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Heat transfer to liquid metals with empirical models for turbulent forced convection in various geometries

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HIGHLIGHTS

- Provision of several sets thermo-physical properties for liquid metals.
- Collection and review of experiments related to liquid metal thermal hydraulics.
- Validation of empirical correlations for liquid metals thermal hydraulics.
- Discussion of uncertainties related to liquid metal thermal hydraulics.
- Validation of empirical heat transfer models for best estimate system codes.

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ABSTRACT

This paper gives a summary of liquid metal properties and empirical models for thermal-hydraulic investigations. Liquid metals are used as coolant in nuclear and fusion energy and concentrated solar power systems, which requires a correct representation of their thermal-hydraulic behavior. Current generations of system codes, describing the thermal-hydraulic behavior of plants or experimental facilities, include only a few metals (sodium and lead-bismuth) flowing only in circular tubes and rod bundles. Empirical heat transfer models for rectangular ducts or annular channels are usually not used in system codes used. Furthermore, many experiments for liquid metal heat transfer have been performed with metals other than sodium and lead-bismuth. Therefore, thermo-physical properties of several liquid metals are presented based on a literature review. Empirical models for various geometries and boundary conditions are presented in this paper, too. Empirical models are implemented into a system code and validated by means of post-test analyses of experiments. The verification and validation process of the properties and the empirical models shows a good agreement between experiment and prediction for all considered conditions. It also shows the difference between the investigated geometries, which justifies the provision of tailored empirical models for comprehensive investigations of liquid metal flows.

1. Introduction

The purpose of this paper is to serve as a reference for thermal-hydraulic investigations of liquid metals under turbulent forced convection conditions with best-estimate system codes. First of all, thermo-physical properties for 12 liquid metals are provided. These liquid metals are: sodium (Na), potassium (K), sodium-potassium alloy (NaK) in four different material compositions, mercury (Hg), lead (Pb), lead-bismuth alloy (PbBi), lithium (Li), lithium-lead alloy (LiPb) and indium-gallium-tin alloy (InGaSn). Second, existing empirical models for the heat transfer are presented for several geometries including circular pipes, annular channels, rectangular ducts, parallel plates and rod bundles. The thermo-physical properties and the empirical thermal-hydraulic models are implemented into the system code TRACE (USNRC, 2012). The empirical models are used in the system code to calculate the heat transfer. These results are compared afterwards with experimental data. Thereby, TRACE serves as a demonstrator for the applicability of the empirical models. In theory, the presented properties and models can be implemented into any other system code following a knowledge based best-estimate approach like RELAP, CATHARE, MARS, ATHLET, which are used to describe power or process engineering plants and facilities.

System codes like TRACE are designed for the analysis of nuclear reactors, hence the number of coolants/fluids is limited. The system codes contain, besides water and several gases, only sodium and/or lead-bismuth eutectics as metallic coolant. Liquid metals as coolants are of interest in nuclear engineering (David,

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Nomenclature

cp	specific isobaric heat J/kg·K	ρ	density, kg/m^3
D	outer diameter of the annulus, m	σ	surface tension, N/m
d	inner diameter of the annulus, m	Nu	Nusselt number, Nu = f(Re, Pr)
h	heat transfer coefficient, W/m^2·K	Pr	Prandtl number, Pr = cp· η/k
k	thermal conductivity, W/m·K	Re	Reynolds number, Re = ρ·v·d/η
l	length, m		
n	number of rods, –	*Subscript*	
p	rod pitch, m	char	characteristic
p	pressure, Pa	l	liquid
q	heat flux density, W/m^2	sat	saturation
T	temperature, K	w	wall
v	velocity, m/s		
η	dynamic viscosity, Pa·s		
ν	kinematic viscosity, m^2/s		

2005; Rachkov, 2014). Sodium cooled reactors (IAEA, 2002) are used for many decades and new sodium and lead/lead-bismuth cooled reactor concepts are currently under development (GIF-IV, 2007). In fusion engineering, lithium-lead is used for, e.g., the tritium breeding and cooling in fusion reactor blankets (Morgan and Pasley, 2013). Sodium will be again a prospect candidate for the use in concentrated solar power plants as a heat transfer and a heat storage media (Pacio and Wetzel, 2013). Even though only 3–4 liquid metals are considered for industrial applications, several other metals are used as a replacement to perform experiments. Because all liquid metals are low Prandtl number fluids with very similar thermal hydraulic behavior, a substitution of lead, with a high melting point, with, e.g., Indium-Gallium-Tin, with a very low melting point, presents a substantial benefit. Experiments performed at room temperature are cheaper and less complex than those performed at, e.g., 800 K. Hence, other liquid metals must be implemented into system codes to benefit from all experimental knowledge.

