# Use of numerical methods in generalizing nusselt numbers depending on the reynolds number for a compact tube beam

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***Abstract.*** *When developing new types of heat exchanger constructions, such factors as their mass-size characteristics, efficiency of heat transfer through the separating heat-carrier surface, pressure losses in the paths for each of the heat-carriers and other parameters characterizing the heat-exchange apparatus play an important role. CFD modeling of heat and mass transfer processes in a tube bundle at different Re numbers with compact placement of tubes, using ANSYS Fluent software package, has been conducted. The mathematical model is based on Navier-Stokes equation, energy conservation equation for convective flows and continuity equation. The standard k-ε model of turbulence is used in the calculations. The fields of velocities, temperatures, pressures in the studied channels have been obtained. The hydrodynamic flow conditions in the channels are analyzed and the intensity of heat transfer between the hot and cold coolant through the wall separating them is estimated. Based on the results of CFD modeling, the criterial equation of Nu, number is derived, which can be used in engineering calculations of heat exchange apparatuses with compact tube bundles.*

***KEYWORDS****: HEAT EXCHANGE APPARATUS, CFD MODELING, HEAT AND MASS EXCHANGE, TUBE BUNDLE, NUMBER NU.*

## *1. Introduction*

Bundles of smooth cylindrical tubes with chessboard and hallway arrangement are widely used in various heat-exchange apparatuses and devices of power installations. The review of literature sources and results of a significant number of experimental studies of heat-hydrodynamic characteristics of smooth tube bundles in their transverse flow, including studies of heat release of chessboard bundles at Re numbers shows that such bundles have higher heat release in comparison with corridor bundles. However, at the same time, they have higher hydraulic resistance compared to corridor beams.

It should be noted that surfaces of this type, used in shell-and-tube heat exchangers, lead to an increase in their mass and dimensions. One of the ways to improve these characteristics is the use of fins and heat transfer intensifiers on convective surfaces. However, the use of finned surfaces and intensifiers significantly increases the hydraulic resistance in the paths of heat exchanger and requires the use of pumps and fans of higher power for pumping heat-carriers. A promising direction of reducing hydraulic resistance and intensification of heat exchange on convective surfaces of heat exchangers is the use of smooth tube bundles with compact configuration.

Heat exchangers are primarily classified either by flow configuration (counterflow, direct flow and crossflow) or by constructive implementation (concentric tube, shell-and-tube and compact) [1]. The ultimate goal of every heat exchanger or heat transfer study is to find methods or constructions that increase the heat transfer rate. One of the main features of increasing heat transfer is to play with the nature of the flow and change it from laminar to turbulent [2]. The more turbulence, the more it contributes to heat transfer [3, 4]. To increase turbulence, this can be done in two ways, called active and passive methods [5]. Active methods require the use of external energy, which can be mechanical, hydromagnetic or electrohydrodynamic [6, 7]. While the use of extended surfaces, called edges, is a widely used method among passive methods to increase heat transfer. The effective heat transfer area increases with the use of extended surfaces, resulting in turbulent flow, which increases the transfer rate. In passive methods, the heat transfer rate increases due to modification of the heat transfer interface surfaces [8]. For example, using a method of artificial roughness by using low-height repeating ribs on the heat transfer surface to break the laminar layer and increase turbulence in heat transfer [9]. Others report the use of V-shaped, W-shaped, angular and transverse ribs to create artificial roughness [10, 11].

However, there is another solution to the passive method of increasing the intensity of heat transfer, it is a compact arrangement of tubes in the tube bundle [12, 13].

Therefore, the development of new constructions of shell-and-tube heat exchangers with compact tube bundles is relevant and requires a solution.

Research objective – Development of new constructions with compact placement of bundles of smooth tubes at their cross flowing by coolants and CFD modeling of heat and mass transfer processes in heat exchanger channels with subsequent derivation of criterial equation of number Nu.

