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Extending the reactivity initiated accident (RIA) fuel performance code SCANAIR for boiling water reactor (BWR) applications

Asko Arkoma

VTT Technical Research Centre of Finland Ltd., Kivimiehentie 3, P.O. Box 1000, FI-02044 VTT, Finland

HIGHLIGHTS

- SCANAIR RIA fuel modelling code, developed for PWRs, is extended for BWRs.
- SCANAIR is coupled with GENFLO thermal hydraulics code.
- The coupling broadens the code's application field to bulk boiling conditions of BWR.
- In PCMI phase, failure predictions are evaluated with EPRI's CSED criterion.

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ABSTRACT

In this paper, capabilities of the SCANAIR transient fuel performance code are evaluated and extended for boiling water reactor (BWR) fuel low temperature cladding failure predictions and high temperature thermal hydraulics modelling. The SCANAIR code, developed by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), is designed for modelling the behaviour of a single fuel rod during reactivity initiated accident (RIA) in a pressurized water reactor (PWR). In a previous study (Arffman et al., 2012), new BWR cladding material property correlations were developed and implemented into SCANAIR. Here, SCANAIR's ability to predict BWR cladding failures due to pellet-cladding-mechanical interaction (PCMI) is evaluated by modelling the NSRR FK test series. SCANAIR is found to give correct predictions with reasonably good accuracy when applied to a larger dataset of several tests. As the standard thermal hydraulics model in SCANAIR is one-dimensional and able to model single phase coolant only, the simulation of a BWR RIA, the control rod drop accident, is not possible when the bulk boiling regime is reached. In this study, the code's application field is broadened to consider bulk boiling in BWRs. In the chosen approach, SCANAIR is coupled with an external thermal hydraulics code. For that, VTT's in-house general thermal hydraulics code GENFLO has been used. The first demonstration simulations show promising results.

1. Introduction

Transient fuel performance codes are important tools in transforming integral and separate effect test results into the expected outcomes of transients and accidents in commercial reactors. In reactivity initiated accident (RIA), four distinct fuel failure modes may be specified. The only low temperature cladding failure mechanism is caused by the pellet-cladding mechanical interaction (PCMI), while burst failure, quenching failure, and melting happen at high temperatures (OECD/NEA, 2010). Thermal hydraulics (TH) plays important role in high temperature region, whereas in low temperature PCMI it is less important. In this study, both low and high temperature phenomena are considered.

In order to model BWR fuel in an RIA, the cladding mechanical properties and failure criteria need to be adapted for Zircaloy-2 (Zry-2) cladding alloy used in BWR fuel rods. In particular, the plastic behaviour of Zry-2 is different from that of e.g. Zry-4 cladding used in PWRs. To this end, the Zry-2 cladding yield stress (YS) and ultimate tensile stress (UTS) correlations have been fitted and implemented (Arffman et al., 2012) into SCANAIR fuel performance code developed by IRSN (Moal et al., 2014). In this paper, the EPRI's updated critical strain energy density (CSED) criterion (EPRI, 2015) is applied for cladding low temperature failure analysis with SCANAIR.

In the high temperature region, in which the cladding temperature is strongly affected by the TH behaviour, there is still plenty of room for improvements in modelling. Namely, one of the outcomes in the RIA modelling benchmark Phase II

E-mail address: asko.arkoma@vtt.fi

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Nomenclature

Abbreviations

AECL	atomic energy of canada ltd
BST	Bishop-Sandberg-Tong film boiling correlation
BWR	boiling water reactor
CEA	commissariat à l'énergie atomique et aux énergies alternatives
CHF	critical heat flux
CSED	critical strain energy density
CZP	cold zero power
DFFB	dispersed flow film boiling
EPRI	electric power research institute
FWHM	full width at half maximum
GENFLO	GENeral FLOw, thermal hydraulics code by VTT
HFP	hot full power
HZP	hot zero power
IAEA	international atomic energy agency
IAFB	inverted annular film boiling
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
JAEA	Japan atomic energy agency
LOCA	loss-of-coolant accident
MTA-EK	Hungarian academy of sciences, centre for energy research
NEA	nuclear energy agency
NSRR	Nuclear Safety Research Reactor
ODESSA	organisation of data exchanges in scientific software architecture
OECD	organisation for economic co-operation and development
PBF	power burst facility
PCMI	pellet cladding mechanical interaction
PROMETRA	PROpriétés MEcaniques en TRAnsitoire
PWR	pressurized water reactor
QT	quantum technologies AB
RIA	reactivity initiated accident
SCANAIR	Système de Calcul et d'ANalyse d'Accident d'Insertion de Réactivité
SED	strain energy density
SPERT	special power excursion reactor
SSM	strålsäkerhetsmyndigheten
TC	thermocouple
TH	thermal hydraulics
UTS	ultimate tensile stress
VTT	VTT technical research centre of Finland Ltd.
WGFS	working group on fuel safety
YS	yield stress
Zry	zircaloy

