Progress in Nuclear Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Review

Review on heat transfer and flow characteristics of liquid sodium (1): Single-phase

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ARTICLE INFO

Keywords:
Liquid sodium
Single-phase
Heat transfer
Flow
Friction factor

ABSTRACT

Single-phase liquid sodium as a kind of ideal coolant is widely applied in the fields of nuclear reactor engineering, aerospace, solar energy and industrial waste heat utilization, due to the good heat transfer and flow characteristics. Therefore, numerous studies have been carried out experimentally and theoretically to investigate the heat and mass transfer performance by using liquid sodium in past decades, and most of them are concentrated on the experimental results, mechanisms and models of heat transfer and flow of liquid sodium. However, no comprehensive review article concerns on the thermal hydraulic characteristics of single-phase for liquid sodium. Thus, in this study, an analytical overview on thermal hydraulic characteristics of single-phase for liquid sodium is presented, using widely scattered available information from existing literature. It can be taken into account as a quick reference guide to have an overview of the thermal hydraulic characteristics of single-phase for liquid sodium in different channel geometries (circular tube, annular tube and rod bundles etc.) under different conditions.

1. Introduction

Liquid sodium is widely applied in the fields of nuclear reactor engineering, aerospace, solar energy and industrial waste heat utilization. With different applied fields, there are various geometries, such as circular tubes, annuli and rod bundles (Qiu et al., 2013, 2015a, 2015b). Many studies have been conducted on the flow and heat transfer characteristics of liquid sodium flowing in different geometries in the past several decades and mainly concentrated on experimental and theoretical research (Ma et al., 2012, 2014; Wang et al., 2013).

Generally, in the experimental research, the liquid sodium was made flow under certain conditions. Heat transfer correlations were obtained based on a large amount of experimental data with different geometries. With the development of the calculation method, the theoretical research was developed from the early analytical solutions, the semi-empirical method based on the empirical correlation by introducing some correction factors, to the numerical simulation method based on mass, momentum and energy equations.

Previous studies (Bonilla, 1955; Brown et al., 1957; Isakoff and Drew, 1951) have shown that, flow characteristics of liquid sodium are not much different from that of non-metallic fluid, such as water. The friction coefficient and local resistance coefficient of liquid sodium can be obtained by using the conventional method or looking-up table as water. However, the heat transfer of liquid sodium is very different from that of conventional fluids, due to the large difference in the Prandtl number. The Prandtl number of conventional fluids is in the range of 1–10, as that of liquid sodium is 0.001–0.01. The thickness of the laminar sublayer is not very important for liquid sodium, its thermal resistance is only a small part of the total thermal resistance. The smaller the Prandtl number is, the closer the fluid temperature between the wall and the center line in the flow channel is more close to the wall temperature, and the temperature changing from the wall to the center of the flow channel is closer to the linear. This shows that unlike conventional fluids, the thermal resistance of liquid sodium in the flow channel is not concentrated in the laminar bottom or buffer layer inside, but evenly distributed on the whole cross section relatively. The turbulent heat transfer will play an important role in the heat transfer only when the Reynolds number is very high. This special property of liquid sodium brings a great deal of influence on the heat transfer as follows:

(1) Many existing heat transfer correlations for nonmetallic fluids are not suitable for liquid sodium. It is necessary for exploring new correlations.
(2) The effect of boundary conditions has more influence on the temperature distribution of liquid sodium for its high heat conductivity.

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http://dx.doi.org/10.1016/j.pnucene.2017.11.004
Received 26 June 2017; Received in revised form 17 October 2017; Accepted 2 November 2017

Nomenclature

A	flow area, m^2
c_p	specific heat at constant pressure, J/kg
D, d	diameter, m
f	friction factor, if no subscript means bundle average value
F	correction coefficient
Gr	Grashof number
g	acceleration due to gravity, m/s^2
H	wire lead length, m
L	length of flow channel or perimeter, m
Nu	Nusselt number
P	pitch, m
ΔP	pressure drop, Pa
Pe	Peclet number
Pr	Prandtl number
q	heat flux, W/m^2
Re	Reynolds number
s	slip ratio
T	temperature, K
Δt	temperature difference, K
W	edge pitch parameter defined as (D + gap between rod and bundle wall)
X	flow split parameter for each sub-channel
V	velocity, m/s

