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ScienceDirect
Procedia Engineering 157 (2016) 148 – 157
Procedia Engineering
www.elsevier.com/locate/procedia

IX International Conference on Computational Heat and Mass Transfer, ICCHMT2016

Heat transfer in turbulent tube flow of liquid metals

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Abstract

New heat transfer correlations for forced turbulent flow of liquid metals in the tubes have been proposed. Turbulent heat transfer in the circular tube was analyzed for a constant heat flux at the inner surface. Four various turbulent number models developed by Aoki, Weigand et al., Kays, and modified Aoki's model were considered. Using the universal velocity profile determined experimentally by Reichardt and different relationships for the turbulent Prandtl number, the energy conservation equation was integrated. Subsequently, the Nusselt numbers for a broad range of Reynolds and Prandtl numbers were calculated using the Lyon integral. Based on the determined Nusselt numbers, new correlations for Nusselt number as a function of Reynolds and Prandtl numbers have been proposed for various relationships for the turbulent Prandtl number. Nusselt numbers calculated using the proposed correlations were compared with the experimental data. Constants in different models for the turbulent Prandtl number were adjusted so as to obtain good agreement between calculated and experimentally obtained Nusselt numbers.

Peer-review under responsibility of the organizing committee of ICCHMT2016

Keywords: liquid metal; heat transfer; turbulent tube flow; heat transfer correlation; experimental data

1. Introduction

Liquid metals [1-3] and molten salts [4-5] are widely used as high-temperature heat transfer media in nuclear as well as in many other industries. Heat transfer in liquid metals arouses interest in many industries, including the continuous casting of steel, the production of glass, the manufacture of crystals in the semiconductor industry and the construction of fast breeder reactors, wherein the coolant is liquid metal. In a float glass manufacturing process,

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Peer-review under responsibility of the organizing committee of ICCHMT2016
doi:10.1016/j.proeng.2016.08.350

the glass is stretched on a molten metal bath and instability of the flow in the bath effects the quality of the glass [6-7].

Nomenclature

c_p	specific heat at constant pressure, J/(kgK)
d_w	inner diameter of a circular tube , $d_w = 2r_w$, m
k	thermal conductivity, W/(mK)
L	tube length, m
Nu	Nusselt number, $\mathrm{Nu} = h\,d_w / k$
Pr	Prandtl number, $\mathrm{Pr} = c_p\,\mu / k$
Pr_t	turbulent Prandtl number, $\mathrm{Pr}_t = \varepsilon_\tau / \varepsilon_q$
q	heat flux, W/m^2
q_m	molecular heat flux, W/m^2
q_t	turbulent heat flux, W/m^2
q_w	heat flux at the inner surface of the tube, W/m^2
r	radial coordinate, m
r_w	inner radius of the tube, m
R	dimensionless radius,
Re	Reynolds number,
T	temperature, ^{o}C or K
$\bar{T}_1(x)$	time and mass averaged fluid temperature, ^{o}C or K
$\bar{T}_2(r)$	time averaged radial component of the temperature $\bar{T}(x,r)$, ^{o}C or K
u_τ	friction velocity, $u_\tau = \sqrt{\tau_w / \rho}$, m/s
$\bar{u}$	velocity component in the x direction, m/s
u_m	mean velocity, m/s
x	a spatial coordinate in Cartesian or cylindrical coordinate systems or distance from the tube inlet, m
y	a spatial coordinate in a Cartesian system or distance from distance from the wall surface, m

Greek symbols

α	thermal diffusivity,
ε_q	eddy diffusivity for heat transfer, m^2/s
ε_τ	eddy diffusivity for momentum transfer (turbulent kinematic viscosity), m^2/s
μ	dynamic viscosity, kg/(ms)
ν	kinematic viscosity, $\nu = \mu / \rho$, m^2/s
ξ	Darcy-Weisbach friction factor
ρ	fluid density, kg/m^3
τ	shear stress, Pa
τ_w	shear stress at wall surface, Pa

Natural and mixed convection in rectangular cavities filled with liquid metals was investigated by Mohamad and Viskanta [6-7]. The transient convective motion in a two-dimensional square cavity was analyzed in [6]. The cavity was filled with a liquid metal. The vertical walls were maintained at uniform but various temperatures, while the horizontal boundaries were thermally insulated. Experiments and three-dimensional numerical simulations were also conducted to study unsteady natural and mixed convection in a shallow rectangular cavity filled with liquid gallium [7]. The cavity was heated at the lower and cooled at the upper surface either in the absence or presence of lid motion. The numerical and experimental results showed that lid motion had a significant effect on the flow and temperature distribution in the cavity.

