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# Investigation on the applicability of turbulent-Prandtl-number models in bare rod bundles for heavy liquid metals

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## HIGHLIGHTS

- Turbulent-Prandtl-number models are investigated for liquid meatals bundle flow.
- Wall-resolved low Reynolds number turbulence model is adopted.
- Effects of differenet $Pr_t$ models on several parameters are detailedly analyzed.
- Models of Kays and Aoki are recommended according to the present simualtions.

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## ABSTRACT

The study of turbulent heat transfer in heavy liquid metals has been undertaken till now as promising coolants for advanced nuclear fast reactors. However, the low Prandtl number property of liquid metals makes their heat transfer differ from traditional coolants and a constant turbulent Prandtl number is proven to be inappropriate for complex conditions. In this paper, in order to assess the applicability of different turbulent-Prandtl-number models in the bundle flow, turbulent heat transfer in triangular and square lattices with different pitch-to-diameter ratios are simulated. The low Reynolds $k-\epsilon$ Launder and Sharma turbulence model is adopted for turbulent momentum transport, and different turbulent-Prandtl-number models are used to solve turbulent heat transport. Deviations of these models on overall Nusselt number and local temperature distributions are analyzed. Based on the results achieved, turbulent-Prandtl-number models of Kays and Aoki are recommended for heat transfer simulation in bundle flow. A constant turbulent Prandtl number of 1.5 seems to be also acceptable compared with the recommended turbulent-Prandtl-number models.



## 1. Introduction

With the rapidly growing demand for energy, nuclear power is playing a more and more important role in future energy supply. Among six kinds of advanced nuclear energy systems proposed by the Generation IV International Forum (GIF) (Abram and Ion, 2008), two of them choose liquid metals as their coolants. Actually, heavy liquid metals (HLM) such as lead (Pb) or lead–bismuth eutectic (LBE) have been investigated for nuclear facilities since the middle of the last century because of their good performance in heat transfer, chemical inertness and natural circulation potential.

To gather basic knowledge of the characteristics of flow and heat transfer of liquid metals in rod bundles, experimental studies have been conducted in the framework of fast-reactor development programs. A good review of the experimental data and heat transfer correlations for tube bundles is given in (Mikityuk, 2009), and most of these data are for triangular lattices. Only (Zhukov et al., 2002) provided a total of 36 data pairs of Nusselt number (*Nu*) vs. Peclet number (*Pe*) for square lattice. For the sake of completeness, (Pacio et al., 2014) summarized detailed experimental information for liquid-metal heat transfer in triangular bare rod bundles in a table. As we can see most of these experiments are about sodium and mercury, and they were conducted at least 40 years ago. It is doubtful to directly apply the empirical correlations derived from these outdated data to advanced fast reactor using pure lead or LBE as coolants. Additionally, large discrepancies are observed when these correlations are compared with each other and it is hard to acquire a universal one covering wide range of flow parameters. Besides, Schulenberg and Stieglitz (2010) pointed out that it is challenging to measure local flow parameters and temperature in liquid-metal cooled reactor components.

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In addition to experimental efforts, growing activities in computational fluid dynamics (CFD) for liquid metals are ongoing worldwide. Heavy liquid metals have a common physical property called low molecular Prandtl number (*Pr*), typical of the order of 0.01 at operating conditions. This results in different heat transfer phenomenon compared to water or air. Advanced simulation methods such as direct numerical simulation (DNS) and large eddy simulation (LES) have been applied to investigate the characteristics of the heat transfer for liquid metals (Bricteux et al., 2012; Duponcheel et al., 2014; Kawamura et al., 1998, 1999). DNS and LES results of turbulent channel flow for low Prandtl number fluids show that the smallest temperature scales are much larger than those of the velocity and the boundary layer of the temperature field is much thicker than that of the momentum field. This invalidates the Reynolds analogy assumption for modeling turbulent heat transfer and leads to new challenges in numerical modeling for liquid metals (Grotzbach, 2013; Roelofs et al., 2013).

Roelofs et al. (2015) has reviewed the status and development routines of turbulence modelling for the industrial application of liquid metal flows. Two kinds of methods were put forward to make up the deficiency in turbulence heat flux modelling for liquid metals in all flow regimes. One is called algebraic heat flux model (AHFM). This method constructs algebraic formulation for turbulent heat flux and aims to provide improved solutions for the natural convection flow regions. Shams et al. (2014) combined a newly proposed set of model coefficients into AHFM-2005 model (Kenjeres et al., 2005) and gained significant improvements in the prediction of heat transfer in liquid metals in all flow regimes. The other is simpler which uses a turbulent-Prandtl-number model to calculate turbulent heat flux. Duponcheel et al. (2014) has assessed several turbulent-Prandtl-number models compared to the DNS/LES results in channel flow for liquid metals. Results showed that using local $Pr_t$ correlations is much more accurate than using a global one. Nevertheless, Roelofs et al. (2015) has also pointed out that the use of a turbulent Prandtl number as well as of a wall-function can probably not easily be extended to the mixed and natural convection flow regimes, further validation in more complex geometries should be performed.

In this paper, the effect of different turbulent-Prandtl-number models on heat transfer in bare rod bundles for liquid metals is investigated. Both global and local $Pr_t$ models were taken into consideration for triangular and square lattice in our work. Universal $Pr_t$ models are expected to provide much more accurate predictions in connection to best practice guidelines for RANS simulations.

