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Prediction of the Turbulent Mixing in Bare Rod Bundles

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Abstract

The turbulent mixing rate is a very important variable in the thermal-hydraulic design of nuclear reactors. In this study, the turbulent mixing rate the fluid flows through rod bundles is estimated with the scale analysis on the flow pulsation phenomenon. Based upon the assumption that the turbulent mixing is composed of molecular motion, isotropic turbulent motion (turbulent motion without the flow pulsation), and flow pulsation, the scale relation for the mixing is derived as a function of *P/D*, *Re*, and *Pr*. The derived scale relation is compared with published experimental results and shows good agreements. Since the scale relation is applicable to various Prandtl number fluid flows, it is expected to be useful for the thermal-hydraulic analysis of liquid metal coolant reactors as well as of moderate Prandtl number coolant reactors.

1. Introduction

Nuclear fuel assemblies are comprised of many subchannels. A subchannel is not an isolated but an open flow channel to each other. The flow field in a subchannel communicates with adjacent ones by exchange of mass, momentum and energy. Hence, in order to predict the thermal-hydraulic behavior precisely, it is important to understand the exchange mechanisms of major physical quantities as well as to analyze the thermal-hydraulic field of the single and isolated subchannel.

Many thermal-hydraulic subchannel analysis codes adopt the lumped parameter approach, where many empirical correlations are used to simplify the complex exchange phenomena between subchannels. Therefore, the prediction

Key Words : rod bundle, turbulent mixing rate, prandtl number, flow pulsation, scale analysis

capability of a subchannel analysis code depends thoroughly on the pertinent usage of the models and correlations. For single phase flows, most important models are the cross-flow and the turbulent mixing models. If there is no blockage in the flow field, the turbulent mixing model is the most important. The principal parameter related to the model is the turbulent mixing parameter β_M, that is the turbulent mixing rate W_{ij}'.

Turbulent mixing is a natural mixing phenomenon caused by the turbulent processes, so that it can redistribute momentum and temperature without net mass transfer. Hence, to obtain the turbulent mixing parameter, the characteristics of the turbulent mixing phenomenon between subchannels should be understood fundamentally and the rate of mixing has to be estimated.

There have been many attempts to explain turbulent mixing. The turbulent diffusion and the macroscopic flow, such as secondary flow, may be the causes of turbulent mixing. According to the previous studies, the mixing rates predicted from only using turbulent diffusion were smaller than those observed experimentally[1-3]. Moreover, if the turbulent diffusion is the main process of the mixing, the mixing rate should be proportional to the relative gap size (g/D). However, in fact, it is not sensitive to g/D[4]. Secondary flows also hardly contribute to the mixing because these are confined inside the subchannel[1-3,5].

Based upon many experimental researches on the turbulent mixing phenomenon in rod bundles, it was found that there is the periodic and macroscopic flow, namely 'cyclic and almost periodic flow pulsation,' and this is regarded as a main cause of the turbulent mixing[5]. Also, systematic experiments have shown that the principal frequency of the flow pulsation depends on Reynolds number and gap size[6-7]. Kim and Park[8] derived the scale relation for the turbulent mixing rate with the scale analysis methodology based on the fact that such flow pulsation is a main reason of the mixing. However, Kim and Park' s model does not account for the effect of Prandtl number, so that it is not applicable to low Prandtl number fluid such as liquid metals. In this study, a new scale relation of the turbulent mixing rate accounting for the effect of Prandtl number is derived with the methodology of Kim and Park. The turbulent mixing is assumed to be composed of three parts: molecular motion, isotropic turbulent motion (turbulent motion without the flow pulsation), and flow pulsation. Each length and velocity scales are estimated so as to derive the scale relation of the mixing rate which can be used for various Prandtl number fluids.

2. Derivation of the Scale Relation for Turbulent Mixing Rate

In the flow field in rod bundles like Fig. 1, we can observe the flow pulsation phenomenon which can not be found in the flows through circular tube and the flows between parallel plates. Recently, it was reported that this phenomenon could be found even in the gaps between axial fins[9-10]. The large scale eddies by the flow pulsation move across the gap between rods and blend mass, momentum and energy, so the pulsation is known as a main contributor to the turbulent mixing in rod bundles. Kim and Park[8] assumed that the mixing is composed of isotropic turbulent part without the pulsation and flow pulsation part and obtained the effective mixing velocity by the estimation of the length and velocity scales for each part. They modelled the flow pulsation as a hypothetical flow circulating across the gap with the period corresponding to the principal frequency of the pulsation. The detailed description of the modelling can be found in Kim and Park' s study[8].

