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A review of experimental data and heat transfer correlations for parallel flow of alkali liquid metals and lead-bismuth eutectic in bundles

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HIGHLIGHTS

- Comprehensive review of convection heat transfer of alkali liquid metals and LBE in bundles of bare heated tubes in a triangular lattice.
- Compiled database, for wide ranges of P/D and Pe, is used to develop Nu correlation for alkali metals.
- The alkali metals' Nu correlation is in good agreement with the compiled data for LBE.

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ABSTRACT

A comprehensive review is performed of the reported experimental data on convection heat transfer for parallel flows of the alkali liquid metals of sodium, NaK-44, NaK-56, and NaK-78 alloys, and liquid lead-bismuth eutectic (LBE) in bundles of uniformly heated bare tubes in a triangular lattice at Pe = 4–3074. The performed experiments by various investigators have employed either a heat exchanger or hexagonal and cylindrical bundles of 7–37 heated tubes with P/D = 1.06–1.95. The compiled experimental database of 746 Nusselt number values for Na and various NaK alloys is used to develop the following continuous correlation:

$$Nu = [10.7(P/D) - 7.1] + 0.024[1 - e^{-10.4((P/D)-1)}]Pe^{0.85}$$

For the entire ranges of P/D and Pe values in the experiments, this correlation is in good agreement, within ±15%, with the compiled Nu data. The compiled Nu database for LBE flows in bundles of bare heated tubes with grid spacers, has 205 values for P/D = 1.33–1.80 and Pe = 211–3049. The present Nu correlation for alkali liquid metals agrees with the LBE data to within ±20%. This agreement suggests that the proposed Nu correlation for alkali liquid metals in bundles of bare tubes may also be used to calculate Nu for LBE.

1. Introduction

Liquid metals are being used for cooling and heating in many engineering systems. Examples are solar thermal power, fast-spectrum small modular, large commercial, and space fission nuclear reactors, high temperature heat exchangers, and super-heated steam generators (Chang et al., 2008; Dieckamp, 1967; El-Genk and Palomino, 2015; Faust, 1972; IAEA, 2006, 2013; Le Coz et al., 2011; Mason et al., 2008; Nikitin et al., 2000; Schriener and El-Genk, 2013). Liquid metals of interest include sodium (Na), potassium (K), lithium (Li), sodium-potassium alloys (NaK), molten lead (Pb), and molten lead-bismuth eutectic (LBE). The primary advantages of liquid metals, compared to gases (e.g. helium or helium-xenon) and non-liquid metal fluids, such as water, are the high thermal conductivity, and the low dynamic viscosity and specific pumping power. In addition, the low vapor pressure of liquid metals makes it possible to operate at high temperatures at low or near atmospheric pressure. Nonetheless, the thermosphysical properties of the different liquid metals vary widely. Fig. 1a–d compare the properties of alkali liquid metals of interest and mercury (Hg), only for a historical perspective (IAEA, 2008; OECD, 2015). Although Hg had routinely been used in the past in many convection heat transfer experiments with tubes and

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Nomenclature

A	cross sectional flow area (m^2)
ARD	absolute relative difference
C_p	specific heat capacity (J/kg.K)
D	tube outer diameter (m)
D_e	equivalent hydraulic diameter (m), 4A/WP
$D_{e,b}$	equivalent hydraulic diameter for an entire bundle (m), $4A_b/WP_b$
$D_{e,s}$	equivalent hydraulic diameter for a subchannel in a hexagonal bundle of bare tubes (m), $D\left[\frac{2\sqrt{3}}{\pi}(P/D)^2 - 1\right]$
D_{ff}	hexagonal bundle flat-to-flat (m)
ERH	electric resistance heater
FD	fully developed
HEX	heat exchanger
h	heat transfer coefficient ($W/m^2.K$)
k	thermal conductivity (W/m.K)
L	tube length (m)
LBE	lead-bismuth eutectic alloy
dotm	mass flow rate (kg/s)
n	number of rods or tubes in a bundle
N_{rings}	number of rings of heated tubes in a hexagonal bundle
N	number of experimental Nu values compiled
NaK	sodium-potassium alloy
NL	not listed
Nu	Nusselt number for a subchannel, $(hD_{e,s}/k)$
Nu_b	Nusselt number for an entire bundle, $(hD_{e,b}/k)$
OEB	overall energy balance
P	pitch (m)
P/D	pitch-to-diameter ratio
Pe	Peclet number for a subchannel, $(\dot{m}\, D_{e,s}/A.C_p.k)$
Pe_b	Peclet number for an entire bundle, $(\dot{m}\, D_{e,b}/A.C_p.k)$
Pr	Prandtl number $(\dot{m}\, C_p/k)$
Re	Reynolds number $(\dot{m}\, D_e/\mu.A)$
T	temperature (K)
T_b	bulk temperature (K), $(T_{ex} + T_{in})/2$
TC	thermocouple
WP	wetted perimeter (m)