## *2. Materials and Methods*

Let us consider a tube bundle of compact configuration in their transverse flowing (Fig. 1). The geometry of arrangement of tubes with diameter $d = 10$ mm is peculiar, different from traditional chessboard, hallway arrangement. The distance between the tubes is 5 mm. Thickness of a pipe is 1 mm. Material of the pipe is "Steel 3". On the third pipe, the boundary condition "wall_L" and "wall_R", set the heat source to 2070.064 $W \cdot m^{-2}$. All other pipes are set to the temperature corresponding to the inlet temperature. See Table 1 for details. In order to derive the criterion equation for the number Nu it is necessary to change the number *Re*, which depends on the air velocity at the inlet. The *Re* number varied from 332 to 4946.

Numerous simulations of heat and mass transfer processes in tube bundles of compact configuration using the ANSYS Fluent application package have been performed.

Mathematical model is based on Navier-Stokes equations [14-16] and convective energy transfer equation. We chose the standard k-ε turbulence model [17].

***Table 1.*** *Inlet air parameters*

| Parameter | Value | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Inlet air velocity, $m \cdot s^{-1}$ | 0.5 | 1.4 | 2.3 | 3.4 | 4.0 | 4.7 | 5.4 | 6.0 | 6.6 | 7.4 |
| Inlet air temperature, $^{o}C$ | 17.1 | 16.2 | 16.7 | 16.4 | 16.1 | 15.6 | 15.5 | 15.5 | 15.5 | 15.5 |
| Number *Re* | 331.9 | 934.5 | 1530.5 | 2254.9 | 2658.4 | 3149.2 | 3609.0 | 4007.9 | 4409.9 | 4946.0 |

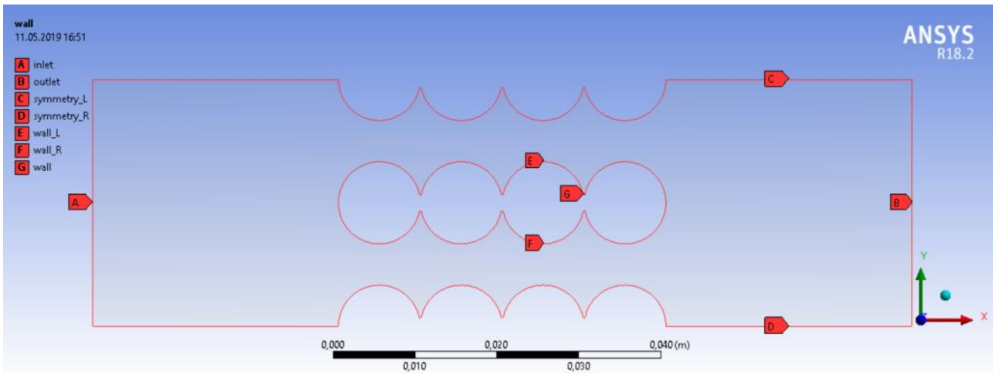
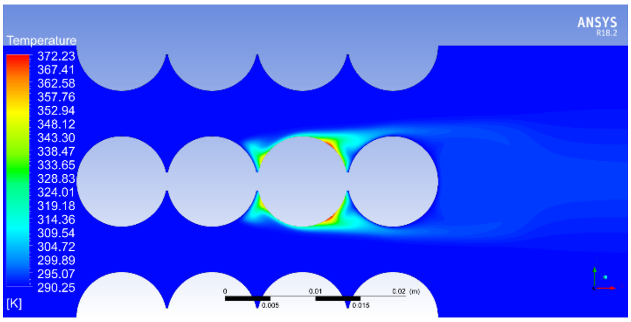


***Figure 1.*** *Geometry of the tube bundle arrangement and boundary conditions designation for CFD modeling*

## *3. Results and discussions*

The results of numerical calculations are shown in Figures 2-3. Fig. 2 shows the distribution of the temperature field in the channels of the tube bundle. The amount of heat released by the third tube is the same for all models. Due to the increase in air flow in the channels of the tube bundles, the temperature is different and ranges from 288$^o$ K (+15$^o$ C) to 372$^o$ K (+99$^o$ C).