2. Liquid metals

To perform investigations on liquid metal heat transfer in general, more liquid metals have to be made available in system codes. To make additional coolants available in TRACE, as well as in other system codes, thermo-physical properties must be provided. These are the density, the specific heat, the dynamic viscosity, the thermal conductivity, the surface tension and the saturation pressure. These six thermo-physical properties are implemented into TRACE as functions of temperature. No pressure dependency is considered because the experiments and the nuclear reactor operate at low pressures (geodetic pressure). In addition, information regarding the melting and boiling points are needed. Because this investigation is related to single phase flow, the melting and boiling point defines the lower and upper operational temperature, respectively. These temperatures along with the composition of each liquid metal are given in Table 1. For alloys with unknown boiling point, the value of the constituent with the lowest boiling point is coded in TRACE.

In the following, the thermo-physical properties of the selected metals are re-cited based on a literature survey. In general, the intention is to select correlations which have the most solid experimental background or which are based on the literature review of other researchers. In some cases, only one source could be found for a certain property. Sometimes it was not possible to derive the whole set of properties of one metal from one source. These correlations are a verbatim copy from the cited literature, with the exception that the units have been adapted, e.g., from g/cm^3 to kg/m^3 for the density and from mPa·s to Pa·s for the dynamic viscosity.

For all correlations given in the next sub-subsections the temperature (T) is given in K, the density (ρ) in kg/m^3, the specific heat (c_p) in J/kg·K, the thermal conductivity (k) in W/m·K, the dynamic viscosity (η) in Pa·s, the surface tension (σ) in N/m and the saturation pressure (p_{sat}) in Pa. The range of validity for each correlation is given, too. In case the range is enveloping the melting and the boiling point the correlations are for the saturated liquid along the saturation line.

Sodium (Na)

Density [370 K < T < 1100 K]

$$\rho = T \cdot [T \cdot (T \cdot 0.9667 \cdot 10^{-9} - 0.46005 \cdot 10^{-5}) - 0.1273534] + 954.1579 \quad (1)$$

Specific heat [370 K < T < 1100 K]

$$c_p = 1630.14 - 0.4631 \cdot (1.8 \cdot T) + 0.14284 \cdot 10^{-3} \cdot (1.8 \cdot T)^2 \quad (2)$$

Thermal conductivity [370 K < T < 1100 K]

$$k = 93.9892 - 3.2503 \cdot 10^{-2} \cdot t_f + 3.6197 \cdot 10^{-6} \cdot t_f^2 \quad (3)$$

$$t_f = [1.8 \cdot (T - 273.15)] + 32 \quad (4)$$

Dynamic viscosity [370 K < T < 1100 K]

$$\eta = \frac{0.11259 \cdot 10^{-3} \cdot e^{\frac{749.08 \cdot \rho}{1000 \cdot T}}}{\left(\frac{1000}{\rho}\right)^{0.3333}} \quad (5)$$

Surface tension [370 K < T < 1100 K]

$$\sigma = 206.7 \cdot 10^{-3} - 1.0 \cdot 10^{-4} \cdot (T - 273.15) \quad (6)$$

Saturation pressure [370 K < T < 1150 K]

$$p_{sat} = [10^{6.354 - \frac{5567}{T} - 0.5 \cdot \log(T)}] \cdot 1.01325 \cdot 10^5 \quad (7)$$

Potassium (K):

Density [334 K < T < 2270 K]

$$\rho = [0.8415 - 2.172 \cdot 10^{-4} \cdot (T - 273.15) - 2.70 \cdot 10^{-8} \cdot (T - 273.15)^2 + 4.77 \cdot 10^{-12} \cdot (T - 273.15)^3] \cdot 10^3 \quad (8)$$

Specific heat [373 K < T < 1423 K]

$$c_p = [0.2004 - 0.8777 \cdot 10^{-4} \cdot (T - 273.15) + 1.097 \cdot 10^{-7} \cdot (T - 273.15)^2] \cdot 4186.8 \quad (9)$$

Thermal conductivity [373 K < T < 1300 K]