rate of oxidation of the material with temperature defined by the pattern of the heat-conducting component.

It is assumed that oxidation of the materials followes the parabolic equation for the production rate

$$\frac{d\delta}{dt} = \frac{A}{\delta} e^{(\frac{-B}{T})} \tag{1}$$

where

δ = gain weight or thickness (kg / m^2 or m)

T = temperature (K)

t = time (s)

A, B = constants taken from materials proprieties library present in the code.

For a constant temperature, this equation can be integrated on the time interval Dt, in order to arrive at:

$$\delta^2 - \delta_0^2 = 2Ae^{(\frac{-B}{T})}\Delta t \tag{2}$$

Where δ_o is the value at the time interval start. For the zirconium alloy, three separete parabolic equations are solved for weight gain of oxygen and increase of α type material and ZrO_2 layers. For all other materials only increase of the mass of oxygen is calculated.