The number of published papers relating to the heat transfer in liquid metals is not significant. Only recently due to the start of research on fast breeder reactors appear publications dedicated to this subject. However, reliable and validated experimentally heat transfer correlations for predicting the heat transfer coefficient in turbulent tube flows are still missing.

The review and evaluation of existing turbulent relationships to calculate the turbulent Prandtl number for turbulent flow of liquid metal in the pipes is presented by Cheng and Nam [1]. Also, a CFD (Computational Fluid Dynamics) code was used to model the turbulent flow of lead-bismuth eutectic (LBE) in a circular tube for various turbulence models. The authors have found that among a large number of models for turbulent Prandtl number, empirical equations are the best. Pacio et al. [2] carried out a critical analysis of the experimental data and experimental heat transfer correlations available in the literature for turbulent flow of liquid metals in pipes. They proposed to calculate the Nusselt number for a uniform wall temperature boundary condition by multiplying by the Nusselt number for a uniform heat flux boundary condition.

Heat transfer to liquid metals in rod bundles of various tube arrangements was studied in [8-10].

Smirnov et al. [8] carried out experiments and numerical simulations of thermal and hydraulic processes in the core of the lead-cooled BREST-OD-300 reactor. Data and correlations for tube bundles were examined by Mikityuk [9]. Four heat transfer data for liquid metals flowing through rod bundles were used to assess the accuracy of some heat transfer correlations recommended for liquid metals. Ma et al. [10] developed a method to use the relationships and experimental data of annuli for rod bundles including triangular or square lattices.

Engineering correlations play a significant role in the proper design and operation of thermal systems. However, results of previous studies show significant discrepancies, and there is a need to carry out new studies of hydraulic and thermal problems occurring in the liquid metal.

In this paper, using the universal velocity profile determined experimentally by Reichardt [11] and different relationships for the turbulent Prandtl number, the energy conservation equation was integrated. Based on the determined Nusselt numbers, new correlations for Nusselt number as a function of Reynolds and Prandtl numbers have been proposed for various models for the turbulent Prandtl number. Engineering correlations developed in the paper can be used for the proper design and operation of thermal systems, in which liquid metals are the heat transfer media.

2. Theory

Energy conservation equation for turbulent tube flow averaged by Reynolds has the following form [12-14]

$$\rho c_p \bar{u} \frac{\partial \bar{T}}{\partial x} = \frac{1}{r} \frac{\partial}{\partial r}\left(r q\right) \tag{1}$$

Heat flux q is the sum of the molecular q_m and turbulent q_t component

$$q = q_m + q_t \tag{2}$$

where

$$q_m = k \frac{\partial \bar{T}}{\partial r}, \quad q_t = \rho\, c_p\, \varepsilon_q \frac{\partial \bar{T}}{\partial r} = k \frac{\mathrm{Pr}}{\mathrm{Pr}_t} \frac{\varepsilon_\tau}{\nu} \frac{\partial \bar{T}}{\partial r} \tag{3}$$

It should be noted that the heat flux q is positive when the heat flows from the wall of the fluid. In such case, the function $T(r)$ is an increasing function, and the derivative $\partial \bar{T} / \partial r$ is positive.
Equation (1) is subject to the following boundary conditions

$$k \frac{\partial \bar{T}}{\partial r}\Big|_{r=r_w} = q_w \tag{4}$$

$$\left[\frac{\partial \bar{T}}{\partial r} \right]\Bigg|_{r=0} = 0 \tag{5}$$

$$\bar{T}\big|_{x=0} = T_m\big|_{x=0} \tag{6}$$

where the mass average (bulk) temperature $T_m(x)$ is defined as follows

$$T_m(x) = \frac{2}{r_w^2\, u_m} \int_0^{r_w} \bar{u}(r) \bar{T}(x,r)\, r \,\mathrm{d}r \tag{7}$$

