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Numerical simulation of liquid metal turbulent heat transfer from an inline tube bundle in cross-flow☆

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Abstract

Results of the numerical simulation of turbulent flow field and heat transfer of liquid metal in cross-flow over inline tube bundles consisting of smooth round tubes are presented. Computations have been performed with CFD-code ANSYS Fluent on the base of a two-dimensional unsteady RANS formulation using the SST turbulence model by Menter and assuming constant physical properties of a fluid with the Prandtl number equal to 0.023. The Reynolds number ranged from 26,200 to 52,400. Instantaneous and time-averaged velocity and temperature fields obtained for bundles of different intertube spacing with a variation of the bundle width (number of tube rows in the cross direction) were analyzed. Integral characteristics of heat transfer were compared with the experimental data.

Keywords: Tube bundle; Liquid metal; Turbulence; Heat transfer; Numerical simulation; URANS.

1. Introduction

Many of the current issues facing the nuclear industry require extended and trustworthy knowledge of the specifics of turbulent flow and heat transfer in liquid metals; among these are, in particular, the problems arising when designing liquid metal-cooled fast reactors. The geometrical configurations of the reactors include cylindrical construction components, such as tubular heat exchangers, pumps, control system elements, etc., partially or fully immersed into the volume of circulating liquid metal.

The issue of the flow and heat transfer in cross-flowed tube bundles is among the most practically important 'canonical' cases [1,2] of the problem on liquid metal coolant thermohydrodynamics. This problem was extensively studied experimentally in the 1950s and the 1960s in the laboratories of the Central Boiler and Turbine Institute named after I.I. Polzunov (CBTI) [1,3] and of the Institute for Physics and Power Engineering named after A.I. Leypunsky (IPPE) [2,4]. The subjects of the research were the intensities of the local and the average heat transfer of inline and staggered tube bundles of various configurations in cross-flow, as well as the flow of heavy and alkali

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liquid metals around isolated cylinders with the Péclet number varying over a wide range. Measurement procedures were developed, and the effects of various factors on the heat transfer processes were studied, in particular, the operating parameters, the number of tube rows in the cross direction, bundle configurations, etc.

In the last decade, there has been a renewed interest towards this area of research, primarily, due to the large-scale projects in building nuclear power plants with new-generation high-safety fast reactors providing opportunities for implementing a closed nuclear fuel cycle. The results of the studies on the problem of heavy metal thermohydrodynamics (the metals in question were molten lead and lead-bismuth eutectics) in tube bundles in cross-flow that have been recently carried out in IPPE are partially described in Refs. [5,6].

The experimental approach to studying the flow structure and the thermal state of metal melts involves considerable costs and overcoming a number of intrinsic difficulties. Currently, numerical simulation based on the unsteady equations of motion and heat transfer is considered the most promising area of research for gaining more knowledge required for developing new projects. The computation techniques that are used nowadays can be classified into two groups, the engineering type (which is relatively cost-effective) based on the Reynolds-averaged Navier–Stokes equations (RANS, URANS); and vortex-resolving techniques (DNS, LES, DES); the latter are highly accurate but demand a lot of computational resources. The computations of turbulent flow of liquid sodium around an isolated circular cylinder with significant buoyancy effects can serve as an example of applying the direct numerical simulation method to a similar problem [7].

The experience of numerical simulation of turbulent flow and heat transfer in tube bundles in cross-flow described in literature mostly concerns the media with Prandtl numbers around unity. Early computations were based on the assumption that the flow field was periodic in the streamwise and the cross directions, which corresponded to the infinite bundle model [8,9]. However, when setting up laboratory experiments, researchers prefer to use bundles with the least possible number of tubes, especially for costly experiments with liquid metal flows. Consequently, this raises the question about the influence that the boundary effects have on the flow structure and the heat transfer characteristics. When carrying out numerical simulations whose results are compared to the experimental data, it is reasonable to eliminate (or at least substantially reduce) uncertainties of this sort. This can be done by rejecting the assumption that the flow is periodic, i.e., by using a computation domain comprising all of the tubes forming the bundle in the experimental prototype (see, for example, Refs. [10,11]).

