Available online at www.sciencedirect.com

ScienceDirect

Nuclear Energy and Technology 2 (2016) 132–135

www.elsevier.com/locate/nucet

Effects of impurities on heat transfer in lead coolants

V.I. Belozerov, E.R. Sitdikov*, Ye.V. Varseev

Obninsk Institute for Nuclear Power Engineering, NRNU "MEPhI", 1 Studgorodok, Obninsk 249030, Kaluga Region, Russia

Abstract

A feature of the heavy liquid metal coolant technology has been investigated, namely the effect of impurities on the heat transfer in the wall-adjacent area. An analysis of the accumulated theoretical base for the problem under consideration has showed that earlier studies did not take into account the presence of impurities in heavy coolants. Recent experimental data used to update the calculated dependencies of heat transfer has turned out to be rather controversial. However, an explanation has been proposed for one of the observed effects that influenced the experimental data (for the coolant heating conditions). The dependencies in question are generalized in this paper. Using the obtained dependency, the effects of impurities on heat transfer have been estimated for various Peclet numbers as compared to "pure" conditions.

Keywords: Lead coolant; Heavy liquid metal coolant; Thermodynamic activity; Oxygen; Heat transfer; Heat loss; Annular channel; Annular gap.

Problem status

Heavy liquid metal coolants (HLMC) are known to be specific in a fairly high corrosion activity with respect to structural materials. Therefore, one of the major problems involved in the use of lead-bearing liquid metal coolants is to provide the corrosion stability of the materials contacting these coolants. Currently, the protection of HLMC-contacting structural materials is achieved through the oxygen passivation (inhibition) of the structural material surfaces, involving the formation and maintenance of oxide films on the surfaces of the materials. When present, such films improve considerably the corrosion stability of structural materials. Being oxides by nature, protective films have their state in the process of the plant operation depending heavily on the oxygen behavior, i.e. on the level of oxygen's thermodynamic activity (TDA) in the coolant [1].

A great deal of experience has been gained in Russia in the development and operation of plants with heavy liquid metal coolants. Also, activities have been under way in the country to develop the BREST and SVBR reactor facilities with lead and lead-bismuth coolants respectively.

The 1950s through 1970s saw a great deal of research performed on liquid metal coolants, especially by experts of the Institute for Physics and Power Engineering led by Academician V.I. Subbotin. There was also research performed in other countries, in particular by O.A. Dwyer [2].

Dependencies of heat transfer in liquid metals

Most of the heat transfer dependencies described in the existing literature have been obtained theoretically or are given for conditions when the content of impurities is negligible. Much attention is devoted to heat transfer in the liquid metal flow through a circular tube. Thus, the theoretically obtained Martinelli–Lyon and Seban–Shimazaki equations in [3,4] have respectively the following form:

$$Nu = 7 + 0.025 \times Pe^{0.8}, \qquad (1)$$

---

* Corresponding author.

E-mail addresses: v.i.belozerov@iate.obninsk.ru (V.I. Belozerov), emilsitdikov@gmail.com (E.R. Sitdikov), eugeny.varseev@gmail.com (Ye.V. Varseev).

Peer-review under responsibility of National Research Nuclear University MEPhI (Moscow Engineering Physics Institute).

Russian text published: Izvestia Visshikh Uchebnikh Zavedeniy. Yadernaya Energetika (ISSN 0204-3327), 2016, n.1, pp. 130-137.

http://dx.doi.org/10.1016/j.nucet.2016.05.011

$$Nu = 5 + 0.025 \times Pe^{0.8}, \tag{2}$$

A number of studies on liquid metal coolants were conducted by V.I. Subbotin and his associates. The results obtained for $20 < Pe < 10^4$ are described by the following relationship [3,5]:

$$Nu = 4.36 + 0.025 \times Pe^{0.8}. \tag{3}$$

Provided fairly high requirements to the metal purity are satisfied, the equation derived by M.A. Mikheev with a team of coworkers has the form [5]:

$$\begin{aligned} Nu &= 4.8 + 0.014 \times Pe^{0.8} \quad \text{for } 40 < Pe < 3.2 \times 10^4, \\ Re &> 10^4. \end{aligned} \tag{4}$$