In order to evaluate the turbulent mixing rate including the Prandtl number effect, at first, it is assumed that the parallel component of turbulent thermal diffusivity α_P is comprised of three parts; molecular (laminar) α_L, isotropic turbulent (turbulent excluding the flow pulsation) α_T, and flow pulsation parts αx. Actually, the heat transfer is composed of conduction (molecular motion) and convection (flow motion). If there is no geometrical asymmetry in the flow domain, the anisotropic turbulence can not be observed. For rod bundle flow fields, however, the asymmetry exists and it causes anisotropic turbulent structure. The flow pulsation phenomenon is also due to such geometrical asymmetry. Hence, the total heat transfer behavior may be assumed to be expressed as a superposition of the above three components: molecular motion, isotropic turbulent motion, and flow pulsation (anisotropic turbulent motion).

The length and velocity scales for each part are estimated so as to derive the scale relation of turbulent mixing;

$$\alpha_P = \alpha_L + \alpha_T + \alpha_x = \frac{\nu}{Pr} + \frac{\nu_T}{Pr_T} + \alpha_x \cdot (1)$$

Pr and Pr_T denote Prandtl number and turbulent Prandtl number, respectively. ν and ν_T are kinematic viscosity and isotropic eddy viscosity without flow pulsation. If ν_T can be regarded as the eddy viscosity for a circular tube, we can use the following general expression of the eddy viscosity

$$\frac{\nu_T}{\nu} = \frac{Re}{\gamma}\sqrt{\frac{f}{8}} = \frac{Re^{1-\beta/2}}{\gamma}\sqrt{\frac{a}{8}} = \frac{1}{\gamma}\frac{u^* D_H}{\nu}, \quad (2)$$

where f is friction factor and can be usually expressed as $f = \alpha Re^{-\beta}$ with $\alpha = 0.18$ and $\beta = 0.2$[5]. D_H is hydraulic diameter and γ is empirical constant. $\gamma = 20$ is used as recommended by Rehme[5].

The eddy viscosity and diffusivity are regarded as a product of velocity and length scales as Prandtl suggested in the mixing length hypothesis. Expressing α_P, ν_T, and α_x as products of each velocity and length scales,

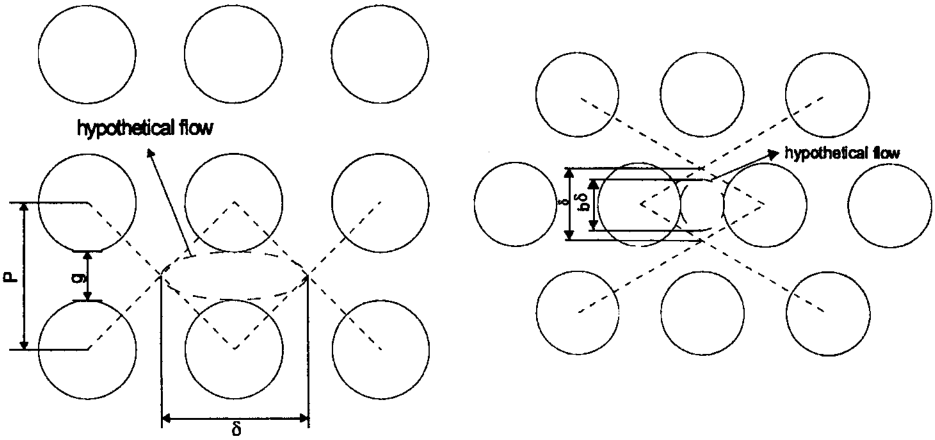
$$\nu_T = Cu^* g, \qquad \alpha_P = CU_{HP}L_{HP}, \quad \alpha_x = CU_x L_x, \quad (3)$$

Eq. (1) becomes

$$U_{HP}L_{HP} = \frac{1}{C}\frac{\nu}{Pr} + \frac{1}{Pr_T}u^* g + U_x L_x . \quad (4)$$

The velocity scale of the isotropic eddy viscosity is selected as the friction velocity u^* since u^* is the most typical velocity scale in turbulent flows. As for the length scale, the gap size g is adopted while Kim and Park[8] suggested the profile length at the gap, $g/2$. However, g seems to be more pertinent because the eddy may extend itself to the maximum size that the geometry permits. U_{HP} and L_{HP} are the parallel velocity and length scales of total eddy diffusivity. Also, U_x and L_x are the velocity and length scales of the flow pulsation. It should be noted that the proportional constant C is assumed to be the same for both turbulent thermal and momentum diffusion. In fact, eddy diffusivity and eddy viscosity are not fluid properties but flow characteristics which govern the transport process of all physical quantities.

Now, the parallel velocity and length scales of the flow pulsation, U_x and L_x, should be determined. In order to simulate the flow pulsation, Kim and Park[8] suggested hypothetical macroscopic flows which move through the gap to the center region of the subchannel circulating clockwise and counter-clockwise alternately between adjacent subchannels. The ellipse in Fig. 1 denotes the hypothetical flow path assumed in this study. The flow path is an ellipse whose major and minor axes are half of the parallel and normal length scales of the flow pulsation, $L_x/2$ and $L_y/2$, respectively.



