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Application of frequency response methods in separate and integral effects tests for molten salt cooled and fueled reactors

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ABSTRACT

Molten salt cooled and fueled reactors can be distinguished from other reactor types by their low volatility liquid coolant, which remains single-phase under most operating and accident conditions, and by the substantial heat capacity of both the coolant and solid structures. Forced and natural circulation of the molten salt coolant provide the primary heat transport mechanisms under power and shutdown operation, but thermal coupling to solid heat structures has important effects on dynamic system response during transients. These characteristics make frequency response methods particularly suitable to characterizing and predicting system response to transients. Predicting the temperature of coolant boundary structures during transients, including accidents, is also important for assessing whether damage may occur due to thermal stresses or accelerated thermal creep. This paper discusses how frequency response methods may be used in separate effect and integral effect tests, particularly with simulant fluids to measure the thermal inertia and coupling properties of heat structures and to validate transient response models. The methodology is discussed, followed by examples for application. The scaling parameters developed in this paper can be expected to play a major role in the design of integral effect test facilities for FHRs and MSRs.

1. Introduction

In fluoride salt cooled high temperature reactors (FHRs) the temperatures required to cause damage to the high-temperature TRISO fuel are over 1600 °C, which is far above peak coolant temperatures anticipated during transients and accidents (< 1000 °C). Instead, thermal and power limits in FHRs are established by thermal creep and thermal stress limits in metallic structures outside the reactor core, particularly the reactor coolant boundary. Likewise, in liquid fueled molten salt reactors (MSRs) with ceramic core structural materials, the primary goal of transient analysis is to predict temperatures of metallic structures outside the reactor core.

Molten salts used in FHRs and MSRs are chemically stable, have high volumetric heat capacity, and, due to high boiling temperatures, do not exhibit phase change under anticipated operating conditions and design-basis events. The flow is in single phase unless cover gas entrainment or salt-to-gas heat exchanger leaks occur (noble gas fission products may also create bubbles in liquid fuels). The high volumetric heat capacity of salts results in compact reactor designs, with reactor vessel volumes (per MWe) generally 1/3 or less of the volume of comparable modular high-temperature gas reactor (mHTGR) and sodium fast reactor (SFR) designs (Andreades et al., 2014). For this reason, in FHRs and MSRs the thermal inertia of the coolant and of solid heat structures have comparable magnitude, while in HTGRs thermal inertia is provided dominantly by solid structures (vessel, reflectors and fuel), and in SFRs thermal inertia is provided dominantly by the sodium coolant, as shown in Table 1.

Light water reactors (LWRs) also differ from FHRs and MSRs because water is a volatile fluid that has a large latent heat of vaporization. Because LWRs operate at high pressure, they use thick-walled vessels that have substantial thermal inertia. Thus the latent heat of boiling and condensation can dominate over sensible heat transport during transients and accidents.

The transient modeling used for licensing nuclear reactors generally uses control-volume methods, where the reactor system is discretized into nodal elements. In each control volume, coupled ordinary differential equations are written for each solid structure and each fluid phase for conservation of mass, energy, and momentum. An excellent example of this type of modeling tool is the RELAP5-3D code (RELAP5-3D© Code Manual, 2015, which is currently the most extensively applied simulation tool for modeling FHR transient response.

A wide variety of techniques exists to analyze systems of linear ordinary differential equations, using both time-domain and frequency-domain analysis. When the ordinary differential equations are not

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Nomenclature

Acronyms

APEX	advanced plant experimental facility
CIET	compact integral effects test
CSAU	code scaling, applicability, uncertainty analysis methodology
DRACS	direct reactor auxiliary cooling system
FHR	fluoride salt cooled high temperature reactor
HTGR	high-temperature gas reactor
IET	integral effects test
LWR	light water reactor
MASLWR	multi-application small light water reactor
Mk1 PB-FHR	UC Berkeley reference pebble-bed FHR design
mHTGR	modular high-temperature gas reactor
MSR	molten salt reactor
MSRE	molten salt reactor experiment
PB-HTX	pebble-bed heat transfer experiment
PBMR	pebble-bed modular reactor
PWR	pressurized-water reactor
SET	separate effects test
SFR	sodium fast reactor
S-PRISM	super power reactor innovative small module
TRISO	tristructural-isotropic
UCB	University of California, Berkeley

