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Consideration on Nusselt numbers of liquid metals under low Peclet number conditions

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ABSTRACT

The Nusselt number of liquid metal in the low Peclet number region is discussed in the present paper. Old data measured by Johnson et al. (1953b) are investigated carefully from the stand point of instrumentation of the test section because their Nu numbers are extremely lower than the theoretically deduced Nu number under the low Peclet number conditions. Seven selected experimental conditions are simulated by the FLUENT code. The laminar flow model and transition k-kl-ω model are used to simulate corresponding experimental conditions. Calculated outlet fluid temperatures are compared with the measured results in order to confirm the consistency of the input energy. Other calculated results are compared to investigate the deficiencies in the data processing. As a result, it is a most likely cause that the temperature difference used to deduce the heat transfer coefficient is overestimated in the experiment. This is possibly caused by the estimation of the wall temperature without taking into account thermal resistances due to contacts and the simple estimation of the fluid temperature. The low Nu numbers based on the measured result should be corrected and it is clarified that the re-evaluated values by CFD simulations show similar trend as measured data by Skupinski et al. (1965) and by Ampleyev et al. (1969). All other data which show the lower Nu numbers by Subbotin (1974) in the low Peclet number region, and Stromquist (1953), and Johnson et al. (1953a) in the high Peclet number region should be investigated again.

1. Introduction

We use the Nusselt number to calculate the heat transfer between a heating surface and coolant. There are a couple of correlations for many liquid metal coolants such as liquid sodium, lead-bismuth, and mercury. Pioneer researchers in this area are Martinelli (1947), Lyon (1951), and Seban and Shimazaki (1951). They correlated the Nusselt (Nu) number as a function of the Peclet (Pe) number based on the theoretical approach under the turbulent flow conditions and measured data. Their correlations are shown below.

$$Nu = 7 + 0.025Pe^{0.8} \quad \text{Lyon,} \tag{1}$$

$$Nu = 5 + 0.025Pe^{0.8} \quad \text{Seban and Shimazaki} \tag{2}$$

Subbotin et al. (1962) also studied the heat transfer of liquid metal and deduced the same correlation as the Seban and Shimazaki. Lubarsky and Kaufman (1955) reviewed heat transfer data in turbulent flow and laminar flow regimes. Fig. 1 illustrates the measured data in the handbook of the Japan Society of Mechanical Engineers (JSME, 2009) which is practically the same figure as in the report of Lubarsky and Kaufman although several data are reinforced. Among them, we can find the data by Johnson et al. (1953b) which are well below the above correlations in the low Pe number region. Lubarsky and Kaufman proposed the following empirical correlation including all data in those days.

$$Nu = 0.625Pe^{0.4} \quad \text{Lubarsky and Kaufman} \tag{3}$$

This correlation is a kind of compromise in order to include the low Nu numbers in the low Pe number region. Nevertheless, many data in the low Pe number region remain well below the correlation. These data and correlations are widely introduced in various handbooks. Kutateladze et al. (1959) also reviewed the major works in Soviet Union with the forms of empirical correlations. Some correlations show the low Nu numbers in the low Pe number region. Due to these data, we have been bothered for several decades. Lyon (1951) deduced the Nu number as 4.36 in the laminar flow under the uniform heat flux heating conditions. The first theoretical study of the heat transfer was conducted by Norris and Streid (1940) for the laminar flow under the isothermal heating conditions. The Nu number is 3.66 in this case. These Nu numbers should be the lowest values for any fluid. However, the measured Nu numbers by Johnson et al. (1953b) decrease as the Pe number decreases, and the Nu number approaches to unity when the Pe

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Nomenclature

A	heat transfer area (m^2)
Cp	specific heat (J/kg K)
De	heat transfer equivalent diameter (m)
f	ratio of heat rate in metal and gap (–)
Gr	Grashof number (–) ($=g\beta\Delta T\, De^3/\nu^2$)
h	heat transfer coefficient (W/m^2 K)
H_M	Meyer's hardness (Pa)
k	thermal conductivity (W/m K)
l	wave length of roughness (m)
Nu	Nusselt number (–) ($=h/k\, De$)
Pe	Peclet number (Re·Pr)
Pr	Prandtl number (–) ($=\mu Cp/k$)
Q	net electrical input (W)
q	heat flux (W/m^2)
R	overall thermal resistance (m^2K/W)
r	radius (m)
Re	Reynolds number ($\rho u De/\mu$)
T	temperature (K)
ΔT	temperature difference (K)
u	velocity (m/s)
W	mass flow rate (kg/s)
α	linear thermal expansion coefficient (1/K)
β	volumetric thermal expansion coefficient (1/K)
δ	gap length (m)
μ	dynamic viscosity (Pa·s)
ρ	density (kg/m^3)