Fig. 3 shows the velocity field in the heat exchanger channels. Analysis of the obtained velocity field shows that the maximum values of flow velocity are observed between the pipes in the narrow section.



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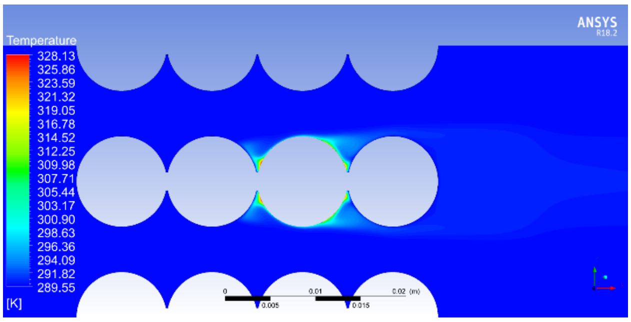

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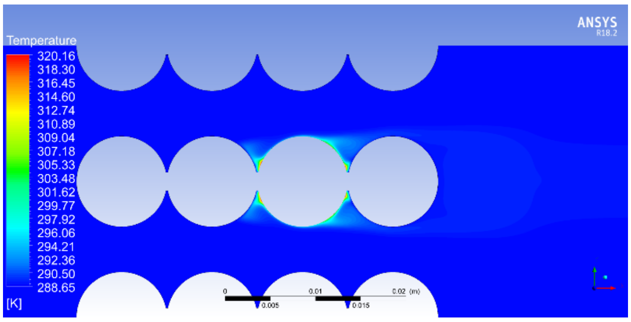

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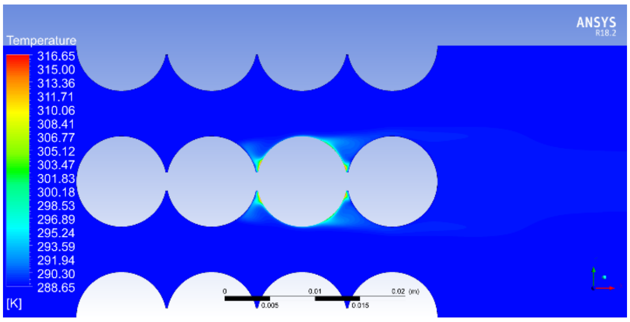

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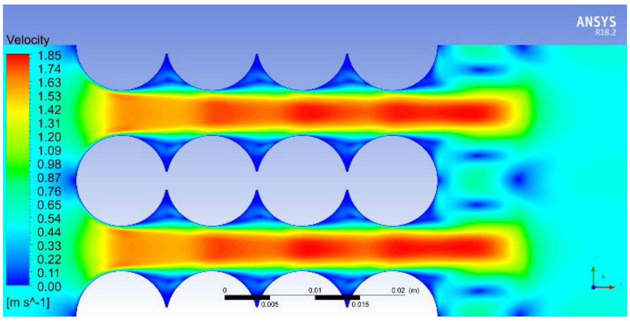
***Figure 2.*** *Temperature field in the tube bundle at different numbers Re, $^o$K: a – Re=332; b – Re=2255; c – Re=3609; d – Re=4946*

The air velocity reaches 24.44 m·s$^{-1}$ at $Re$ = 4946, at some points in the channel, and the average air velocity in the narrow cross section of the channel is about 22.19 m·s$^{-1}$ (Fig. 3d). etailed CFD simulation results are shown in Table 2.