Variables

A	cross-sectional area
Bi	Biot number
c	specific heat
h_E	effective convection heat transfer coefficient
H	elevation difference between major heat source and major heat sink
$(hA)^*$	nondimensional thermal coupling
k_E	effective thermal conductivity
ℓ_E	effective conduction resistance length
m	mass
$\dot{M}$	primary salt mass flow scale rate
(mc)	thermal capacity
θ	nondimensional temperature
ρ	density
ρ_{fo}	average salt density
$\dot{q}'''$	volumetric heat generation
Q''	specific heat transfer rate per unit area
$\dot{Q}$	nominal power in primary loop
t	time
τ	time scale for convective heat transport
T	temperature
T_C	core inlet temperature
T_H	core outlet temperature
$\mathrm{T_L}$	low temperature
ΔT	loop temperature difference
v	velocity
V	volume
V_T	total volume of coolant in primary loop with n control volumes
x	distance coordinate

Common subscripts and superscripts

D	property of volume D
E	property of volume E
f	property of fluid
F	forced circulation parameter
j	evaluation at junction j
N	natural circulation parameter
s	property of solid structure
w	property at wall
$^-$	average value
*	nondimensional
$\cdot$	rate with respect to time

Table 1
Comparisons of thermal parameters for Mk1 PB-FHR, with approximate values for PBMR, S-PRISM, and 1000 MW PWR (Technical Description of the PBMR Demonstration Power Plant, 2006; Hoffman et al., 2006; Boardman et al., 2000).

	Mk1 PB-FHR	1000 MWe PWR	PBMR	S-PRISM
Electrical power (MWe)	100	1092	175	380
Thermal power (MWt)	232	3411	400	1000
Core inlet/outlet temperatures (°C)	600/700	292/326	500/900	355/510
Reactor vessel specific power (MWe/m^3)	0.866	2.839	0.242	0.292
Primary coolant residence time (s)	87	28	31	226
Primary coolant mass (kg/MWt)	360	125	15.0	1302
Fuel mass (kg/MWt)	46.1	29.3	217.1	31.4
Blanket/reflectors mass (kg/MWt)	230	n/a	1554	71.2
Metallic primary structures mass (kg/MWt)	1729	535	6044	2028
Coolant sensible heat capacity (kJ/°C MWt)	870	322	76.5	1456
Coolant latent heat capacity × 100 (kJ/MWt)	n/a	810	n/a	n/a
Fuel sensible heat capacity (kJ/°C MWt)	72.2	9.4	154	10.0
Blanket/reflector sensible heat capacity (kJ/°C MWt)	407	n/a	1101	22.8
Metal primary structures sensible heat capacity (kJ/°C MWt)	809	232	2623	949

linear, numerical solution methods, using codes like RELAP5-3D, are required. However, there may still be ranges of conditions over which linear approximations of the differential equations are valid and frequency domain modeling can be performed, as discussed in the next section on frequency response testing. In this respect, because FHRs and MSRs operate with single phase flow and because both the coolant and solid heat structures have substantial thermal capacity, dynamic response can be linear over significant ranges of operating conditions. This suggests that frequency response testing, using periodic forcing, can be a particularly valuable method for studying FHR and MSR dynamic response and for validating safety models for transient response to initiating events, which generally involve abrupt changes in the reactor system state.

FHRs and some MSRs use core structural materials that have very high thermal margins to structural damage. In modeling response of these reactors to anticipated operational occurrences and to design basis events, which generally involve abrupt changes to the system state, a central goal is to predict potential damage due to thermal stresses and/or accelerated thermal creep deformation. Because these solid structures have substantial thermal capacity, accurately predicting transient heat transfer to and from heat structures is important.

This paper describes approaches to the use of frequency response testing in scaled separate effect and integral effect test experiments to study coupling between heat structures and molten salt coolants. The advantage of using simulant oils is that experiments can be designed to operate at a much lower temperature and smaller geometric scale