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UNIVERSITÀ DI PISA

DIPARTIMENTO DI INGEGNERIA CIVILE E INDUSTRIALE

Tesi di Laurea Specialistica in Ingegneria Nucleare

e della Sicurezza Industriale

Thermal Hydraulic Analysis of Postulated Accidents in a HLM Cooled Fast Reactor

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Anno Accademico 2011/2012

Abstract

This thesis work, carried out at the Dipartimento di Ingegneria Civile ed Industriale (DICI) of the University of Pisa, concerns the thermo-hydraulic analysis of postulated accidents in a HLM cooled fast reactor, i.e. the MYRRHA-FASTEF reactor.

The first part of the work describes the general features and the historical background of the SIMMER-III code, such as the code assessment, and also a state of the art concerning the applications of the code to both separate effect facilities and full scale reactors. In this context, the SIMMER-III code can be adopted in analyses of sodium-cooled fast reactor, lead-cooled and LBE-cooled fast reactors; with some limitations and integration by additional models, it can be also applied to molten salt reactors and light water reactors.

The second part focuses on the description of the MYRRHA-FASTEF system and on its modelling by SIMMER-III, highlighting the adopted modelling of the different components. The reactor was simulated by a 2-Dimensional axial-symmetric geometry. The results of steady-state and transient calculations are then reported.

The steady-state analysis was performed in order to assess the correctness of the code and of the adopted model; so, the obtained results in relation to the major variables were compared with the design values. In particular, the most relevant results obtained for temperature trends and profile, both in the core and in the PHX, and the velocity and mass flow rate trends are reported. Significant thermal stratification is predicted by SIMMER-III in the upper plenum of the vessel which is responsible for temperature oscillation at the PHX inlet.

Finally, transient analyses were performed. Selected design basis condition transients and design extended condition transients were addressed in order to assure a sufficient safety level of the reactor, following postulated accidents or in unprotected transients. The sensitivity to the MOX density on fuel redistribution in the primary circuit has been also investigated. After fuel release, a certain amount of fuel particles is transported by the LBE coolant and, depending on the fuel porosity and the type of circulation, it tends to settle down or to float at the LBE free surface.

to my Granny

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Nomenclature

Acronyms

AC	Alternating Current
ADS	Accelerator Driven System
AEA-T	Atomic Energy Authority Technology
AFDM	Advanced Fluid-Dynamics Model
BoC	Beginning of Cycle
BoL	Beginning of Life
BT	Beam Trip
CAD	Computer-Aided Design
CDA	Core Disruptive Accident
CDT	Central Design Team
CEA	Commissariat A L'energie Atomique
CFD	Computational Fluid-Dynamic
CP	Continuous Phase
CPU	Central Processor Unit
CR	Control Rod
CRGT	Control Rod Guide Tube
CSS	Core Support Structure
DA	Dummy Assembly
DBC	Design Basis Condition
DEC	Design Extension Condition

DHR	Decay Heat Removal
EFIT	European Facility for Industrial Transmutation
ENEA	Agenzia nazionale per le nuove tecnologie, l’energia e lo sviluppo economico sostenibile
EoC	End of Cycle
EoL	End of Life
EOS	Equation Of State
ETD	European Transmutation Demonstration
FA	Fuel Assembly
FAIDUS	Fuel Assembly with Inner DUct Structure
FASTEF	Fast Spectrum Transmutation Experimental Facility
FC	Forced Circulation
FCA	Fast Critical Assembly
FFEOS	Fitting-Free EOS
FZK	Forschungszentrum Karlsruhe
GFR	Gas Fast Reactor
GIF	Generation IV International Forum
HLLW	High Level Long-lived radioactive Waste
HLM	High Liquid Metal
HLW	High Level Waste
HMT	Heat and Mass Transfer model
HTC	Heat Transfer Coefficient
IAEA	International Atomic Energy Agency
IE	Initial Event
IFA	InterFacial Area model

IGR	Impulse Graphite Reactor
ILW	Intermediate Level Waste
IPS	In-Pile Section
IVFHM	In-Vessel Fuel Handling Machine
IVFS	In-Vessel Fuel Storage
JNC	Japan Nuclear Cycle Development Institute
KIT	Karlsruhe Institute of Technology
LANL	Los Alamos National LaboratorY
LBE	Lead-Bismuth Eutectic
LFR	Lead Fast Reactor
LLFP	Long-Lived Fission Product
LMFR	Liquid Metal Fast Reactor
LOF	Loss Of Flow
LWR	Light Water Reactor
M/F	Melting/Freezing
MA	Minor Actinide
MFBT	Minimum Film Boiling Temperature
MFC	Multi-Functional Channel
MOX	Mixed OXide fuel
MRK	Modified Redlich-Kwong
MSBR	Molten Salt Breeder Reactor
MSRE	Molten Salt Reactor Experiment
MWC	Melt Water Contact
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications

NC	Natural Circulation
NNC/RK	National Nuclear Center of the Republic of Kazakhstan
NPSH	Net Positive Suction Head
P&T	Partitioning & Transmutation
PBA	Protected Blockage Accident
PDS-XADS	Preliminary Design Studies of an eXperimental Accelerator Driven System
PHX	Primary Heat eXchanger
PLOF	Protected Loss Of Flow
PLOHS	Protected Loss Of Heat Sink
PNC	Power Reactor and Nuclear Fuel Development Corp
PTOP	Protected Transient OverPower
R&D	Research & Development
RIA	Reactivity Induced Accident
RV	Reactor Vessel
SA	Sub-Assembly
SAEOS	Simplified Analytic EOS
SCRAM	Safety Control Rod Axe Man
SEARCH	Safe ExploitAtion Related CHemistry for HLM reactors
SFR	Sodium Fast Reactor
SG	Steam Generator
S-S	Steady-State
SR	Safety Rod
SS	Stainless Steel
TIB	Total Instantaneous Blockage

TOP	Transient OverPower
TRU	TRansUranium element
UBA	Unprotected Blockage Accident
ULOF	Unprotected Loss Of Flow
ULOHS	Unprotected Loss Of Heat Sink
UTOP	Unprotected Transient OverPower
V/C	Vaporization/Condensation
VF	Volume Fraction
VVER	Voda-Vodyanoi Energetichesky Reaktor
WP	WorkPackage
XS	eXtenSion (SIMMER)
XT-ADS	eXperimental Transmuter and irradiation facility based on ADS concept

Roman Letters

A	interfacial area (m^{-1})
a	binary-contact area per unit volume (m^{-1})
ALPGK	volume fraction of gas
ALPLK4	volume fraction of fuel particles
ALPLK5	volume fraction of clad particles
C_{ORF}	orifice coefficient
c	heat capacity (J/kg/K)
D_h	hydraulic diameter (m)
E	entrainment

e	specific internal energy (J/kg)
f	volume fraction
g	gravity (m/s^2)
Gr	Grashof number
H	heaviside unit function
h	heat transfer coefficient (W/m^2/K)
i	specific enthalpy (J/kg)
K	inter-field momentum exchange function (kg/m^3/s)
L	characteristic length (m)
Nu	Nusselt number
p	pressure (Pa)
$\Pr$	Prandtl number
Q	heat transfer rate (W/m^3)
q	heat transfer rate (W/m^3)
R	gas constant (J/kg/K)
r	radius (m)
Ra	Rayleigh number
Re	Reynolds number
S	interfacial area source term (1/m/s)
T	temperature (K)
TLK3	LBE temperature (°C)
TIPINK	center pin temperature (°C)
TSK1	surface pin temperature (°C)
TSK4	clad temperature (°C)

TSK8	can wall temperature (°C
v	specific volume of the structure
$\vec{V}$	velocity (m/s)
$\vec{v}$	velocity (m/s)
$\overrightarrow{VM}$	virtual mass (kg/m^2/s^2)
We	Weber number

Greek letters

α	volume fraction or void fraction
δ	thermal penetration length (m)
Γ	mass-transfer rate per unit volume (kg/s/m^3)
κ	thermal conductivity (W/m/K)
μ	dynamic viscosity (Pa·s)
ρ	density (kg/m^3)
$\overline{\rho}$	macroscopic density (kg/m^3)
σ	surface tension (N/m)
τ	time constant (s)

Subscripts

a	fuel pin interior node
B	bubbly flow regime

b	fuel pin surface node
c	cladding or continuous phase
CP	continuous phase
Crt	critical (temperature)
D	dispersed flow regime
d	dispersed phase
f	fuel
$film$	film region
FS	liquid film
G	vapour mixture
GL	Terms existing at interface between vapour and liquid velocity
G_m	energy component m in a vapour field
hb	fluid and fuel pellet surface (rate of energy interchange between)
hc	fluid and cladding (rate of energy interchange between)
HT	heat transfer
int	fuel pin interior node
L	liquid component
LCW	left can wall
L_m	energy component m in a liquid field
M	material number or energy component
m	density component
MF	melting/freezing (rate of energy interchange due to)
N	nuclear (heating rate)
nf	non-flow volume

P	particle component
PIN	fuel pin
$pool$	pool flow regime
q, q'	velocity fields
qq'	terms existing at interface between two velocity fields
RCW	right can wall
S	Structure component
$slug$	slug flow regime
S_m	energy component m in a structure
str	structure
VC	vaporization/condensation (rate of energy interchange due to)
VS	vapour structure

Superscripts

I	interface quantity