This study presents the results of two-dimensional parametric computations of turbulent flow and heat transfer of liquid metal in cross-flow over inline tube bundles consisting of smooth round tubes. The computations were carried out on the base of unsteady Reynolds equations (the URANS method) using the ANSYS Fluent computational fluid dynamics software. We have investigated the influence of various factors, such as the operational Péclet number (in the range from 600 to 1200), the packing density and the width of the bundle, and the size of the computational grid, on the structure of the computed velocity and temperature fields, and on the heat transfer characteristics. We have assessed the URANS method's capability for predicting the average heat transfer for the conditions in question by comparing the computation results to the existing experimental data for pure alkali metals.

2. Problem setting and the computational aspects

Unsteady turbulent flow with a small Prandtl number ($Pr = 0.023$) has been examined in the two-dimensional formulation applied to the problem of inline tube bundles consisting of round tubes in cross-flow. We used the model of the incompressible Newtonian fluid with constant physical properties, without the buoyancy effects taken into account. Numerical simulation was based on solving the unsteady Reynolds-averaged Navier–Stokes equations (URANS) combined with the energy equation. The SST turbulence model was used to close the Reynolds system of equations [12].

The computations were carried out for the experimental conditions of Ref. [3], where inline tube bundles with various distances (steps) between them were studied in cross-flow of liquid alkali metals. The operating chamber of the experimental installation was a rectangular box with an inlet diffuser and an outlet confuser. In the experiments of Ref. [3], the central tubes of the first and the sixth rows of the bundles were heated successively by passing the electrical current through them. The rest of the tubes were not heated and served only to create a hydrodynamic similarity.

Table 1
Parameter values used for the simulation.

Parameter	Parameter value	
	Closely packed bundle	Widely packed bundle
Front step	$S_1 = 1.23d$	$S_1 = S_2 = 1.69d$
Depth step	$S_2 = 1.18d$	
Number of tube rows in the direction normal to the flow	1, 3, 5	3 complete
Number of tube rows along the depth	10	10

Notation: d is the length scale.

Only the case of heating the sixth-row tubes was taken for carrying out the computations in this investigation. Numerical simulation was done for two tube bundles:

- a closely packed one, with a front step $S_1 = 1.23d$ and a depth step $S_2 = 1.18d$;
- a widely packed one, with equal front and depth steps $S_1 = S_2 = 1.69d$. From here on the tube diameter d is used as the length scale.

The velocity V^* in the minimal cross-section normal to flow, determined by the ratio

$$V^* = \frac{V_{\text{in}}}{(1 - d/S_1)} \tag{1}$$

where V_{in} is the velocity at the computational domain inlet, is taken as the velocity scale.

The computational domains consisted of a number of tube rows in the direction normal to the flow, and two rows of semicircular 'displacers' and arranged on the side boundaries (the same as in the experiments of Ref. [3]).

One, three or five tube rows were set in the direction normal to the flow in the computations for the closely packed bundle. The computations for the widely packed bundle were carried out for one configuration consisting of three complete tube rows. Ten tube rows were placed along the depth of both bundles. The values of the geometrical parameters used for the simulation are listed in Table 1.

Fig. 1 shows, as an example, the computational domain for the closely packed bundle with one complete tube row. Constant values of the normalized velocity were set at the domain inlet: $V_{\text{in}} = 0.185$ for the closely packed bundle and 0.408 for the widely packed one; the reduced temperature at the inlet was assumed to be zero, $T_{\text{in}} = 0$. The reduced pressure at the outlet boundary was assumed to be zero. No-slip conditions

Depth step	$S_2 = 1.18d$	
Number of tube rows in the direction normal to the flow	1, 3, 5	3 complete
Number of tube rows along the depth	10	10

Notation: d is the length scale.

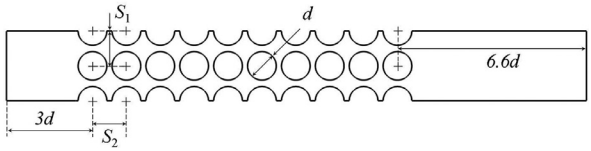

Fig. 1. The computational domain for the closely packed bundle with one complete tube row; S_1 and S_2 are the front and the depth steps, respectively; d is the length scale.

were imposed on the tube walls. The walls themselves were taken to be adiabatic except those of the sixth-row tubes where a constant-rate heat flux was set. The walls with semicircular displacers limiting the flow domain in the cross direction were regarded as adiabatic, and a no-slip condition was set for them as well.