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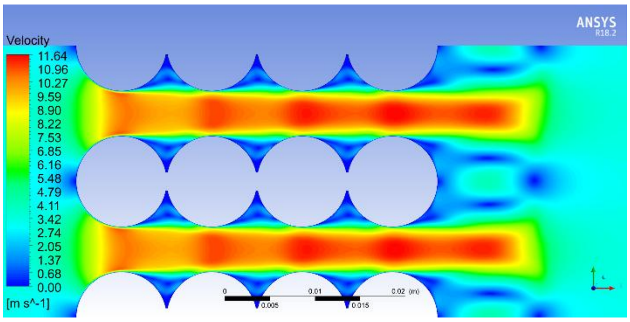

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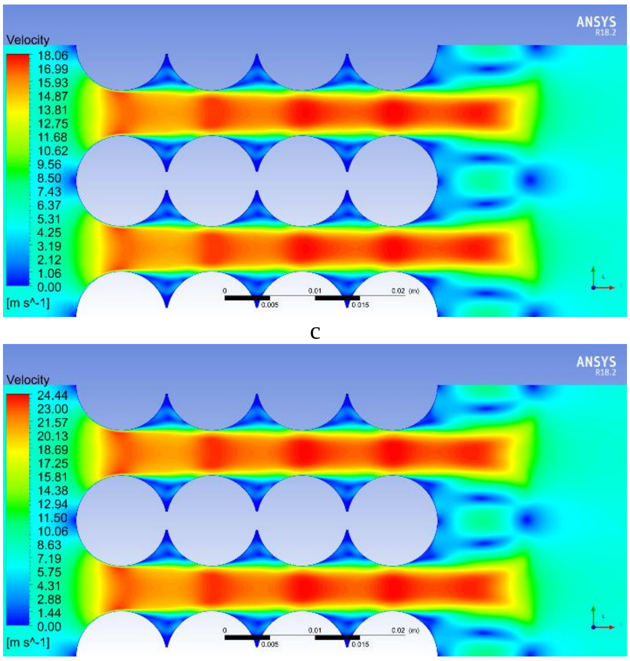

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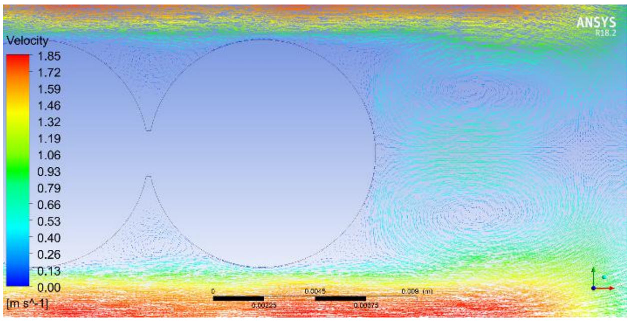
***Figure 3.** The velocity field in the tube bundle at different numbers Re, m·s$^{-1}$: a – Re=332; b – Re=2255; c – Re=3609; d – Re=4946*

Fig. 4 also shows the velocity vectors at the outlet of the tube bundle. There is a boundary layer detachment at the upper point of the tube, and there is a stagnation zone at the junction of neighboring tubes. In this zone, a tear-off vortex is observed, in which the flow velocity is significantly lower than in the main flow. Comparing the obtained results of the air velocity field (Fig. 3-4), the hydrodynamics of the air flow in the channels is the same.



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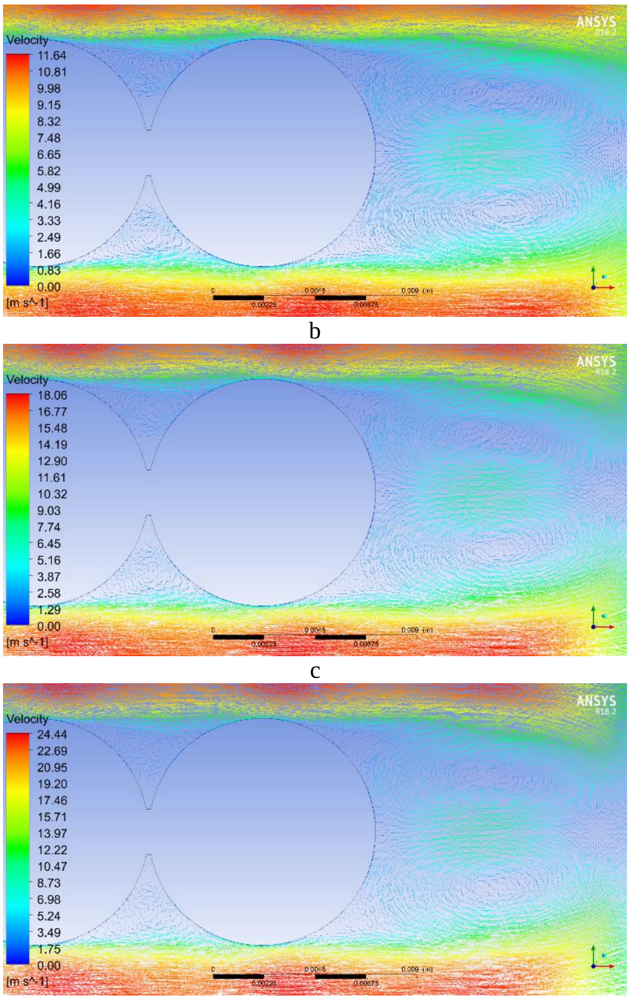