According to the superposition method, the solution of equation (1) is taken as

$$\bar{T}(x,r) = T_m(x) + \bar{T}_2(r) \tag{8}$$

The mass-average fluid temperature $T_m(x)$ is given by

$$T_m(x) = T_m\big|_{x=0} + \frac{2 q_w}{\rho c_p\, u_m\, r_w} x \tag{9}$$

where the mean fluid velocity is defined as follows

$$u_m = \frac{2}{r_w^2} \int_0^{r_w} \bar{u}\; r\; \mathrm{d}r \tag{10}$$

The time averaged temperature $\bar{T}_2$ appearing in the relationship (8) is

$$\bar{T}_2(R) = \frac{2 q_w\, r_w}{k} \left[\frac{1}{\mathrm{Nu}} - \int_R^1 \frac{\int_0^R \frac{\bar{u}}{u_m} R \,\mathrm{d}R}{\left(1 + \frac{\mathrm{Pr}}{\mathrm{Pr}_t} \frac{\varepsilon_\tau}{\nu} \right) R} \mathrm{d}R \right] \qquad 0 \le R \le 1 \tag{11}$$

where: $\frac{\mathrm{Pr}}{\mathrm{Pr}_t} \frac{\varepsilon_\tau}{\nu} = \frac{\varepsilon_q}{\alpha} = \frac{\rho c_p}{k} \varepsilon_q$.

The Nusselt number occurring in the formula (11) is calculated using the Lyon integral [15-16]

$$\frac{1}{\mathrm{Nu}} = 2\int_0^1 \frac{\left(\int_0^R \frac{\bar{u}}{u_m} R\,\mathrm{d}R\right)^2}{\left(1+\frac{\mathrm{Pr}}{\mathrm{Pr}_t}\frac{\varepsilon_\tau}{\nu}\right)R}\,\mathrm{d}R \tag{12}$$

The mean fluid velocity u_m at the tube cross-section is given by Eq. (10). The radial universal velocity profile u^+ can be determined from the formula proposed by Reichardt that is based on experimental data [11].

$$u_\tau = \sqrt{\tau_w/\rho}\,, \qquad u^+ = \frac{\bar{u}}{u_\tau}\,, \qquad u_m^+ = \frac{u_m}{u_\tau} \tag{13}$$

where the friction velocity is given by $u_\tau = \sqrt{\tau_w/\rho}$. The average velocity u_m^+ is given by

$$u_m^+ = 2\int_0^1 R u^+ \mathrm{d}R \tag{14}$$

Also, the eddy diffusivity for momentum transfer ε_τ was calculated using Reichardt's [11] empirical equations. The trapezoidal rule was used to find the definite integrals appearing in the relationships (11-12) considering that $\bar{u}/u_m = u^+/u_m^+$. Then, the Nusselt number Nu is calculated as a function of the Reynolds number Re and Prandtl number Pr to find an appropriate heat transfer correlation.

3. Turbulent Prandtl number

The assumption that the turbulent Prandtl number Pr_t is constant and is in the range of 0.85 to 1 is not valid for the liquid metals. To determine the Nusselt number Nu using the Lyon formula (12) a suitable relationship for the turbulent Prandtl number Pr_t is needed. Many models have been developed for turbulent Prandtl number [18], which, however, give different values of the Nusselt number for the same Reynolds Re and molecular Prandtl Pr numbers.