(a) Square array (b) Triangular array

Fig. 1. Schematic of Rod Bundle Geometries

The principal frequency of the flow pulsation at the gap f_p can be expressed in terms of the path length z_{FP} and the flow pulsation velocity U_{FP} as $f_p = U_{FP}/z_{FP}$. Hence, introducing Strouhal number $Str = f_p\, D/u^*$, the parallel and normal velocity scales of the hypothetical flow U_x and U_y can be obtained as

$$\frac{U_x}{u^*} = a_x \frac{z_{FP}}{D}\, Str \quad and \quad \frac{U_y}{u^*} = a_y \frac{z_{FP}}{D}\, Str\,. \quad (5)$$

The velocity coefficient a_x and a_y denote the ratio of each velocity scale to U_{FP}. Also, Wu and Trupp' s [7] Strouhal number correlation,

$$Str^{-1} = 0.822\left(\frac{g}{D}\right) + 0.144\,, \quad (6)$$

is used as recommended by Kim and Park[8]. Since the hypothetical flow is assumed to have the elliptic motion with the major and minor axes, $L_x/2$ and $L_y/2$, respectively, velocities for each direction can be obtained from the kinetic energy conservation. Assuming that v_x and v_y denote the parallel and normal velocity of the fluid particle moving along the ellipse, the particle satisfies following equations;

$$\frac{x^2}{(L_x/2)^2} + \frac{y^2}{(L_y/2)^2} = 1, \quad (7)$$

$$v_x^2 + v_y^2 = U_{FP}^2\,. \quad (8)$$

If the average value of each velocity component can be regarded as directional velocity scales of the flow pulsation, the velocity coefficients become

$$a_x = \overline{\frac{v_x}{U_{FP}}} = \frac{2}{\pi}\sqrt{\frac{1}{1-\lambda^4}}\,\sin^{-1}\sqrt{1-\lambda^2}$$
$$and \quad a_y = \overline{\frac{v_y}{U_{FP}}} = \frac{2}{\pi}\sqrt{\frac{\lambda^4}{1-\lambda^4}}\,\sinh^{-1}\sqrt{\frac{1-\lambda^4}{\lambda^4}} \quad 9)$$

where the aspect ratio $\lambda = L_y/L_x$. If the aspect ratio is sufficiently small, the velocity coefficients become approximately

$$a_x = 1-\frac{2\lambda^2}{\pi} \quad and \quad a_y = (\ln 2 - 2\ln\lambda)\frac{2\lambda^2}{\pi}\,. (10)$$

These are applicable to any geometry, while in Kim and Park the velocity coefficients obtained for a square-arrayed rod bundles were used for all geometries. As to the path length, it can be approximated as

$$\frac{z_{FP}}{D} = 2\frac{b\delta}{D}\left[1+\left(-\frac{1}{2}\ln(\lambda)+\frac{1}{2}\ln(4)-\frac{1}{4}\right)\lambda^2\right] . (11)$$

Original Kim and Park' expression, however, shows somewhat large differences from the real elliptic path length for small aspect ratios.

On the other hand, the parallel and normal length scales of the flow pulsation, L_x and L_y, is about the centroid-to-centroid distance δ and gap size g, respectively, based on experimental evidences[6,11]. Then, Kim and Park[8] suggested that the parallel length scale should be shortened in the triangular-arrayed rod bundle, since there are obstacles in the front of the flow pulsation. This is different from in the square-arrayed rod bundle. They introduced the shape factor b to reflect such openness as:

$$L_x = b\delta , \quad L_y = g . \qquad (12)$$

In this, for an open path such as in the square array, they recommended b=1.0, and for a blocked path such as in the triangular array, b=2/ 3.

Assuming that the flow pulsation part prevails the other parts, $L_{HP} \sim L_x$ and Eq. (4) becomes

$$\frac{U_{HP}}{u^*} = \frac{1}{C}\frac{1}{Pr}\frac{\nu}{u^* L_x} + \frac{1}{Pr_T}\frac{g}{L_x} + \frac{U_x}{u^*} . (13)$$

If Pr is very small, the flow pulsation effect may not be dominant one. The molecular motion may play the most important role in the thermal mixing and L_{HP} should reflect the length scale of the thermal conduction. As the molecular length scale, the centroid-to-centroid distance δ may be suitable. Hence, with only a little error the molecular length scale can be set to L_x=$b\ \delta$ and Eq. (13) is also valid for small Pr. Then, each terms of right hand side will be discussed.