Subscript

a	*air*
al	aluminum
b	bulk
c	contact
g	gap
i	inlet
M	metal
m	mean
o	outlet or outside of steel pipe
s	steel
t	thermocouple position
w	inside wall of steel pipe

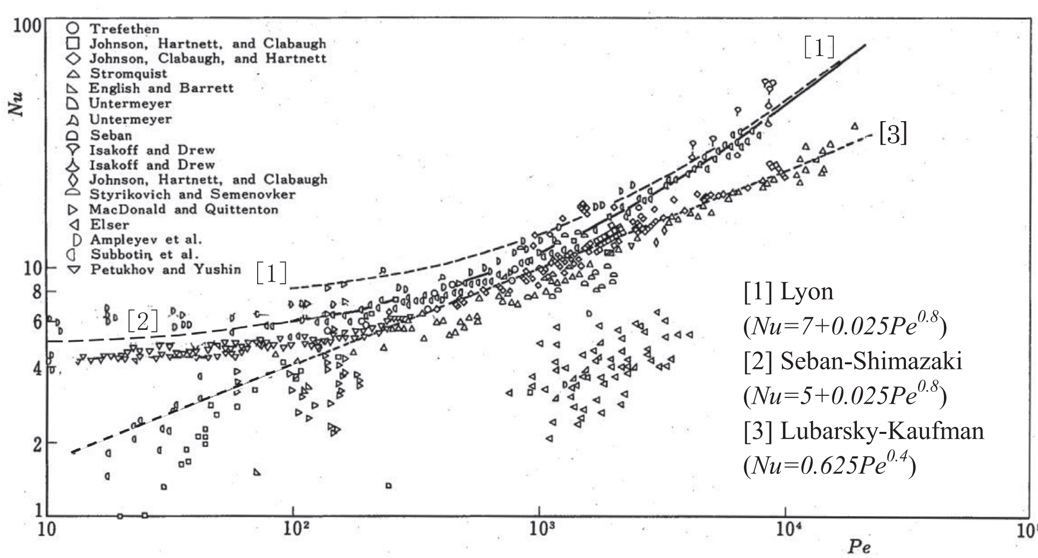

Fig. 1. Nusselt number of liquid metal and correlations (from JSME, 2009).

number is around 30. Similar trend data are reported by Ushakov et al. (1962) and Subbotin (1974). The author had a simple question more than half a century ago why the Nu number was so low in the low Pe number region. This is the motivation of the present study to investigate reasons of the low Nu number in the low Pe number region. Sanogawa introduced several effects on the heat transfer of liquid metal in one chapter of the textbook by Fujii et al. (1973), e.g., effects of wetness of the liquid metal, thermal resistance due to an oxidized film on the wall, cover gas mixing, dissolved oxygen and contained oxidized material. He also introduced the several experimental results that the above sole effect could not be dominant cause of the degraded heat transfer coefficient. Unfortunately, he did not discuss the experimental method itself.

Aoki (1963) studied the Nu numbers of liquid metals based on the eddy diffusivity theory. Since he applied his theory to the Lyon's correlation in order to modify it, the obtained correlation has a similar trend as the correlation by Lyon (1951) and can be applied to the turbulent flow;

$$\mathrm{Nu} = 5.3 + 0.019\mathrm{Pe}^{0.8} \quad \text{Aoki} \tag{4}$$

Skupinski et al. (1965) measured the heat transfer coefficient of NaK under the turbulent and the laminar or transitional flow regimes using a circular tube which was electrically heated from outside, and the measured Nu numbers were around 5 in the low Pe number region. The minimum Pe number in their experiment was 58. They correlated their measured data by the following correlation which has rather similar constants to the correlation by Aoki;

$$\mathrm{Nu} = 4.82 + 0.0185\mathrm{Pe}^{0.827} \quad \text{Skupinski et al.} \tag{5}$$

Ampleyev et al. (1969) measured the heat transfer coefficient of NaK using a movable thermocouple over a wide range of the Pe number. They deduced two kinds of Nu numbers based on the measured temperature distribution in NaK and temperature in the channel wall. Both results are similar and measured Nu numbers are around 7 in the low Pe number less than 40.

Mikityuk (2009) reviewed the Nu numbers of liquid metal. However, the data by Johnson et al. and Subbotin (1974) are not found in