One of the earliest formula for a turbulent Prandtl number is the relationship proposed by Aoki [19]

$$\mathrm{Pr}_t = \left\{0.014\,\mathrm{Re}^{0.45}\,\mathrm{Pr}^{0.2}\left[1-\exp\left(\frac{-1}{0.014\,\mathrm{Re}^{0.45}\,\mathrm{Pr}^{0.2}}\right)\right]\right\}^{-1} \tag{15}$$

Using the form of Eq. (15) the turbulent Prandtl number is approximated by the following two relationships

$$\mathrm{Pr}_t = \left\{a\,\mathrm{Re}^{0.45}\,\mathrm{Pr}^{0.2}\left[1-\exp\left(\frac{-1}{a\,\mathrm{Re}^{0.45}\,\mathrm{Pr}^{0.2}}\right)\right]\right\}^{-1} \tag{16}$$

$$\mathrm{Pr}_t = \left\{b\,\mathrm{Re}^{0.45}\,\mathrm{Pr}^{0.2}\left[1-\exp\left(\frac{-1}{c\,\mathrm{Re}^{0.45}\,\mathrm{Pr}^{0.2}}\right)\right]\right\}^{-1} \tag{17}$$

Unknown parameter a in Eq. (16) and the parameters b and c in Eq. (17) were calculated by the least squares method using the experimental data of Sheriff and O'Kane [20] obtained for the liquid sodium. The Reynolds number varied during the tests from 30 000 to 120 000. The Prandtl number was 0.0072 for Reynolds numbers equal: 30 000, 40 000, 60 000 and 80 000 and 0.0071 for Reynolds numbers 100 000 and 120 000. Using experimental data shown in Fig. 1 [17] and the turbulent Prandtl numbers defined by the relationships (16) and (17) the following parameters were obtained by the method of least squares: a = 0.01592, b = 0.01171, and c = 0.00712. Experimental data and functions (16) and (17) are illustrated in Fig. 1. The coefficient of determination is $r^2 = 0.7736$ and $r^2 = 0.9332$ for the function (16) and (17), respectively. The reason for small values of this parameter is a scatter in the data.

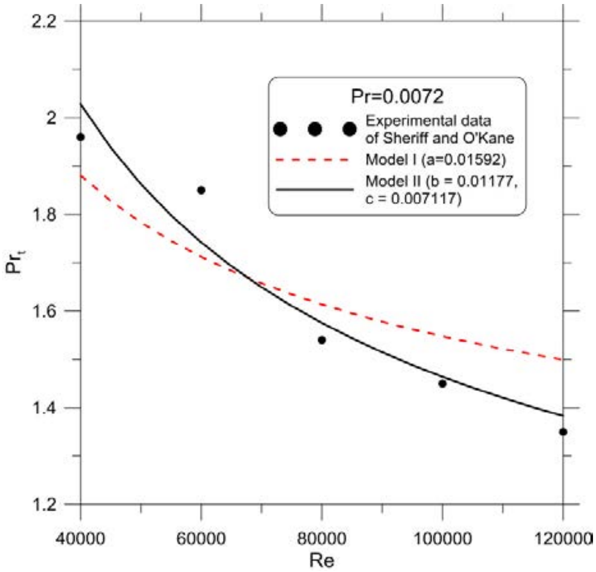

Fig. 1. Turbulent Prandtl number for liquid sodium as a function of Reynolds number- approximation of experimental data of Sheriff and O'Kane [20] by the function (16) and (17).

A model of a different form proposed Kays, Crawford, and Weigand [21-22]

$$\mathrm{Pr}_t = \left\{ \frac{1}{2\,\mathrm{Pr}_{t\infty}} + d\,\mathrm{Pe_t}\sqrt{\frac{1}{\mathrm{Pr}_{t\infty}}} - \left(d\,\mathrm{Pe_t}\right)^2 \left[1 - \exp\left(-\frac{1}{d\,\mathrm{Pe_t}\sqrt{\mathrm{Pr}_{t\infty}}}\right)\right]\right\}^{-1} \tag{18}$$

where turbulent Peclet number is given by $\mathrm{Pe_t} = \mathrm{Pr}\,\varepsilon_\tau / \nu$.
Symbol $\mathrm{Pr}_{t\infty}$ represents turbulent Prandtl number given by Jische and Rieke [13, 23]

$$\mathrm{Pr}_{t\infty} = \mathrm{Pr}_{ts} + \frac{e}{\mathrm{Pr}\,\mathrm{Re}^{0.888}} \tag{19}$$