Comparing Egs (2) and (3),

$$C = \frac{1}{\gamma}\frac{D_H}{g} \qquad (14)$$

is obtained, so that the molecular term in Eq. (13) can be expressed as

$$\frac{1}{C}\frac{1}{Pr}\frac{\nu}{u^* L_x} = \frac{1}{Pr}\frac{\nu}{\nu_T}\frac{g}{b\delta} = \frac{1}{Pr}\frac{g}{b\delta}\left(\frac{\gamma}{Re^{1-\beta/2}}\sqrt{\frac{8}{a}}\right) . (15)$$

In this, Eq (2) is used. Also, the parallel length scale of the flow pulsation is expressed as L_x=$b\ \delta$. Considering the expression for the parallel length scale of the flow pulsation and Eq. (5), we can obtain

$$\frac{U_{HP}}{u^*} = \left(\frac{\gamma}{Pr\,Re^{1-\beta/2}}\sqrt{\frac{8}{a}} + \frac{1}{Pr_T}\right)\frac{g/D}{b\delta/D} + a_x\frac{z_{FP}}{D}Str . (16)$$

Usually, the turbulent mixing rate is expressed in terms of the mixing rate per unit length defined as,

$$W_{ij}' \equiv \rho U_{eff} g , \qquad (17)$$

where U_{eff} is the effective mixing velocity. If the length scale L_{HP} is proper, the virtual velocity responsible for the transfer by turbulence may be CU_{HP}. Also, it is expected that the effective velocity should be proportional to this virtual velocity[8]. Hence, recalling Eq. (14), the effective velocity can be expressed as,

$$U_{eff} = C_{eff}CU_{HP} = C_{eff}\frac{1}{\gamma}\frac{D_H}{g}U_{HP} , (18)$$

where the universal proportional constant C_{eff} is introduced to determine the effective velocity quantitatively. The universal constant for effective mixing velocity assumed to be

$$C_{eff} = \begin{cases} 1 & \textit{for molecular motion} \\ \frac{2}{\gamma} & \textit{for turbulent motion} . \end{cases} \qquad (19)$$

Then, the effective mixing velocity U_{eff} is

$$\frac{U_{eff}}{u^*} = \frac{2}{\gamma^2}\frac{D_H/D}{g/D}\left[\left(\frac{\gamma^2}{2Pr\,Re^{1-\beta/2}}\sqrt{\frac{8}{a}} + \frac{1}{Pr_T}\right)\frac{g/D}{b\delta/D} + a_z\frac{z_{FP}}{D}Str\right] \quad (20)$$

Prandtl number effect in turbulent mixing can be understood by the comparison α_L and α_T. From Eq. (20), the ratio of α_L and α_T is

$$\frac{\alpha_L}{\alpha_T} = \frac{Pr_T}{Pr}\frac{\gamma^2}{2Re^{1-\beta/2}}\sqrt{\frac{8}{a}} \ . \quad (21)$$

If $Pr_T \sim 1$ and $Re=10^5$, the molecular effect prevails the isotropic turbulent effect for $Pr<0.04$. Hence, for $Pr \sim 1$, the molecular term is much smaller than the isotropic turbulent and can be ignored so that the original approach of Kim and Park[8] which neglects Prandtl number effect is effective, but for $Pr \ll 1$, Kim and Park' s model is expected to underestimate the turbulent mixing rate.

3. Verification of the Scale Relation

Usually, experiments on the turbulent mixing in rod bundles is very difficult, so the turbulent mixing correlation is rare and the experimental results are somewhat scattered. Fig. 2 shows the comparison of the predicted values using the present and Kim and Park' s scale relations to the experimental gap Stanton numbers data of Seale[3] and predicted values using Rogers and Rosehart' s correlation (See Ref. [12]);

$$St_g = 0.004\left(\frac{D_H}{g}\right)Re^{-0.1} \ . \quad (22)$$

The gap Stanton number is a dimensionless number describing the turbulent mixing and is defined as

$$St_g \equiv \frac{Q_g}{c_p \Delta T\, g\, \overline{G}} \ , \quad (23)$$

where Q_g is heat transfer rate per unit length by turbulent mixing at the gap. ΔT and $\overline{\mathrm{G}}$ denote

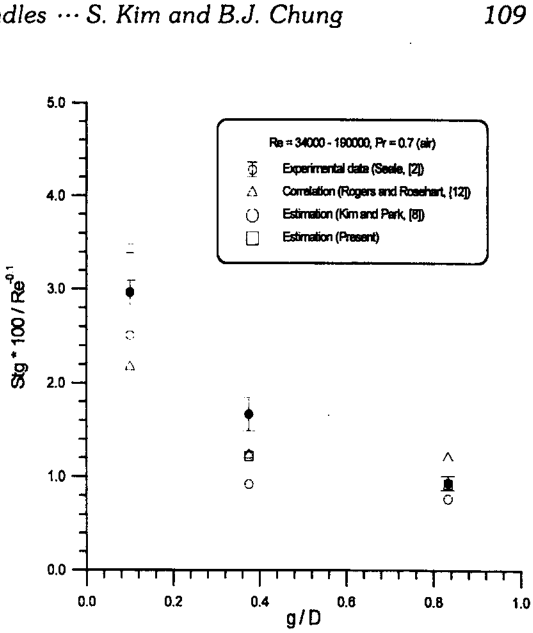


Fig. 2. Experimental and Estimated Gap Stanton Numbers

bulk temperature difference between connected subchannels and average mass flux of the subchannels, respectively. Then, the gap Stanton number can be written as