The basic series of computations were carried out for each specific geometry for the following set of the Péclet number values, $Pe = V^*d/a$: 600, 800, 1000 and 1200 (a is the thermal diffusivity). The Reynolds number values ranged from 26,200 to 52,400.

Unstructured computational grids included, depending on the bundle configuration, from 160 to 500 thousand nodes. An additional computational series was performed for a closely packed bundle with three tube rows (across the flow) on a coarser computational grid, as compared to the basic one (the total number of grid nodes was reduced to about a third). Grid clustering to the cylindrical walls maintained a normalized size of the near-wall cell y^+ not exceeding unity for all the computed variants.

The computations were carried out using the CFD ANSYS Fluent 14.0 package. The turbulent Prandtl number was set to 0.85. The inlet values of the turbulence characteristics were computed based on the turbulence intensity of 5% and the ratio between the turbulent and the molecular viscosities equal to 10.

3. Computational results and discussion

Moving on to presenting and discussing the results, we should first and foremost note that the numerical solution was reduced to a steady one during the computations for the closely packed bundle with one tube row at all the examined values of the Péclet number, and also at its minimal value ($Pe = 600$) for the variants of 3 and 5 rows. In other cases, the flow field

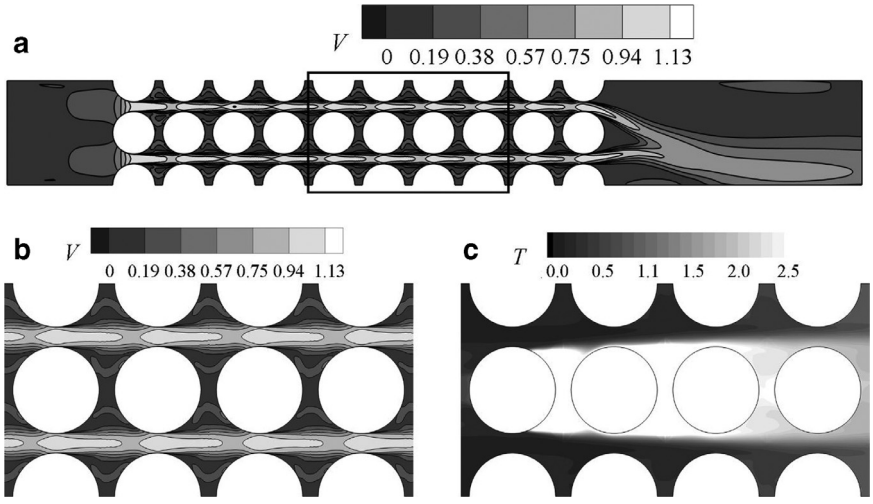

Fig. 2. The instantaneous fields computed at $Pe = 1200$ for the closely packed bundle with one complete tube row: velocity magnitude (a), enlarged fragments of velocity magnitude (b) and temperature (c). Normalized values of the quantities are shown.