Constants d and e appearing in the relationships (18) and (19) are: d = 0.3, Pr_{ts} = 0.85, and e = 182.4. The symbol Pr_{ts} represents a turbulent Prandtl number for large values of the product $\mathrm{Pr}\,\mathrm{Re}^{0.888}$. Instead of $\mathrm{Pr}_{ts} = 0.9$ as proposed in the original expression proposed by Rieke and Jischa [13, 23], $\mathrm{Pr}_{ts} = 0.85$ was adopted according to recent studies [18, 21-22].
A simple and accurate form of the relationship for calculating the turbulent Prandtl number was proposed by Kays [18]

$$\mathrm{Pr}_t = 0.85 + \frac{f}{\mathrm{Pe}_t} = 0.85 + \frac{f}{\frac{\varepsilon_\tau}{\nu}\mathrm{Pr}} \tag{20}$$

In this study, it was assumed that $f = 1.46$ instead of $f = 2.0$ suggested by Kays [18] since the better compatibility of the calculated Nusselt numbers with experimental data can be achieved.

4. Heat transfer correlations

Using the Lyon integral (12), the values of Nusselt number as a function of Reynolds and Prandtl numbers were calculated for various models of turbulent Prandtl numbers. The integrals appearing in formula (12) were calculated numerically using the trapezoidal method. The Nusselt number was calculated for nine different values of the Reynolds number and five various values of the Prandtl number. For small Prandtl numbers typical for liquid metals exponents at Reynolds number and Prandtl number are equal. The correlation for the Nusselt number may, therefore, be written in the following form

$$\mathrm{Nu} = x_1 + x_2 \mathrm{Pe}^{x_3} \tag{21}$$

where the Peclet number is defined as $\mathrm{Pe} = \mathrm{Re}\,\mathrm{Pr} = u_m\, d_w / \alpha$.
Using the Lyon integral (12), the values of Nusselt number as a function of Reynolds and Prandtl numbers were calculated for various models of turbulent Prandtl numbers.
Then the data $\mathrm{Nu}_{ij}^m = f\left(\mathrm{Re}_i, \mathrm{Pr}_j\right)$, $i = 1,\ldots,9$; $j = 1,\ldots,5$ was approximated by the function (21) using the method of least squares

$$S = \sum_{i=1}^{10}\sum_{j}^{5}\left[\mathrm{Nu}_{ij}^m - x_1 - x_2\left(\mathrm{Re}_i\,\mathrm{Pr}_j\right)^{x_3}\right] = \min \tag{22}$$

To determine the optimum values of the parameters x_1, x_2 and x_3 at which the sum of squares (22) reaches a minimum the Levenberg-Marquardt method [24] was used.

Using the relationship (16) with a = 0.01592 (the Aoki model I), the Nusselt number values $\mathrm{Nu}_{ij}^m = f\left(\mathrm{Re}_i, \mathrm{Pr}_j\right)$, $i = 1,\ldots,9$; $j = 1,\ldots,5$ were calculated using the formula (12).
Using the nonlinear least squares method the following relationship was found

$$\mathrm{Nu} = 5.72 + 0.0184\mathrm{Pe}^{0.8205},\ \ 3\cdot 10^3 \le \mathrm{Re} \le 1\cdot 10^6, \quad 0.0001 \le \mathrm{Pr} \le 0.1 \tag{23}$$

If for the calculation of the turbulent Prandtl number the improved Aoki's relationship (17) with b = 0.01171 and c = 0.00712 (the Aoki model II) is used, then the correlation was obtained.

$$\mathrm{Nu} = 5.51 + 0.015\mathrm{Pe}^{0.865},\ \ 3\cdot 10^3 \le \mathrm{Re} \le 1\cdot 10^6,\ \ 0.0001 \le \mathrm{Pr} \le 0.1. \tag{24}$$