$$St_g = \frac{U_{eff}}{U} \ , \quad (24)$$

and the scale relation for gap Stanton number becomes

$$St_g = \frac{2}{\gamma^2}\sqrt{\frac{a}{8}}\frac{D_H/D}{g/D}\left[\left(\frac{\gamma^2}{2Pr\,Re^{1-\beta/2}}\sqrt{\frac{8}{a}} + \frac{1}{Pr_T}\right)\frac{g/D}{b\delta/D} + a_z\frac{z_{FP}}{D}Str\right]Re^{-\beta/2} \quad (25)$$

on the other hand, the mixing Stanton number, $M_{ij} \equiv W_{ij}'/gG_i$, and the turbulent mixing parameter (or thermal diffusion coefficient, TDC), $\beta_M \equiv W_{ij}/g\,\overline{G}$, are essentially the same as the gap Stanton number if mass fluxes of both subchannels are equal. As Seale[12] stated, Rogers and Rosehart' s correlation shows an opposite trend to the experimental results in part, but the scale relation obtained in this study shows comparatively good agreements in both magnitude and overall trend. The derived scale relation is closer to the

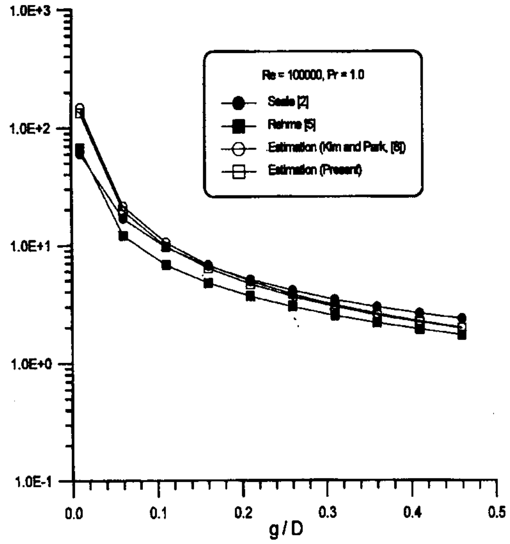


Fig. 3. Correlations of Mixing Factor in a Square Array

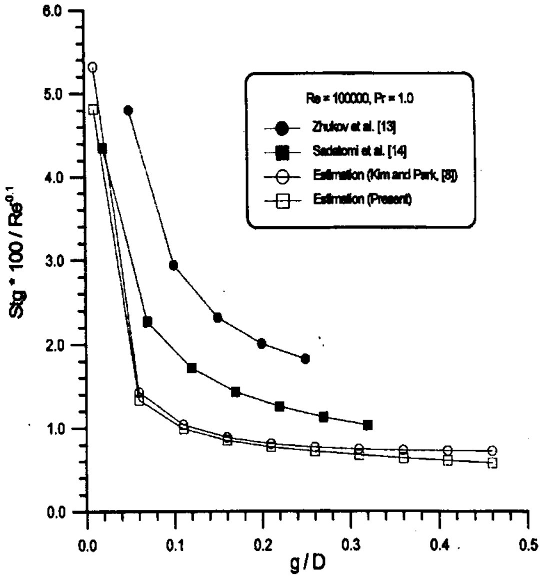


Fig. 4. Correlations of Gap Stanton Number in a Triangular Array

experimental data than that of Kim and Park[8]. Seale[12] also reviewed the work of Ingesson and Hedberg and proposed a mixing factor correlation similar to Ingesson and Hedberg's based on his experimental data;

$$Y = 0.94\left(\frac{P/D}{P/D-1}\right)^{1/2}\left(\frac{P}{D}\frac{P}{D_H}\right)^{3/2}, \quad (26)$$

where Y is mixing factor defined as

$$Y \equiv \frac{U_{eff}\,\delta}{\nu_c}. \quad (27)$$

In this, ν_c is the eddy viscosity of circular tube and is presumed to be same with the aforementioned isotropic eddy viscosity ν_T in Eq. (2). Hence, from Eqs (2) and (20), the scale relation for mixing factor becomes

$$Y = \frac{2}{\gamma}\frac{\delta/D}{g/D}\left[\left(\frac{\gamma^2}{2Pr\,Re^{1-\beta/2}}\sqrt{\frac{8}{\alpha}} + \frac{1}{Pr_T}\right)\frac{g/D}{b\delta/D} + a_z\frac{z_{FP}}{D}Str\right]. \quad (28)$$

In Fig. 3, mixing factor correlations and estimated mixing factors for square-arrayed rod bundles are plotted. The present scale relation as well as Kim and Park's[8] show good predictability of mixing factors.