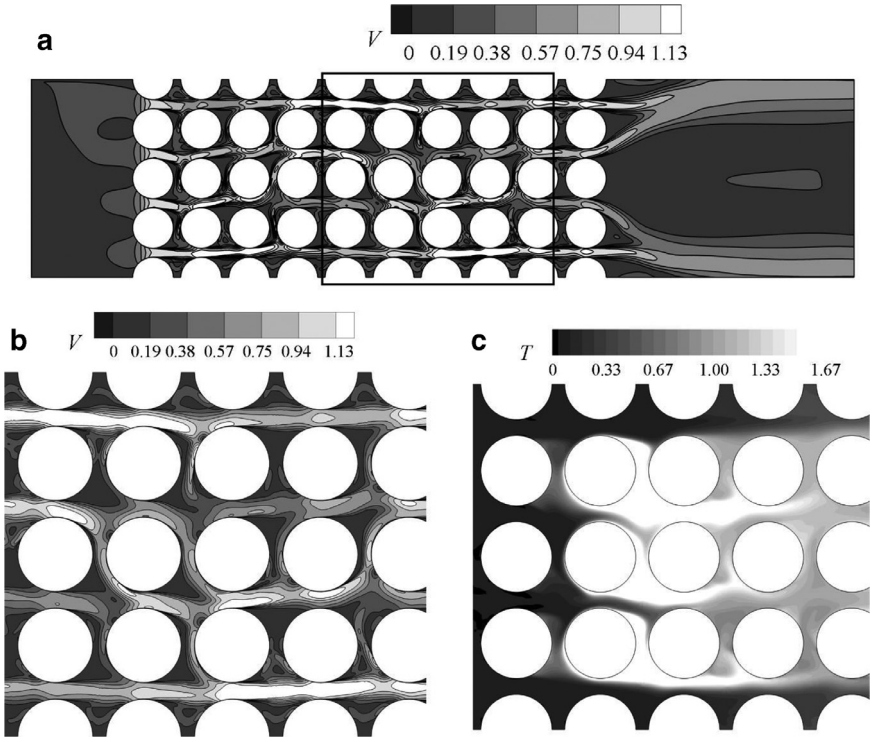

Fig. 3. The instantaneous fields computed at $Pe = 1200$ for the closely packed bundle with three complete tube rows: velocity magnitude (a), enlarged fragments of velocity magnitude (b) and temperature (c). Normalized values of the quantities are shown.

computed was unsteady and non-periodic, which required obtaining a substantially large time sample for subsequent averaging.

Figs. 2–4 show general pictures and enlarged fragments (in the vicinity of the sixth-row tubes) of the instantaneous distributions of the total dimensionless velocity and the normalized temperature, obtained for the closely packed bundle with different numbers of cross-flow tube rows at the highest Péclet number ($Pe = 1200$) of the examined ones. The temperature was normalized to the difference between the outlet bulk temperature and the inlet temperature.

It can be seen that in case of the single-row bundle, two narrow jets coming out of the intertubular space

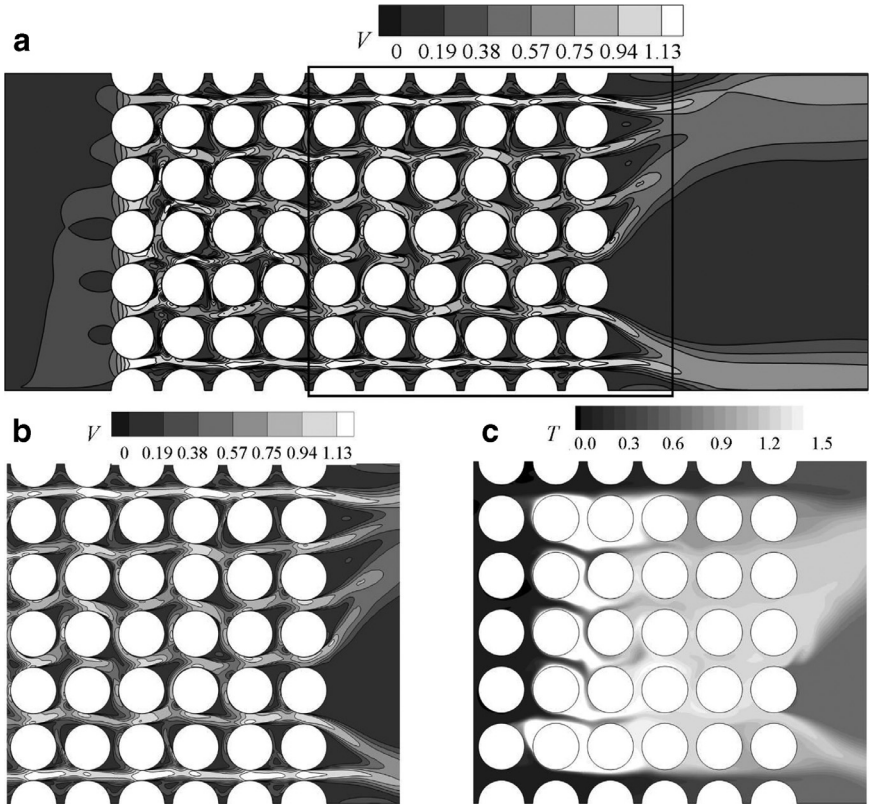

Fig. 4. The instantaneous fields computed at $Pe = 1200$ for the closely packed bundle with five complete tube rows: velocity magnitude (a), enlarged fragments of velocity magnitude (b) and temperature (c). Normalized values of the quantities are shown.

deflect to one of the walls limiting the flow domain in the cross direction; while the numerical solution is being developed, the direction of this deflection is random in character (due to the symmetry of the computational domain and the boundary conditions). The thermal wake propagates in the direction of the flow, enveloping several of the cylinders behind it.