Subscripts

b	bundle, bulk
Corr	correlation
ex	exit
Exp	experiment
ff	flat-to-flat
h	heated
i	index number
in	inlet
s	subchannel

Greeks

α	flow area correction factor for the bundle (m^2), $(A_b - nA_s)$
β	wetted perimeter correction factor for the bundle (m), $(WP_b - nWP_s)$
δ	ratio of hydraulic diameters of the bundle and the sub-channel, $(D_{e,b}/D_{e,s})$
ε	distance between shroud and outer ring of tubes in hexagonal bundle (m)
μ	dynamic viscosity (kg/m.s)
ρ	density (kg/m^3)

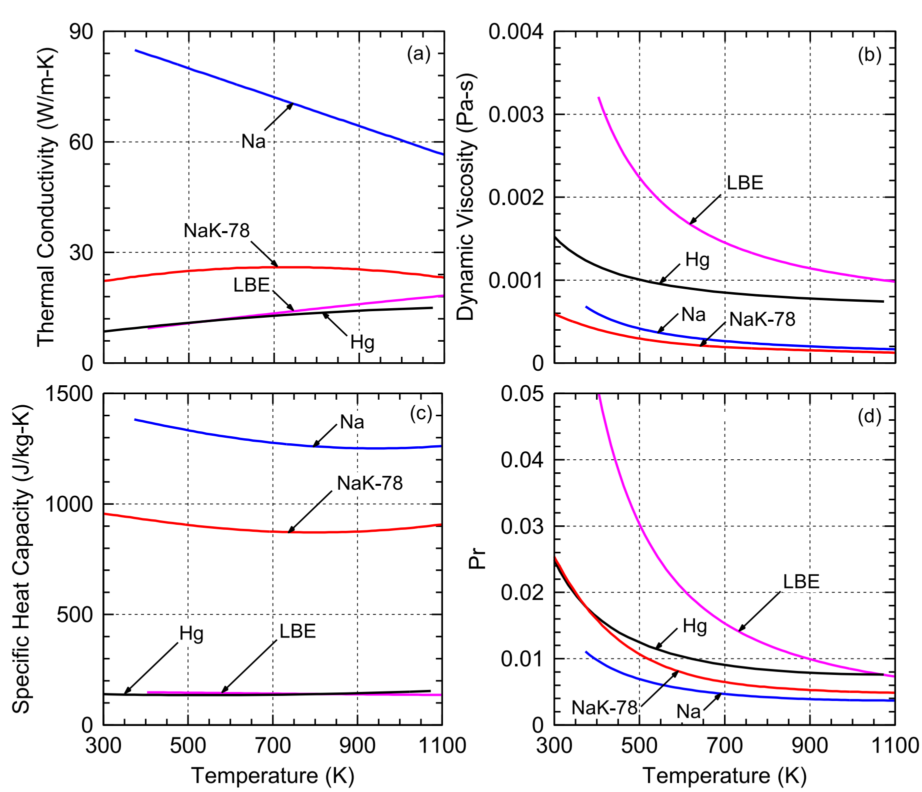

Fig. 1. Comparisons of thermophysical properties of liquid metals (IAEA, 2008; OECD, 2015).