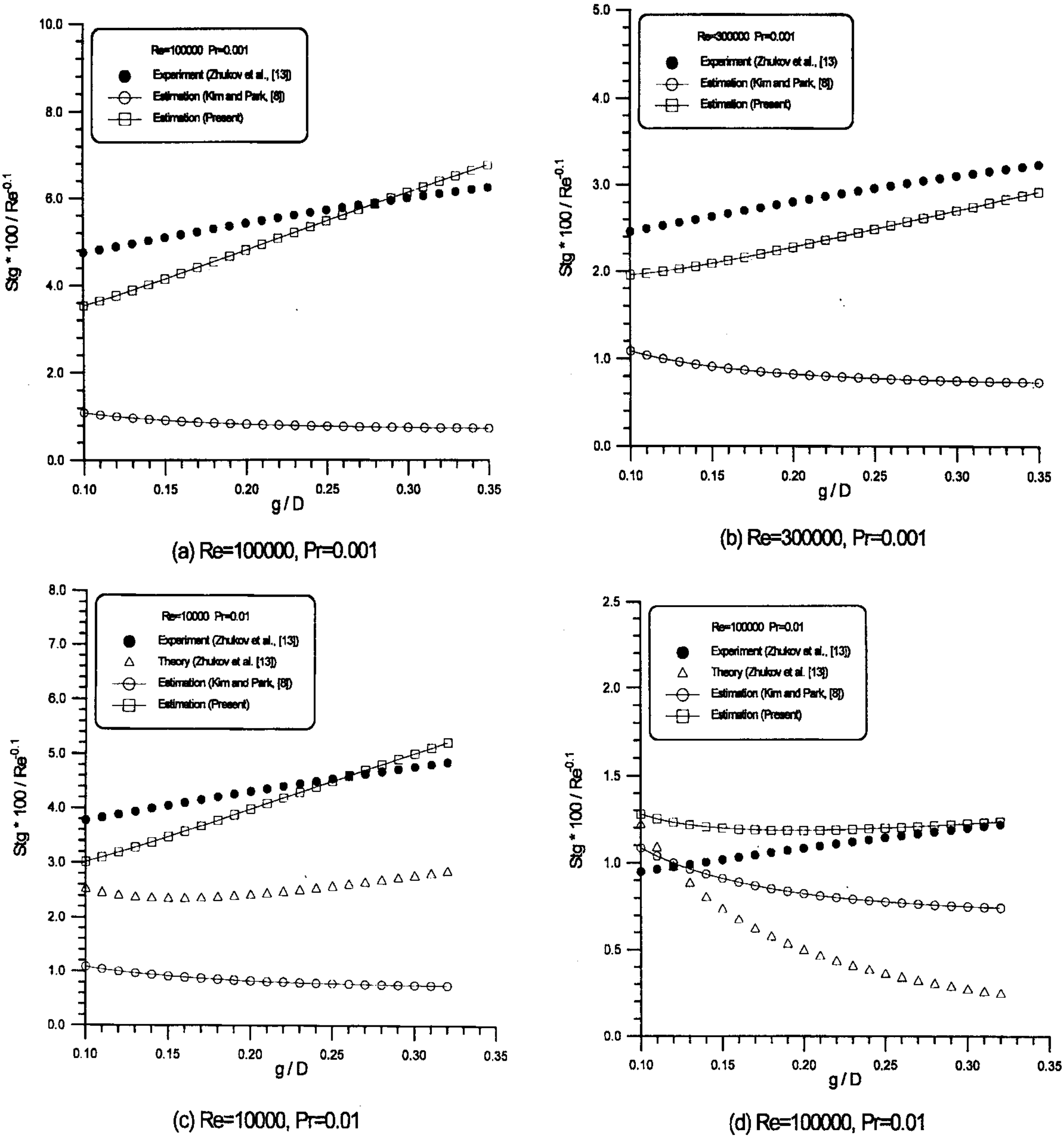
Experimental gap Stanton number correlations of Zhukov et al.[13]

$$St_g = \frac{Re^{-0.1}}{100}\left(1.0744 + \frac{0.1864}{g/D}\right), \quad (29)$$
$$(1.05 < P/D < 1.25\ ,\ 6.5\times10^4 < Re < 18.1\times10^4)$$

and Sadatomi et al.[14]

$$M_{ij} = 0.0018\left(\frac{g}{D}\right)^{-0.52}, \quad (1.02 < P/D < 1.35) \quad (30)$$

are compared with the present and Kim and Park's scale relations for triangular-arrayed rod bundles in Fig. 4. The discrepancy between the correlations and the scale relations is larger than that for square-arrayed rod bundles. However, since the trend of the gap Stanton number as the relative gap size g/D is very similar to each other



(a) Re=100000, Pr=0.001

(b) Re=300000, Pr=0.001

(c) Re=10000, Pr=0.01

(d) Re=100000, Pr=0.01

Fig. 5. Gap Stanton Number Correlation for Liquid Metals (triangular array)

and the scattering among experimental data is usually very large especially for triangular array as can be seen in Ref.[8] the difference seems not to be significant.