For the case of the three-row bundle, the computed flow has a pronounced unsteady behavior with a noticeable crosswise coolant flow in the intertubular space. In contrast to the case of the single-row configuration, the flow pattern is symmetrical at the outlet of the three-row bundle. Here, the jets flowing around the central row of cylinders are merged (each one with its adjacent jet forming between the boundary tube row and the displacers) and deflect in the direction of the nearest horizontal wall. The velocities of the streamwise coolant flow through the lines are different: the flow is more intense in the space between the outer tube rows and displacers.

The patterns of the flow fields inside the five-row tube bundle in cross-flow are qualitatively similar to those obtained for the three-row one. Here, however, the same as in the case of the single-row configuration, the computational results display a solution asymmetry in the region behind the bundle, with the jets combining and subsequently deflecting towards the horizontal walls. We should note that this asymmetry is retained in the time-averaged fields as well.

Fig. 5 illustrates the effect of the Péclet number on the computational results, showing the time-averaged velocity magnitude fields for the three-row bundle at $Pe = 600$ and 1200. It can be seen that flow structures predicted by the URANS method for these regimes differ both within the tube bundle and in the wake of the bundle. For the case of $Pe = 600$, the jets markedly change their direction during inline flow. The flow in the wake is asymmetrical, and the merging of the jets, in contrast to the regime with the highest Péclet number, is unpaired: both a wide jet (via merging the three jets leaving the bundle) and a second one (a single one) form.

The instantaneous velocity and temperature fields computed for the widely packed bundle at $Pe = 1200$ are shown in Fig. 6. The flow, compared to the one obtained for the three-row closely packed bundle, is

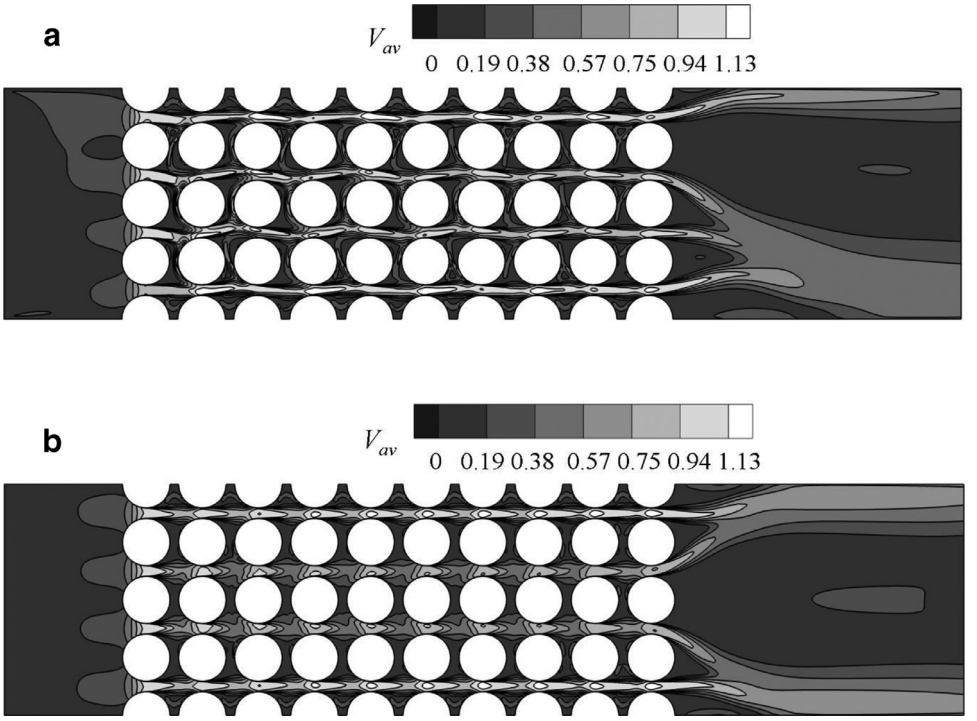

Fig. 5. Time-averaged distributions of the velocity magnitude for the three-row closely packed bundle: $Pe = 600$ (a) and 1200 (b). Normalized values of the quantities are shown.

significantly more chaotic; the degree of flow mixing is also noticeably higher here, due to more intensive cross-flows in the wide intertubular spaces. The thermal wake from the heated tubes diffuses rather quickly, and becomes shorter. These changes in the flow structure have, as shown below, a significant effect on the average characteristics of heat transfer.