Symbols

α	void fraction
ΔT_L	Leidenfrost temperature difference
ε	strain, cladding emissivity (in Table 1)
ρ	steam density
σ	stress, Stefan-Boltzmann constant (in Table 1)
Φ	heat flux
e_0	as-fabricated cladding thickness
e_{ZrO2}	zirconia layer thickness
F	hydrogen pick-up
H	hydrogen
h	heat transfer coefficient
P	pressure
T	temperature
x_l, x_g	liquid and steam mass

(OECD/NEA, 2015, 2017), organized under the OECD Nuclear Energy Agency (NEA) Working Group on Fuel Safety (WGFS), was that the simulated cladding temperatures had very large dispersion among the various RIA fuel codes if the boiling crisis is reached. Poorly modelled cladding temperature evolution affects also many other output parameters of the simulations, undermining the confidence to the results. The difficulty in the RIA TH modelling is that the heat transfer in fast transients differs significantly from that of steady-state or slow transients. The lack of relevant experimental results, and the difficulty to experimentally measure TH phenomena in fast transient conditions, are identified problems (OECD/NEA, 2015).

The pursuit of improved thermal hydraulics modelling in RIA fuel behaviour analyses has accelerated during recent years in many organizations worldwide. In Japan Atomic Energy Agency (JAEA), improvements in the TH modelling of the RANNS code have been accomplished based on old RIA test data from Nuclear Safety Research Reactor (NSRR) tests in Japan in water loop with versatile thermal hydraulic conditions (Udagawa et al., 2013). Quantum Technologies (QT) has developed for Swedish Radiation Safety Authority SSM a simple homogeneous equilibrium model for the two-phase water coolant (Jernkvist, 2016; OECD/NEA, 2015). It is intended for BWR RIA applications, and implemented into SCANAIR. MTA-EK has built an online coupling between the fuel performance code FRAPTRAN and VTT-originated hot-channel code TRABCO, to be applied in RIAs (Keresztúri et al., 2013). In Utah State University, internal coupling of BISON fuel performance code has been created with thermal hydraulics code RELAP5 for RIA applications (Folsom et al., 2016).

The basic TH model in SCANAIR is one-dimensional and able to model single phase coolant. Extending the TH modelling to consider bulk boiling conditions is important for further diversifying the code's application field in terms of initial conditions and transient boiling. In the chosen approach, SCANAIR is coupled with an external thermal hydraulics code. By this way, the two phases of fluid in BWR can be taken into account in a detailed manner. For the coupling, the TH code GENFLO (Miettinen and Hämäläinen, 2002) has been chosen. The coupling, as well as the first results, are presented in this paper.

The paper is structured as follows. The applied modelling codes are described in Section 2. The low temperature cladding failure predictions are presented in Section 3, and the high temperature modelling is presented in Section 4. The summary is given in Section 5.

2. Codes' descriptions with implications to BWR modelling

2.1. SCANAIR

SCANAIR code is specifically designed for modelling fast transient conditions. It considers the fuel rod mechanical behaviour, fission gases, and thermal behaviour including the thermal hydraulics. The current SCANAIR version is V_7, with various subversions. Extensive reviews on SCANAIR models (Moal et al., 2014) and modelling capabilities (Georgenthum et al., 2014) are provided by IRSN. Performance comparisons of the two most applied codes in the RIA benchmark (OECD/NEA, 2017), SCANAIR and FRAPTRAN, have been done by Sagrado and Herranz (2014). The applied SCANAIR subversions in this paper are V_7_2 in the low temperature simulations, and V_7_4 in the high temperature part.