In fact, for moderate Prandtl number flows, Kim and Park's scale relation generates nearly same results compared with the present one as discussed above since the molecular motion hardly affect the mixing.

In some reactors like LMFBRs (Liquid Metal

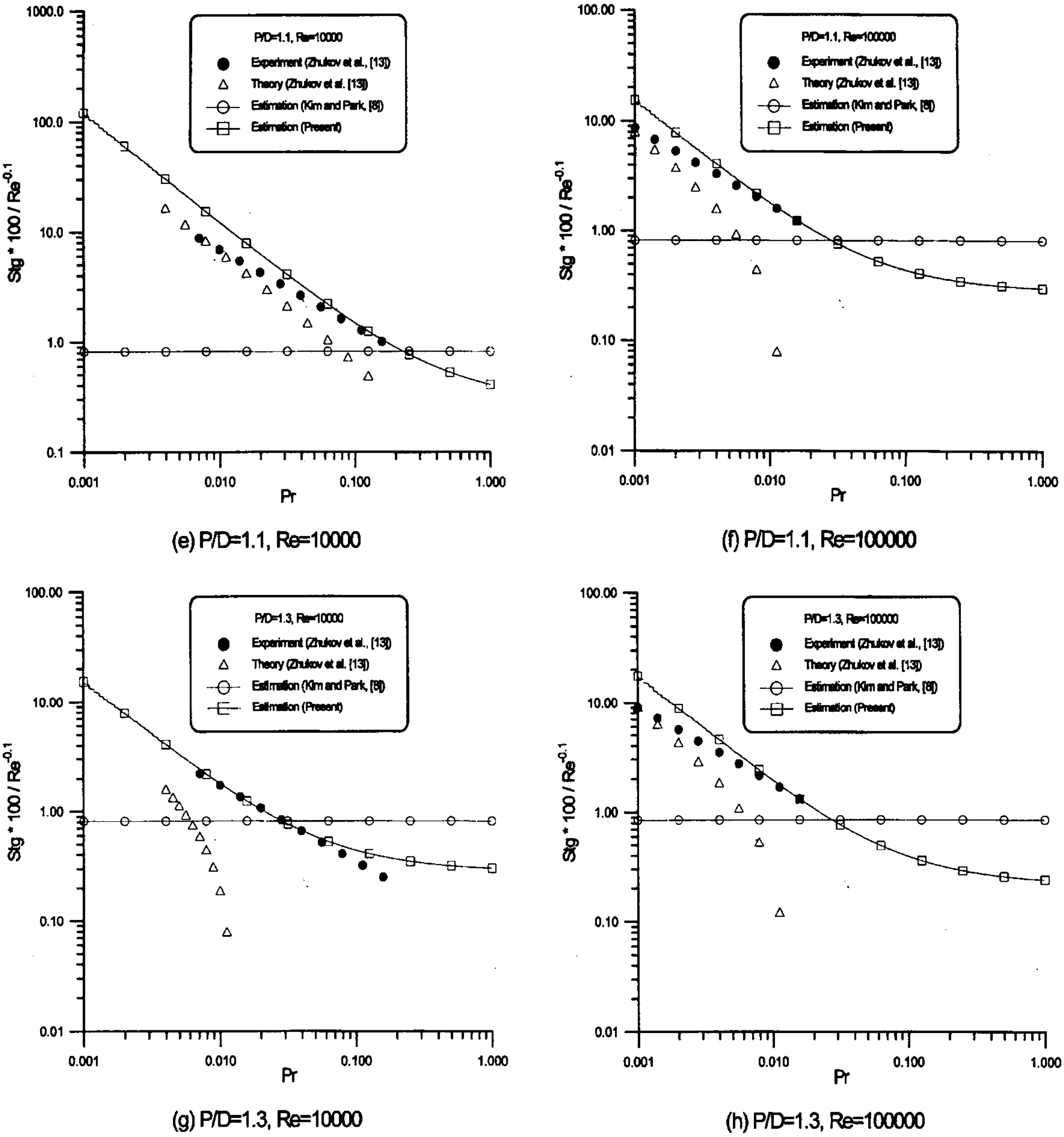


Fig. 5. Gap Stanton Number Correlation for Liquid Metals (triangular array)

Cooled Fast Breeder Reactors) and TRs (Transmutations Reactors), liquid metals are used as coolants. Liquid metal flows may also undergo the mixing process between subchannels, then the process is expected to be quite different from that for water or gas flows since Prandtl number of liquid metals is too small and liquid metals can transfer heat by the conduction as well as the macroscopic flow process.