The computed values of the average Nusselt number Nu for an individual tube were obtained in the following way:

$$Nu = \frac{q_w d}{\lambda(T_w - T_{in})} \tag{2}$$

where T_w is the average temperature of the heated tube surface, q_w is the thermal heat flux density on the tube's surface, λ is the coefficient of thermal conductivity.

Two methods of evaluating the average Nusselt number were used when processing the numerical data obtained for the bundles consisting of more than one tube row in the cross direction: in the first case, only the data for the central cylinder was used (the number is denoted by Nu, the same as in the experiments of Ref. [3]), while in the second case, the arithmetic mean of the Nusselt numbers obtained for all the heated cylinders located in the sixth row was computed (the mean value is denoted by Nu_Σ).

In Fig. 7, the Nusselt number values computed for different bundle configurations are compared with the experimental data obtained for the flow of pure alkali metals in inline bundles with the package parameters under consideration [1].

Fig. 7a shows the Nusselt number values for the closely packed bundles in the configurations of three and five tube rows in cross direction, computed by two different methods. Additionally, the plot includes a generalized approximation $Nu = Pe^{0.5}$, recommended by the authors of Refs. [3,4] for use in estimations of heat transfer for pure liquid metals flowing around inline and staggered tube bundles. Let us note here that the experiments with flowing molten lead and lead-bismuth eutectic (described in Refs. [5,6]), as well as the recent experiments with lead [13], have yielded the heat transfer coefficient values that are several times lower than those estimated by the dependence $Nu = Pe^{0.5}$. The main reason for this discrepancy is that the oxide film on the surface of the construction material forms, together with the near-surface lead layer saturated by impurities and oxide of the coolant, a low-conductivity layer that prevents intense heat transfer (the so-called thermal contact resistance (TCR)

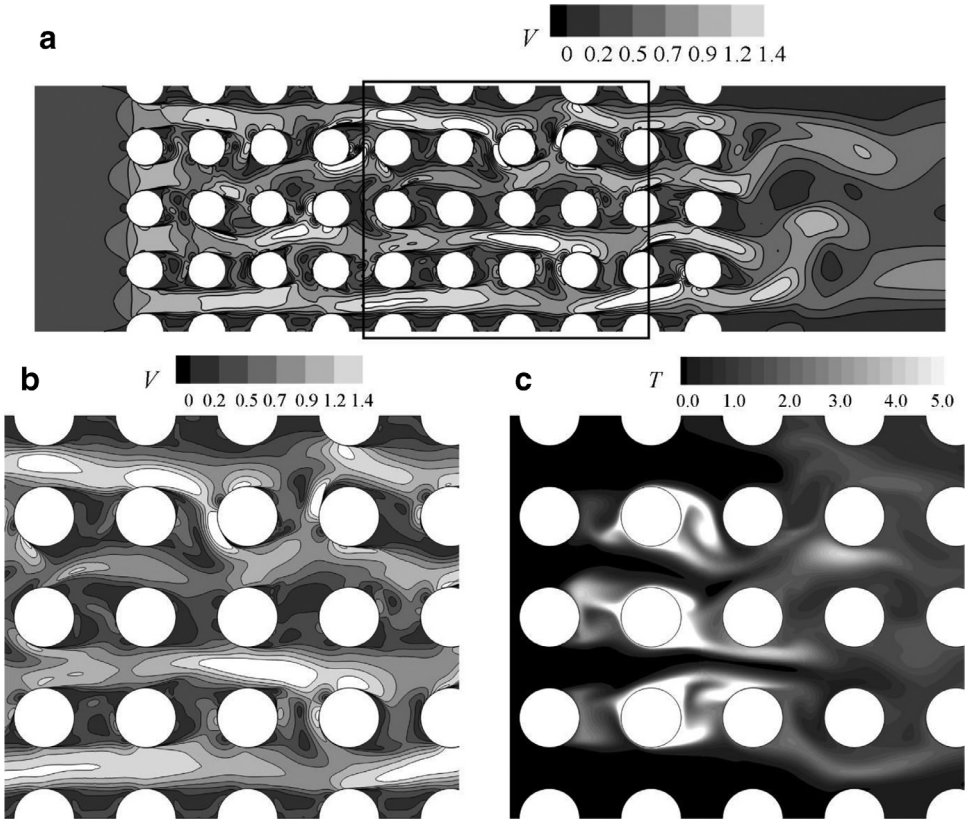

Fig. 6. Instantaneous fields computed at $Pe = 1200$ for the widely packed bundle with three tube rows: velocity magnitude (a), enlarged fragments of the velocity magnitude (b) and temperature (c). Normalized values of the quantities are shown.