Then, to determine the Nusselt number, the turbulent Prandtl number proposed by Kays and Crawford [22] and modified by Weigand, Ferguson, and Crawford [21] was applied.
The correlation for the Nusselt number obtained by applying the Weigand, Ferguson, and Crawford [21] model of turbulent Prandtl number given by Eqs. (18)-(19) with Pr_{ts}= 0.85, d = 0.3, and e = 182.4 is as follows

$$\mathrm{Nu} = 5.51 + 0.018\mathrm{Pe}^{0.8275},\quad 3\cdot 10^3 \le \mathrm{Re} \le 1\cdot 10^6,\quad 0.0001 \le \mathrm{Pr} \le 0.1 \tag{25}$$

Turbulent Prandtl number is also calculated using a modified Kays formula (20). The value of a constant f in Eq. (20) is $f = 1.46$ instead of the originally proposed by Kays constant $f = 2.0$. The values of the Nusselt number were calculated using the Lyon integral (12) while the turbulent Prandtl number defined by the formula (20) was used. The following heat transfer correlation was obtained

$$\mathrm{Nu} = 5.31 + 0.0221\mathrm{Pe}^{0.8174}, \quad 3\cdot 10^3 \le \mathrm{Re} \le 1\cdot 10^6, \quad 0.0001 \le \mathrm{Pr} \le 0.1 \tag{26}$$

Nusselt numbers calculated using the proposed correlations were compared with the experimental data.

5. Comparison of heat transfer correlations with experimental data

The formulas (23)-(26) derived in the paper will be compared with experimental data available in open literature and with the experimental correlations proposed by Seban and Shimazaki [25, 30] and Skupinski et al. [26]. Seban and Shimazaki [25] correlated data for a constant surface temperature of the tube to obtain

$$\mathrm{Nu} = 5.0 + 0.025\mathrm{Pe}^{0.8}, \quad 100 < \mathrm{Pe}, \quad 30 < L/d_w \tag{27}$$

Correlation (27) also approximates well experimental data obtained for constant heat flux at the tube wall [27]. Similar results gives the experimental correlation proposed by Skupinski et al. [26].

$$\mathrm{Nu} = 4.82 + 0.0185\mathrm{Pe}^{0.827}, \quad 100 < \mathrm{Pe}, \quad 30 < L/d_w \tag{28}$$

The comparisons presented in the Figures 2-3 show that the agreement between the correlations (23)-(26) derived in the paper and experimental data is quite good.

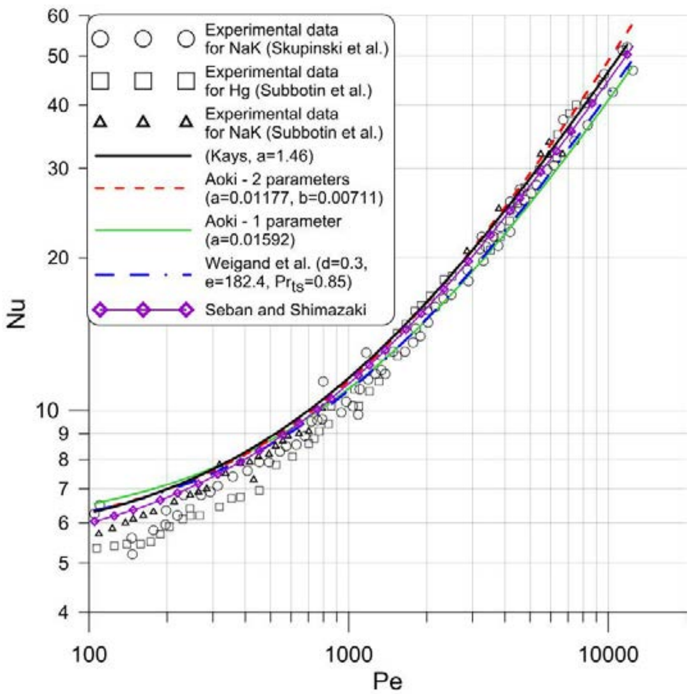

Fig. 2. Comparison of the Nusselt number determined using correlations (23)-(26) with experimental data of Skupinski [26] and Subotin [27].