Greek symbols

α, β, γ	coefficient
δ	thickness of the thermal insulation layer
θ	angle which the wire makes with respective of vertical axis
κ	thermal conductivity, W/(m·K)
μ	dynamic viscosity, Pa·s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
Ψ	intermittency factor

Subscripts

1, 2, 3	denote center, side and corner sub-channels, respectively
'	denotes equivalent bare rod bundles (without considering wire)
b	main flow
bL	the transition value from laminar region to transition region
bT	the transition value from transition region to turbulent region
e	equivalent value
eff	effective value
ei	equivalent value of sub-channel i
f	fluid
i	index of sub-channel type, i = 1, 2, 3
ij	effective mixing value
in	inlet
l, L	laminar
m	measured value
out	outlet
p	predicted value
s	surface
t, T	turbulent
w	wall
wb	wetted parameter of bundles
wt	total wetted parameter

Thus, the molecular thermal conductivity plays an important role in the whole flow channel, the temperature distribution of liquid sodium closely relates with the shape of the boundary.

(3) The thermal entrance effect of liquid sodium in turbulent state is much higher than that of conventional fluids. The distribution of the heat flux on the heating surface has a great influence on the heat transfer coefficient. And the influence of the flow velocity on the thermal entrance effect in liquid sodium is just the opposite of ordinary fluid (Rensen, 1982).

(4) The flow channel geometry in liquid sodium has great influence on the heat transfer coefficient, the pipe size and installation error in the heat exchange equipment have greater influence on the heat transfer and temperature difference.

As mentioned above, there are many reasons leading to the difference in the heat transfer characteristics of liquid sodium. Therefore, this present study focuses on reviewing articles for the heat transfer coefficient and friction factor of liquid sodium and is comprised of comprehensive lists of the experimental section, as well as numerical and simulation sections, to investigate the open literature for researchers and engineers in the field of using liquid sodium as the working fluid. Finally, and probably most importantly, the paper gathered information about the heat transfer and friction factor correlations of liquid sodium for heat exchanger designers.

2. Heat transfer correlation of single phase liquid sodium

The heat transfer characteristic of liquid sodium is significantly different from the conventional fluid. Thus, it is necessary to study the heat transfer characteristics of liquid sodium. To predict the heat transfer characteristics of the single-phase liquid sodium, several researchers have done numerous studies. Research methods mainly include the theoretical analysis, the experimental fitting, and the semi-empirical method between the theory and experiment.

The method of the theory analysis for the laminar flow under the simple geometry can obtain the exact solution by solving the differential equation, but for the turbulent situation or complex geometry, the differential equation can be solved only by the numerical method. The results of the laminar flow can be seen as a special case of the turbulence turbulent flow with very weak turbulent conditions, the heat transfer correlations of liquid sodium are not actually distinguished between the laminar and turbulent flows. Experiments have confirmed that the Nu number of liquid sodium is of the following form:

$$\mathrm{Nu} = \alpha + \beta \mathrm{Pe}^{\gamma} \tag{1}$$

where α, β and γ are constant.

In the above equation, the first and second items represent the contribution of the heat conduction and heat convection respectively. Experiments show that the value of γ closes to 0.8, while the values of α and β are related to the heat transfer geometry. Thus, empirical correlations of the bundle and circular tube are different.

Speculating from Eq. (1), when the Pe number reduces gradually, the Nu number gradually tends to be the constant α. This conclusion is in agreement with the results of the theoretical analysis. When the Pe number is relatively low, the turbulent heat transfer of liquid sodium is zero in a circular tube, annular pipe tube and rod channel under the laminar flow condition. The Nu number is only determined by the number of the pure thermal conductivity.

2.1. Heat transfer correlations of liquid sodium

Single phase heat transfer correlations of liquid sodium are more