Annals of Nuclear Energy 92 (2016) 243–250

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Preliminary thermal-hydraulic sub-channel analysis of 61 wire-wrapped bundle cooled by lead bismuth eutectic

Kefeng Lyu [a,b,c], Liuli Chen [b,c,*], Chenchong Yue [b,c], Sheng Gao [b,c], Tao Zhou [b,c], Qunying Huang [b,c]

[a] University of Science and Technology of China, Hefei 230026, China
[b] Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei 230031, China
[c] Collaborative Innovation Center of Radiation Medicine of Jiangsu Higher Education Institution, Suzhou, Jiangsu 215006, China

ARTICLE INFO

Article history:
Received 25 August 2015
Received in revised form 16 October 2015
Accepted 19 January 2016
Available online 15 February 2016

Keywords:
Sub-channel code
Lead-bismuth eutectic
Fuel pin bundle
Thermal-hydraulic

ABSTRACT

Lead bismuth eutectic (LBE) is one of the most promising materials for coolant and spallation target for Accelerator Driven Systems (ADS). The thermal-hydraulic features in fuel assembly are one of the most important issues for development of this system. Aiming to get a deeper understanding on heat transfer behavior of wire-wrapped bundle cooled by LBE and to support the design of ADS systems, a fuel bundle simulator with 61 electrical rods spaced by helical wire was developed in KYLIN-II facility. In this paper, the preliminary heat transfer experiments with 70 kW under forced and natural circulation regimes were performed. The thermal-hydraulic behaviors including thermal entrance characteristics, heat transfer coefficients, and temperature distribution at the cross section were investigated under both regimes. The experiments depict reasonable results, and the Nu based on center sub-channel shows an agreement with empirical correlations. Besides, a special sub-channel code named SACOS-PB was employed to support the sub-channel analysis; and similar results to each other were obtained. It can be concluded that the SACOS-PB is a reliable tool for LBE system sub-channel analysis. Based on the present work the comprehensive thermal-hydraulic analysis with a detailed test matrix in terms of different flow rates and heating powers will be conducted in near future.

1. Introduction

It should be recognized that in the 20th century, the utilization of fission nuclear energy has greatly eased the demand of fossil energy for human society. However, with the development of fission nuclear plants, some problems emerged. One of the most urgent issues is the disposal of nuclear waste which contains a large amount of minor actinides. Accelerator Driven sub-critical Systems (ADS) are considered as one of the most potential options to incinerate long living nuclear waste by transmutation (Zhan and Xu, 2012). Because of the low melting temperature, high boiling temperature, outstanding heat transfer performance, chemical stability, and good neutron economy, Lead-bismuth eutectic (LBE) are currently attracting more and more attention worldwide to be the coolant for sub-critical reactor core and spallation target in transmutation systems.

In 2011, the comprehensive research of ADS was launched by Chinese Academy of Sciences (CAS). In the frame of this project, Institute of Nuclear Energy and Safety Technology (INEST) undertook the work of reactor cooled by LBE which is named CLEAR-I (Wu et al., 2012a). Based on the former experience and technologies in lead lithium alloy facility (Huang et al., 2007; Wu et al., 2009; Wu et al., 2012b), the KYLIN-II multi-functional facility including material, thermal-hydraulic and safety loops has been established to get a deeper understanding of LBE features and to support the design and construction of CLEAR-I.

Among the planed experimental activities, a series of tests related with flow and heat transfer in fuel pin bundle were taken seriously, because the heat transfer in LBE significantly differs from the well-known heat transfer in water medium (Mikityuk, 2009). Most of the previous studies were conducted with sodium-potassium alloy or mercury to study the similar Pr number heat transfer behaviors in bundle geometries. Moreover, among these previous work wire spacer bundle experiments were very few (Roelofs et al., 2013). Therefore specific experimental tests with lead and lead bismuth eutectic alloy are urgently needed to support the LFR core thermal hydraulic design and the V&V of the corresponding code (e.g. CFD code, subchannel code).

* Corresponding author at: Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei 230031, China.
E-mail address: liuli.chen@fds.org.cn (L. Chen).