In conditions of a liquid metal flow in tubes, with no special measures taken towards the extensive purification of the coolant, the heat transfer coefficient decreases dramatically and fails to agree with the results obtained from Eq. (3– 4). For such cases, [5] presents equations proposed by M.A. Mikheev and others, or by S.S. Kutateladze and B.M. Borishansky:

$$Nu = 3.4 + 0.014 \times Pe^{0.8} \quad (\text{for } 200 < Pe < 2 \times 10^4), \tag{5}$$

$$Nu = 5 + 0.0021 \times Pe^{0.8} \quad (\text{for } 100 < Pe < 2 \times 10^4). \tag{6}$$

No heat transfer in annular channels has been sufficiently investigated, so there are no reliable equations for this case. In [4], the following dependencies are proposed to calculate the heat transfer in concentric annular gaps with $d_2/d_1 = 1.05–2.0$ and $300 < Pe < 4000$:

for one-side heating

$$Nu = 5 + 0.0021 \times Pe^{0.8} \quad (\text{for } 100 < Pe < 2 \times 10^4). \tag{6}$$

$$Nu = 6 + 0.02 \times Pe^{0.8} \quad \pm 15\%; \tag{7}$$

for two-side heating

$$Nu_1 = 10 + 0.028 \times Pe^{0.8} \quad \pm 20\%, \tag{8}$$

$$Nu_2 = 7.2 + 0.028 \times Pe^{0.8} \pm 20\%. \tag{9}$$

The above expressions for determination of the heat transfer characteristics suggest a very low impurity content in the coolant, which does not practically have an effect on the heat transfer.

The foregoing proves it to be reasonable and necessary to investigate heat transfer as applied to lead coolant in the event of operational occurrences, as well as during and after emergencies caused by a major change in the content and in the physical and chemical state of impurities.

To address this problem, dedicated test benches are built to develop (or update) calculation techniques and the formulas used to calculate heat transfer in the event of a monitored and controlled content of impurities in the circuit, primarily, of oxygen. One of such benches was built at the Nizhny Novgorod State Technical University [6,7].

The test bench was used to experimentally obtain the correlations between the Nusselt numbers and the Peclet numbers for lead and lead–bismuth coolants. This gives rise to a question concerning the integration of experimental data on the heating and cooling conditions for heavy coolants, as well as the quantitative assessment of the impurity effects given in this paper.

Analysis of experimental data on lead coolant heat transfer

Thermal contact resistance is influenced by two factors: the presence of oxide and other films on the heat-release surface and the coolant contamination by oxides and other impurities. In the latter case, the key role is played by suspended impurities which accumulate near the heat-release surfaces and create a thermal contact resistance [8].

A long-term experience in the operation of test benches for the nuclear power plants of projects 645, 705 and 705 K has shown that the deterioration in the performance of systems with heavy liquid metals, when the impurity content exceeds the standard values, manifests itself in a degraded performance of the plant components, including the reactor core and the coolant circuit as a whole. Some impurities (Al, Zn, Ag, Cu, Bi, Au, Hg, etc.) may enter the circuit with the coolant itself when the circuit is initially filled, while others form the basis of the structural steel or may be alloying additions (Fe, Cr, Ni, etc.), or come from the rest of the circuit's equipment, as well as from the outside. Depending on the affinity to oxygen, impurities either exist in an oxidized form and form a part of complex formations based on lead oxide, or have the form of a solution with no formation of solid compounds [9].

Heat transfer in conditions of a lead coolant flow in annular gaps was investigated in [6,7]. The results obtained by the authors in a study into the process of heat transfer in heavy coolants (lead, lead-bismuth alloy) were rather unusual and occasionally contradictory to the well-established views on the behavior of thermal contact resistance depending on the key parameters and the heat transfer from thermal resistance. That made it necessary to investigate the results obtained in [6,7]. In this paper, the conditions with low impurity content in the coolant, i.e. the conditions in which the heat transfer may be believed to be governed by theoretical dependencies, are referred to as "pure". The rest of the conditions are referred to as "impure" [10].

As can be seen in the Fig. 1, the experimental data in [6,7] described by curves 3 and 4 shows a lower heat transfer when the oxygen content is lower (see the thermodynamic activities $A = 10^{-4} – 10^{-1}$ and $A = 10^{-5} – 10^{-4}$ for curves 3 and 4 respectively). This is also the case for curves 5 and 6 when $Pe \le 1000$.

This also gives rise to a question of no oxygen impurity impact on the Nu numbers in a broad range of thermodynamic activities: $A = 10^{-4} – 10^{-1}$ (curve 3) and $A = 10^{-3} – 10^{-1}$ (curve 6).

According to [6,7], the larger is the Pe number (coolant velocity), the greater is the measure of deviation between the