## 2. Turbulent-Prandtl-number models of liquid metals

For near unity Prandtl number flows, temperature field is analogous to the flow field so it is proper to use a constant turbulent Prandtl number, e.g. typically $Pr_t \approx 0.85$. However, for low Prandtl number, the aforementioned DNS and LES results show it is no longer valid. Therefore suitable turbulent Prandtl number should take the low Prandtl number effects into consideration. Two classes of turbulent-Prandtl-number models have been reviewed in Chen et al. (2013) and Duponcheel et al. (2014). One is called global models, represented by Aoki (1963), Cheng and Tak (2006), Jischa and Rieke (1979) and Reynolds (1975). These models give a single value as a function of the flow conditions, i.e. Reynolds number (*Re*), *Pr*. The other is called local models, represented by Kays (1994) and Weigand et al. (1997). These two models are based on the local turbulent viscosity $v_t$ and give a $Pr_t$ field. Detailed correlations are given in Table 1 in chronological order. The Reynolds number defined in Table 1 is based on bulk velocity and hydraulic diameter and *Pe* equals the product of *Re* and *Pr*. It should be noticed that the Kays correlation has a singularity because $v_t$ approaches zero near the wall. This will result in infinity $Pr_t$ and infinitesimal $\alpha_t$. However, this would not be an issue since the heat transfer is essentially molecular in the near-wall region.

**Table 1**
Turbulent-Prandtl-number models of liquid metals.

| Investigators | Correlations |
|---|---|
| Aoki (1963) | $Pr_t^{-1} = 0.014Re^{0.45}Pr^{0.2}[1 - \exp(-\frac{1}{0.014Re^{0.45}Pr^{0.2}})]$ |
| Reynolds (1975) | $Pr_t = (1 + 100Pe^{-0.5})(\frac{1}{1+120Re^{-0.5}} - 0.15)$ |
| Jischa and Rieke (1979) | $Pr_t = 0.9 + \frac{182.4}{PrRe^{0.888}}$ |
| Kays (1994) | $Pr_t = 0.85 + \frac{0.7}{Pe_t}$, $Pe_t = \frac{v_t}{\nu}Pr = \frac{v_t}{\alpha}$ |
| Weigand et al. (1997) | $\frac{1}{Pr_t} = \frac{1}{2Pr_{t\infty}} + CPe_t\frac{1}{\sqrt{Pr_{t\infty}}} - (CPe_t)^2\left[1 - \exp\left(-\frac{1}{CPe_t\sqrt{Pr_{t\infty}}}\right)\right]$, $Pe_t = \frac{v_t}{\nu}Pr = \frac{v_t}{\alpha}$, $Pr_{t\infty} = 0.85 + \frac{100}{PrRe^{0.888}}$, $C = 0.3$ |
| Cheng and Tak (2006) | $Pr_t = \begin{cases} 4.12, & Pe \leqslant 1000 \\ \frac{0.01Pe}{[0.018Pe^{0.8} - (7.0 - A)]^{1.25}}, & 1000 < Pe \leqslant 6000 \end{cases}$ $A = \begin{cases} 5.4 - 9 \times 10^{-4}Pe, & 1000 < Pe \leqslant 2000 \\ 3.6, & 2000 < Pe \leqslant 6000 \end{cases}$ |

## 3. Heat transfer correlations for liquid metals in bundles

As mentioned above, there are several sets of experimental data for triangular lattice in the open literature and a few of heat transfer correlations have been proposed. Mikityuk (2009) assessed these correlations and recommended three good ones for triangular lattice as listed in Table 2. As for square lattice, experimental data are rare and in many cases the correlations for square lattice are derived from the corresponding correlations for triangular lattice. Table 3 offers several correlations for reference. All these correlations are based on overall heat transfer for bare rod bundle and the influence of grid spacers or wires should be considered separately.

Fig. 1 gives the comparison of heat transfer correlations for square and triangular lattices at two different pitch-to-diameter ratios ($x = P/D$). The scope of some correlations is appropriately extrapolated to adapt for $x = 1.2$. For the square lattice, big deviations are observed between Zhukov correlation and the other two. While the other two correlations coincide with each other well except at the small range of very low *Pe*. Here we choose Mikityuk correlation which is very close to Subbotin's for comparison. As for the triangular lattice, good agreement with each other is achieved for $x = 1.4$. But Mikityuk correlation underestimates the value by about 18 percent on average for $x = 1.2$. Because Gräber correlation is derived from 246 data pairs and Ushakov correlation is always in agreement with it, we prefer to trust Gräber correlation instead of Mikityuk correlation at $x = 1.2$. However, more detailedly experimental and analytical work is necessary in future to improve the consistency of these correlations, particularly for square lattices.

## 4. CFD simulation of turbulent LBE bundle flow

### 4.1. Geometric descriptions

Fig. 2 depicts two typical subchannels and grid schematic diagrams for triangular and square lattices. Due to the structural symmetry, only 1/6 subchannels of triangular lattice and 1/8 subchannels of square lattice are chosen to be simulated. The symmetry boundary condition is applied on the symmetry plane. Constant heat flux is imposed on the rod wall. To save the computational effort, periodic boundary conditions were exerted on the inlet and outlet plane. Hence only three times the hydraulic diameter ($D_h$) length in the axial direction are modeled.