http://dx.doi.org/10.1016/j.anucene.2016.01.034
0306-4549/

Nomenclature

a	apothem of the hexagonal channel (mm)
B_o	buoyancy parameter, $B_o = GrRe^{-1.9}\,Pe^{-0.8}$
c_p	specific heat transfer ($Jkg^{-1}\,K^{-1}$)
d_h	hydraulic diameter of the bundle (mm)
d_r	rod diameter (mm)
d_{schi}	hydraulic diameter of sub-channel (mm)
d_{tc}	thermocouple diameter (mm)
d_w	wire diameter (mm)
f	flow resistance coefficient
g	gravity (ms^{-2})
H	winding pitch of the wire (mm)
L	Length (mm)
m	mass flow rate (kg/s)
N	number of the rods
Nu	Nusselt number, $Nu = \alpha d_h \lambda^{-1}$
$Nu_{2,1}$	Nu of SCH #1 at measuring plane 2 (z = 400 mm)
$Nu_{2,2}$	Nu of SCH #2 at measuring plane 2 (z = 400 mm)
$Nu_{3,1}$	Nu of SCH #1 at measuring plane 3 (z = 775 mm)
$Nu_{3,2}$	Nu of SCH #2 at measuring plane 3 (z = 775 mm)
p	pitch (mm)
Pe	Pelect number, $Pe = RePr$
Pr	Prandtl number, $Pr = c_p \mu \lambda^{-1}$
Q	electrical heating power (kW)
q''	wall heat flux density (Wm^{-2})
t	time (s)
T	Temperature (°C)
V	volume flowrate (m^3/h)
w	rod-to-wrap gap (mm)
z	axial position in the heated zone (mm)

Greek letters

α	heat transfer coefficient ($Wm^{-2}\,K^{-1}$)
λ	thermal conductivity ($Wm^{-1}\,K^{-1}$)
ρ	density (kgm^{-3})
μ	dynamic viscosity ($kgm^{-1}\,s^{-1}$)
χ	pitch to rod diameter ratio, $\chi = p/d$
σ_x	standard deviation of X
Θ	non-dimensional temperature, see Eq. (1)

Subscripts

b	refers to the bulk condition
heat	refers to heated region
in	refers to inlet region
out	refers to outlet region
tot	total value
w	refers to the heated rod wall
f	refers to coolant

Acronyms

ADS	Accelerator Driven Systems
FC	forced circulation
LBE	lead bismuth eutectic
NC	natural circulation
RSD	relative standard deviation
Sch	sub-channel
TC	thermocouple

In the present work, a wire-wrapped fuel pin bundle with 61 electrically heated rods was described. And the preliminary heat transfer experimental results with 70 kW under both forced and natural circulation regimes were discussed. Finally, a special sub-channel code named SACOS-PB (Wang et al., 2013) was employed to support the sub-channel analysis.

2. Experimental setup

2.1. Test loop

The thermal-hydraulic experiments of 61 wire-wrapped bundle were conducted in KYLIN-II thermal-hydraulic mixed circulation loop which has three different circulation modes, e.g. pump, gas lift and natural circulation. The experimental facility was designed to perform experimental campaigns of fluid-dynamics and heat transfer related with LBE to support the design and construction of ADS. The general layout of this facility was shown in Fig. 1. It is composed of a primary loop with LBE and a secondary loop with 10 MPa high pressure water. The primary loop is a rectangular loop which consists of two vertical pipes working as riser and downcomer. In the bottom of the riser, a heat source consisted of 61 electrical pins with wire-wrapped spacer is installed, while the upper part of the downcomer a "double-tube" heat exchanger is mounted. The difference in height between the center of the heating section and center of the heat exchanger is 2 m. In addition, the gas lift test section with 4 m height is placed in the upper part of heat source, while the mechanical pump with the maximum flow rate 100 kg/s is parallel with the natural circulation bypass installed in the bottom of the loop. Two flowmeters are installed in the loop to measure the flow rate, an electromagnetic flow

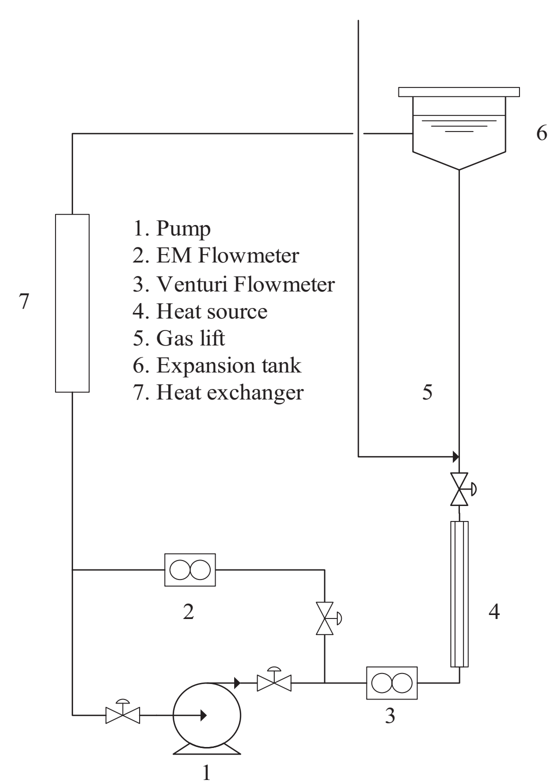

Fig. 1. The general layout of KYLIN-II mixed circulation loop.