Progress in Nuclear Energy 97 (2017) 182–196

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Review

A review on clogging of recirculating steam generators in Pressurized-Water Reactors

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ARTICLE INFO

Article history:
Received 3 August 2016
Received in revised form
9 January 2017
Accepted 24 January 2017

Keywords:
Iron
Reactor conditions
High-temperature-high-pressure test loop
Modelling studies
Precipitation
Magnetite particle deposition

ABSTRACT

Corrosion product deposits in the secondary side of nuclear power plant steam generators may result in Tube Support Plate (TSP) clogging and tube fouling. Magnetite has an inverse solubility above 150 °C, which favours iron precipitation when temperature increases. Flashing and electrokinetics are two strengthening processes for precipitation in TSP clogging. Surface chemistry of magnetite particles was discussed to understand its' interaction with TSP. Particle deposition by boiling was identified as the limiting process by performing numerical applications with nominal conditions. Guidelines drawn from this review for investigating specifically TSP clogging consist on conducting representative condition experiments and electrokinetics investigations.

1. Introduction

Électricité de France (EDF) nowadays operates 58 Pressurized Water Reactors (PWR) that produce more than sixty-three thousand megawatts of installed power capacity and more than 85% of electricity in France (Prusek et al., 2013). Safety and performance of these reactors are crucial targets to ensure electrical supply to the whole national territory. Steam generators (SG) play a crucial role as a heat exchanger from the primary to the secondary flow and as one of the three safety barriers.

The steam generators in PWRs are shell-and-tube heat exchangers that use the heat from the primary reactor coolant to make steam drive turbine generators. Fig. 1 presents a cross-section of a simplified PWR recirculating steam generator. In this design, the tube bundle consists of 3000–6000 individual tubes, each welded to a thick plate (called a tube support plate (TSP)) with a hole for each tube. The thermal hydraulic characteristics of PWR steam generators were well studied by groups of Xi'an jiaotong University (Cong et al., 2013, 2015; Tian et al., 2016; Zhang et al., 2017), by numeric simulations based on the porous media models and experimental single-phase and steam-water two-phase flow investigations. Heat transfer from primary to secondary side, pressure drop for a vertical two-phase flow across a horizontal rod bundle and the effects of power level on thermalhydraulic characteristics were particularly discussed. As an example, the maximum and minimum mass fractions of vapour phase (C_g) in steam generators were found to be 0.659 and 0.073, respectively. Other thermalhydraulic parameters can be found in these referenced works.

Under complex thermal hydraulic conditions, steam generators manufactured using different materials are susceptible to various forms of degradation (Delaunay, 2010): carbon steel, present in large numbers of pipes upstream of SG, is mainly affected by accelerated flow corrosion (FAC); SG tube materials, including Alloy 600, Alloy 690 and Alloy 690 TT, can be affected by pitting, thinning, and intergranular stress corrosion cracking; TSP, which is made of stainless steel containing 13% Cr, can be affected by clogging or blockage phenomenon. Whilst corrosion degradation of these materials were carefully investigated by many groups (Morrison et al., 2012), there is relatively few published work detailing the TSP clogging formation mechanism. Therefore, the present paper is more focused on the comprehension of the physicochemical phenomena involved in TSP clogging.

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http://dx.doi.org/10.1016/j.pnucene.2017.01.010

Nomenclature

Abbreviations

XRD	X-ray Diffraction
GDOES	Glow Discharge Optical Emission Spectrometry
AFM	Atomic Force Microscopy
WRL	Wide Range Level
EDL	Electrical Double Layer
FAC	Flow Accelerated Corrosion
NPP	Nuclear Power Plant
TSP	Tube Support Plate
SG	Steam Generator
SCC	Stress Corrosion Cracking
PZC	Point of Zero Charge
EDF	Electricité De France
AECL	Atomic Energy of Canada Limited
EPRI	Electric Power Research Institute
SGOG	Steam Generator Owners' Group
HTCC	High Temperature Chemical Cleaning
ASCA	Advanced Scale Conditioning Agents
DMT	Deposit Minimization Treatment
PACCO	Preventive Acid Chemical Cleaning Operation
SHE	Standard Hydrogen Electrode