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***Figure 4.** Velocity vector in the tube bundle at different numbers Re, m·s$^{-1}$: a – Re=332; b – Re=2255; c – Re=3609; d – Re=4946*

*Table 2. CFD simulation results of a compact tube bundle*

| Parameter | Value | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reynold's number (*Re*) | 331.9 | 934.5 | 1530.5 | 2254.9 | 2658.4 | 3149.2 | 3609.0 | 4007.9 | 4409.9 | 4946.0 |
| Average air velocity in the narrow section of the rope, m·s$^{-1}$ | 1.506 | 4.205 | 6.903 | 10.201 | 11.999 | 14.096 | 16.195 | 17.993 | 19.792 | 22.188 |
| Average temperature at the wall of the third pipe, $^{o}$C | 63.584 | 44.031 | 38.334 | 33.905 | 32.033 | 30.056 | 28.766 | 27.914 | 27.181 | 26.355 |
| Heat transfer coefficient of the tube bundle W·m$^{-2}$·$^{o}$K$^{-1}$ | 59.377 | 99.173 | 127.58 | 157.67 | 173.24 | 190.93 | 208.06 | 222.36 | 236.29 | 254.27 |
| Prandtl number (*Pr*) | 0.703 | 0.7032 | 0.7031 | 0.7029 | 0.703 | 0.7033 | 0.70323 | 0.70324 | 0.70325 | 0.70326 |
| Nusselt number (*Nu*) | 22.668 | 37.979 | 48.782 | 60.172 | 66.187 | 73.233 | 79.678 | 85.179 | 90.514 | 97.413 |

Criterion equation of *Nu* number is used in engineering calculations of heat exchange apparatuses. This equation characterizes the intensity of heat transfer (heat transfer) at flow-wall boundaries for stationary convectional heat transfer processes in a single-phase incompressible fluid with constant (except density) physical properties. The dependence $Nu = f(Re, Pr)$ can be interpreted as follows: the amount of heat transferred (*Nu*) depends on the type of velocity field (*Re*) and its relationship with the temperature field (*Pr*). A detailed methodology for deriving the number *Nu* is described in [18, 19]. Thus, deriving the equation of the number *Nu*, we obtain the following:

$$Nu = 1.46 \cdot Re^{0.54} \cdot Pr^{1.19}. \qquad (1)$$

The error of equation (1) is within 6% relative to CFD simulations of the compact tube bundle, the results of which are shown in Table 2. This equation can only be used for *Re* from 300 to 5000 and *Pr* from 0.7029 to 0.7033.

## 4. Conclusion

1. A new construction of compact arrangement of pipes in tube bundles of heat exchange apparatus is proposed and developed.

2. CFD modeling of heat and mass transfer processes in the channels of tube bundles using ANSYS Fluent software package has been carried out. The fields of velocities and temperatures in the studied channels have been obtained. The conditions of hydrodynamic flow in the channels and heat transfer processes in these channels were analyzed.

3. Based on the results of CFD modeling, a criterial equation for the number Nu is derived, which can be used in engineering calculations of heat exchangers with compact tube bundles. This equation has an error of up to 6%.

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