Experimental data about the turbulent mixing for liquid metal flows in rod bundles are very rare and, to our knowledge, Russian researchers are only ones publishing the correlation for the mixing in liquid metal flows. Zhukov et al.[13] and Bogoslovskaya et al.[15] proposed gap Stanton number St_g correlation based on the experimental data for triangular-arrayed rod bundle;

$$St_g = \frac{0.393\left(\frac{2\sqrt{3}}{\pi}(P/D)^2 - 1\right)}{Pe^{0.7}(P/D)\sqrt{P/D-1}} \tag{31}$$

$$(1.10 < P/D < 1.35\ ,\ 70 < Pe < 1600\ ,\ Pr \ll 1)$$

where Pe is Peclet number. They also derived gap Stanton number correlation theoretically. The theoretical correlation of Zhukov et al. is somewhat different from that of Bogoslovskaya et al., but the difference is not significant. The following is the correlation of Zhukov et al.;

$$St_g = 10^{-2}\left[\left\{\frac{138}{Pe} + \frac{0.125[1-\exp\{1-\exp(-0.62\times 10^{-4} Re Pr^{1/3})\}]}{(P/D-1)^{1/2}}\right\}\frac{D_H/D}{P/D} + \frac{0.15}{P/D-1}\frac{1}{Re^{0.1}}\right][1-\exp(-80(P/D-1))] \tag{32}$$

$$(1.0 < P/D < 1.32\ ,\ 0.005 < Pr < 0.03\ ,\ 40 < Pe < 1500)\ .$$

Figure 5 shows the comparison of the present scale relation with the experimental and theoretical correlation. Turbulent Prandtl number is set to be $Pr_T = 0.9$. As shown in Fig. 5, the derived scale relation predicts the turbulent mixing rate for low Prandtl number fluid flow while Kim and Park' s[8] fails. Moreover, the present scale relation seems to be closer to the experimental correlation than the theoretical one proposed by Zhukov et al.[13]. As a consequence, the effectiveness of the scale relation derived in this study is proved. Also, it is worthwhile to note the trend of the mixing rate according to gap size. The mixing rate predicted by Kim and Park' s scale relation deduced neglecting the molecular effect on the mixing decreases as gap size increases. However, the mixing rate for very low Prandtl number fluid actually increases as gap size increases because the thermal conduction significantly contributes to the mixing.

4. Conclusions

A scale relation for the turbulent mixing rate in rod bundle flow fields is derived. Based upon the Kim and Park' s study on flow pulsation phenomenon, the turbulent mixing rate is predicted. The derived scale relation is verified with many experimental data and correlations which were obtained from various geometries and fluids. Hence, it is confirmed that the flow pulsation phenomenon plays a main role in the turbulent mixing. The scale relation reflects the effect of Prandtl number, so that it can be applicable to various Prandtl number fluid flow, therefore it is expected to be useful for the design and analysis of various types of reactors, especially for the selection of coolant and the thermal-hydraulic design of TRs (Transmutation Reactors), as whose coolants liquid metals are considered, lying in conceptual design stage.

Acknowledgements

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Nomenclature

a_x, a_y	velocity coefficients
b	shape factor
C	arbitrary proportional coefficient
C_{eff}	proportional constant for effective mixing velocity
D	rod diameter
D_H	hydraulic diameter
f	friction factor

f_p principal frequency of flow pulsation
g gap size
G mass flux
L_x, L_y length scales of flow pulsation
L_{HP} parallel length scale of total eddy diffusivity
M_{ij} mixing Stanton number
P rod pitch
Pe Peclet number
Qg heat transfer rate per unit length by turbuleut mixing at the gap
St_g gap Stanton number
Str Strouhal number
u^* friction velocity
$\bar{U}$ mean axial velocity
U_{eff} effective mixing velocity
U_{FP} velocity of flow pulsation at the gap
U_x, U_y velocity scales of flow pulsation
v_x, v_y velocity of hypothetical circulating flows
W_{ij}' mixing rate per unit length
Y mixing factor
z_{FP} hypothetical path length of flow pulsation

Greek

α, β, γ empirical constants for friction factor
δ centroid-to-centroid distance
θ azimuthal coordinate
ν molecular kinematic viscosity
ν_c eddy viscosity for circular tube
ν_T isotropic eddy viscosity
ρ density

Subscript

i, j index denoting subchannel i, j
N normal to the wall
P parallel to the wall

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