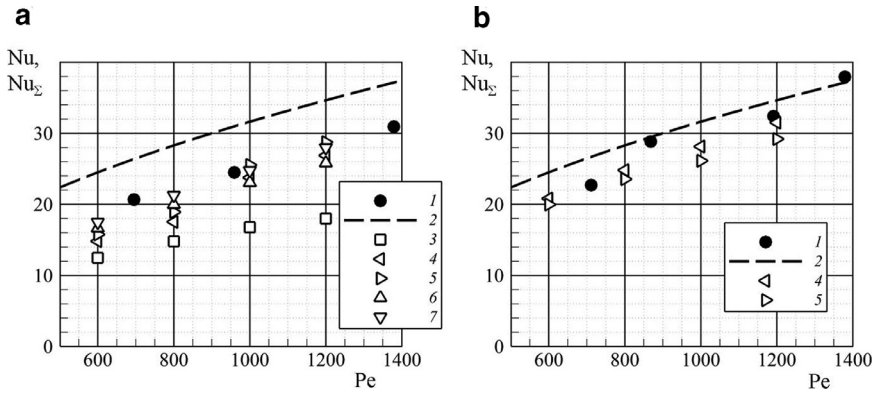

Fig. 7. Experimental (1) and computed (3 – 7) Nusselt number values Nu (1 – 3, 5, 7) and Nu_Σ (4, 6) depending on the Péclet number, and an approximation of the experimental data (2) for the closely packed (a) and the widely packed (b) bundles. The computations were performed for one (3), three (4, 5) and five (6, 7) tube rows.

appears). In case of pure alkali metals, the TCR effects were relatively small.

The analysis of the computed data presented in Fig. 7a reveals that for the case of the single-row closely packed bundle the URANS method (actually the steady RANS solution) predicts for all the computed regimes a heat transfer intensity that is significantly lower compared with the experimental data [1]. The computed values are approaching the experimental ones with an increase in the number of rows. The best agreement is achieved at high values of the Péclet number. Furthermore, the influence of the number of

Table 2
The effect of grid size, Péclet number and averaging method on the Nusselt number values.

Péclet number	Nu		Nu_Σ	
	Coarse grid	Fine grid	Coarse grid	Fine grid
600	16.64	15.77	16.13	14.83
800	20.45	18.90	19.49	17.53
1000	23.70	25.53	22.17	23.75
1200	25.13	26.88	26.41	28.74

rows and the method of computing the average heat flux is less pronounced here.

Table 2 shows the Nusselt number values evaluated by two different methods from the computational results for the three-row closely packed bundle on computational grids with varying degrees of refinement. The differences in the results obtained for various grids do not exceed 5–7%, with the higher Nusselt values predicted for the two lower Péclet values on a coarser grid; on the contrary, the computations on a finer grid for $Pe = 1000$ and 1200 predict a higher intensity of average heat transfer.

The computed Nusselt number values obtained for the widely packed bundle (Fig. 7b) show a good agreement with the experimental data for all regimes [1].

There is no doubt that the professional application of the vortex-resolving techniques can provide a more adequate simulation of the turbulent field structure, the spatial and temporal flow evolution, the local and the average heat transfer from the surface of the heated tubes in the bundle. However, despite known deficiencies of the computationally effective URANS approach, its application turned out to be quite productive in our purposes. Even with computational grids of moderate sizes, we managed to obtain an acceptable degree of agreement with the experiments for the average heat transfer that is required in practice.

4. Conclusion

The cost-effective computational approach based on solving the unsteady Reynolds-averaged Navier–Stokes equations (the URANS method) was used for two-dimensional numerical simulation of turbulent flow and heat transfer of liquid metal in cross-flow around inline tube bundles. The influence that the variation of the Péclet number ranged from 600 to 1200, the tube packing density in the bundle, and its width had on the flow field and the average heat transfer was studied when taking into account the confining wall effects. It follows from comparing the computed integral characteristics of heat transfer with the experimental data that an acceptable level of agreement is achieved if the computational domain includes three or more tube rows in the cross direction.

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