Roman symbols

a	modelling coefficient
g	standard gravity constant (9.8 m/s^2)
C_p	particle concentration (kg/kg)
C_l	mass fraction of liquid phase
C_g	mass fraction of vapour phase
C_b	ion concentration in the bulk (kg/m^3)
C_i	ion concentration at the solid-liquid interface (kg/m^3)
C_s	saturation concentration (kg/m^3)
E	activation energy (J/mole)
E_r	re-entrainment rate (s^{-1})
H_{lg}	heat of vaporization (J/kg)
ΔH_l	enthalpy variation of liquid phase (J/kg)
S	solubility of soluble species (kg/kg)
T_l	fluid temperature (K)
T_s	surface temperature (K)
S_c	Schmidt number of particles
Re_l	Reynolds number of liquid phase
D_p	diffusion coefficient of particles (m^2/s)
U	friction velocity (m/s)
U_l	average velocity of liquid phase (m/s)
U_z	vertical mixture velocity (m/s)
R	universal gas constant (8.314 J/mole/K)
N	function of the nucleation sites provided by particles
M_f	mass of deposit at time t (kg)
M_{fg}	mass of deposit at the start of crystal growth (kg)
K_0	constant (m/s)
K_d	particle deposition rate (m/s)
$K_d(1\varphi)$	particle deposition rate for one-phase flow (m/s)
$K_d\,(2\varphi)$	particle deposition rate for two-phase flow (m/s)
K_t	particle transport rate (m/s)
K_a	particle attachment rate (m/s)
K_b	deposition rate due to boiling process (m/s)
K_{diff}	diffusion rate (m/s)
K_s	sedimentation rate (m/s)
K_i	inertial rate (m/s)
K_{th}	thermophoresis rate (m/s)
$K_{t,s}$	soluble iron transport rate (m/s)
$K_{b,s}$	soluble iron precipitation rate (m/s)
$K_{v,p}$	particle deposition rate in "vena contracta" mechanism (m/s)
K_r	reaction rate constant (m^4/kg s, if $n = 2$)
m_d	deposit mass (kg/m^2)
m'	deposit mass by crystallization fouling (kg/m^2)
t	time (s)
n	order of reaction
n'	exponent
k_b	Boltzmann constant (1.38×10^{-23} $J.K^{-1}$)
t_p^+	relaxation time
d_p	particle diameter (m)

Greek letters

β	mass transfer coefficient (m/s)
$\rho_{p/l}$	particle/fluid density (kg/m^3)
ρ_m	average density of liquid/gas mixture (kg/m^3)
μ_l	dynamic viscosity of fluid (kg/m/s)
ν_l	kinematic viscosity of fluid (m^2/s)
φ_w	heat flux (W/m^2)
φ_l	mass flux of liquid (kg/s)
φ_s	mass flux of soluble specie precipitation (kg/s)
λ_p	particle thermal conductivity (W/m/K)
λ_l	fluid thermal conductivity (W/m/K)

In the early 1990's, SG water oscillations were observed at Surry Power Units 1 and 2 in Virginia, at Kori Units 3 and 4 and Yongwang Units 1 and 2 in Korea (Rummens et al., 2004; Schindler et al., 2012). This phenomenon was caused by a severe deposit build-up in the TSP quatrefoil-shaped holes. EDF Nuclear Power Plants (NPPs) have been recently affected by the same phenomenon. Between 2004 and 2006, three primary-to-secondary leaks occurred in NPP located in Cruas (France). In-situ investigations showed that the flow holes of the uppermost TSP (8th TSP in SG 51B) were partially or completely clogged by corrosion products (Corredera et al., 2008; Bodineau and Sollier, 2008) (Fig. 2). This phenomenon, so-called TSP clogging or TSP blockage, was considered potentially generic for EDF NPPs.

Tube fouling (Fig. 3) is a deposit on the tube surfaces which is penalizing for the heat exchanges between the primary and the secondary circuits (Varin, 1996; Demasles et al., 2007). Tube fouling can also induce a decrease in outlet steam pressure and a loss of efficiency of steam generators.

TSP blockage is a deposit at the inlet of TSP flow holes. This phenomenon can induce high velocity zones and transverse velocities in the secondary flow, which can imply flow induced vibrations, tube cracks and leaks in some cases as it was observed in the NPP located in Cruas (France) as described above. TSP clogging phenomena can also decrease the recirculation ratio of the steam generator. In other words, the secondary side effective flow of water available for cooling is decreased. Thus, fouling and clogging phenomena in nuclear steam generators may lead to dramatic consequences for NPP operation and may lead to safety issues (Bodineau and Sollier, 2008).

In order to prevent these phenomena, various countermeasures, especially chemical or mechanical cleaning and high pH water treatment of the secondary circuit, are being implemented by EDF.