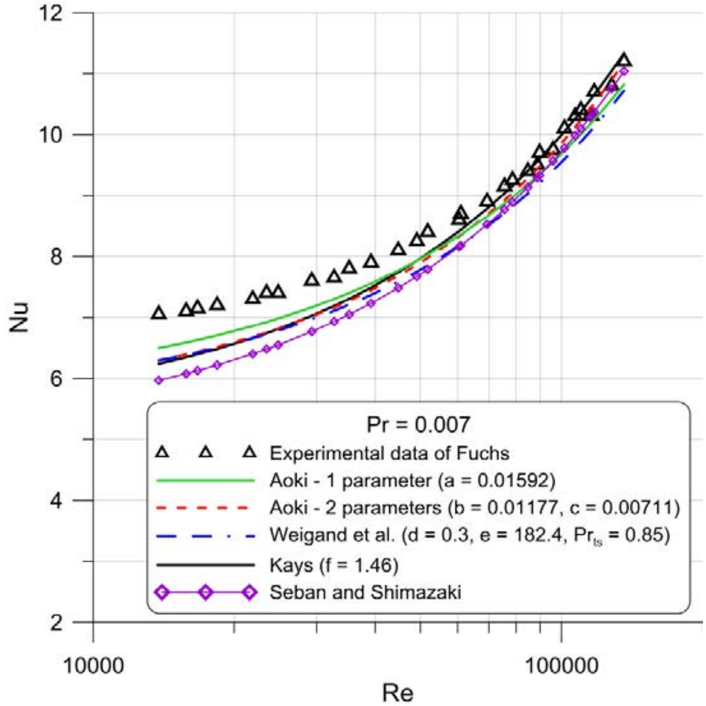

Fig. 3. Comparison of the Nusselt number determined using correlations (23)-(26) with experimental data of Fuchs [28].

The comparisons presented in the Figures 2-3 show that the agreement between the correlations (23)-(26) derived in the paper and experimental data is quite good.

Only for smaller Peclet numbers differences between calculated and experimentally determined Nusselt numbers are slightly larger. It should be stressed that all four relationships for the turbulent Prandtl number analyzed in the paper lead to very similar Nusselt number values for a given Peclet number value. It can be seen that the experimental data shown in Figures 1-3 have a scattering. This is due to the high sensitivity of physical properties of liquid metals to the impurities. Even a very small amount of impurities causes significant changes in thermophysical properties of the liquid metal.

6. Conclusions

Turbulent heat transfer in the circular tube was analyzed for a constant heat flux at the inner surface. Using the universal velocity profile determined experimentally and various relationships for the turbulent Prandtl number, the energy conservation equation was integrated. Four different turbulent number models developed by Aoki, Weigand et al., Kays, and modified Aoki's model were considered. Constants appearing in the formula for turbulent Prandtl number proposed by Aoki, as well as in improved Aoki's relationship proposed in this work were determined by the method of least squares based on experimental data of Sheriff and O'Kane. The Nusselt number values have been calculated $\mathrm{Nu}_{ij}^{m} = f\left(\mathrm{Re}_i, \mathrm{Pr}_j\right)$, $i = 1,\ldots,9$; $j = 1,\ldots,5$ for the Reynolds and Prandtl numbers changing in the following ranges: $3 \cdot 10^3 \le \mathrm{Re} \le 1 \cdot 10^6$, $0.0001 \le \mathrm{Pr} \le 0.1$. Using the calculated Nusselt number values, new heat transfer correlations for forced turbulent flow of liquid metals in the tubes have been proposed. All correlations for calculating the Nusselt number as a function of Peclet number derived in the paper approximate the experimental data quite satisfactory.

Acknowledgements

The author would like to acknowledge the Polish National Science Center for a financial support. The computational results presented in this paper are the part of the research grant OPUS 6. The project was financed by the Polish National Science Centre awarded based on the decision number DEC-2013/11/B/ST8/00340.

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