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Numerical simulation of heat transfer in a tube bundle of a shell-and-tube heat exchanger used in transport

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Abstract

Currently, the problem of heat removal and recovery in transport is relevant. Of the many existing designs of heat exchangers, about 80% are shell-and-tube heat exchangers. In this work, numerical simulation of the transverse air flow around a tube bundle with a diameter of 5 mm is carried out. The bundle is formed by pipes with a diameter of 0.1 to 0.5 mm. For each pipe diameter, a bundle model with different packing porosity was created. Porosity ranged from 0.7 to 0.95. The calculations were carried out in the ANSYS software package (v. 19.2). The influence of pipe diameter and packing porosity on the heat flow and pressure drop was analyzed.

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Keywords: Transport, tube bundle, heat exchanger, heat transfer, diameter, porosity

1. Introduction

The heat exchanger plays an important role in production and is a universal equipment for chemical, oil, energy, automotive and many other industries.

Diesel engines, which are widely used in vehicles, convert less than 40% of fuel energy into useful work, and the rest is lost through exhaust and cooling systems. In the work (Kabeyi and Oludolapo, 2020) proposed and designed heat exchangers for heat recovery from exhaust gases and from refrigerant for low temperature application in drying corn kernels (air heated to 55ºC). The amount of energy extracted from the exhaust gases is 90.5 kW, and from the coolant – 95 kW, with heat exchanger efficiency of 0.68 and 0.58, respectively.

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Of the many existing designs of heat exchangers, about 80% are shell-and-tube heat exchangers, which is primarily due to the possibility of their use at high temperatures and pressures. A large amount of research is aimed at improving their performance.

In recent decades, more attention has been paid to the transition to more streamlined hulls. The drop-shaped tube is one of the most suitable options for creating the best heat exchanger core (Deeb, 2022). Compared to round and elliptical pipes with the same pipe cross-sectional area, the Nusselt number for the drip pipe increases by 28% and 18.5%, while the pressure drop decreases by 45.5% and 90%, respectively (Wu el al., 2018). The results obtained in (Abbasian Arani and Uosofvand, 2021) showed that, at the same mass flow, twisted oval tubes with a segmented baffle reduce the pressure drop by 53.6% and 35.64% compared to round and elliptical tube bundles, respectively. A shell and tube heat exchanger with a twisted oval tube bundle (both segmented and inclined baffle) has better performance than other types of tube bundles.

Based on experimental data, the study (Li el al., 2021) numerically simulated a turbulent air flow through a staggered tube bundle consisting of a twisted elliptical tube (TET) with a constant tube wall temperature. The excellent heat transfer characteristics of staggered TET bundles are confirmed by comparing the complex heat transfer characteristics with round tube bundles.

The work (Zhao el al., 2022) simulates the characteristics of heat transfer in horizontal tube bundles under various conditions. The average value of the HTC (heat transfer coefficient) of the tube bundle does not change significantly with a change in the pitch of the tube. In addition, the triangular bundle provides the best heat transfer performance compared to the square bundle. It is confirmed by (Khan el al., 2021) that, compared with a conventional smooth round tube, a bundle of twisted oval tubes provides a better improvement in heat transfer due to a higher pressure drop.

Based on a new type of elastic spiral tube bundle (ESTB) heat exchanger, in the work (Ji el al., 2022) investigated the effect of shell-side inlet liquid flow rate on improved heat transfer performance using the two-way liquid-solid connection calculation method. Increasing the inlet velocity is useful for improving the heat transfer performance of the ESTB.

The work (Gorobets el al., 2021) carried out numerical simulation of thermal and hydrodynamic processes in the channels of compact tube bundles of small diameter with various transverse displacements. The intensification of heat transfer processes in the channels of tube bundles is accompanied by an increase in hydraulic resistance, however, the absolute values of the pressure drop are quite small.

The airflow and heat transfer characteristics of spiral finned tube bundles have been studied using numerical simulations (Chu and Yuan, 2021). The research results showed that the optimal combination of Qv, Nu, Δp and f is a fin pitch of 3.5 mm, a fin height of 15.5 mm, a distance between pipes in the transverse direction of 67 mm and a distance between pipes in the longitudinal direction of 53.69 mm.

The study (Mohanan el al., 2021) concluded that staggered tubes lead to a 20-30% improvement in heat transfer and a 20-35% reduction in pressure drop compared to in-line arrangement of pipes.

The aerodynamic processes of heated air in a ventilation shaft installed above a heat-transfer bundle of bimetallic finned tubes were studied (Marshalova el al., 2020). The practical efficiency of single-row and double-row bimetallic finned tube bundles with a finning factor of 21 and an intertube distance of 58 mm in air-cooled heat exchangers has been scientifically proven.

The study (Sakhaei el al., 2020) was aimed at investigating the influence of pipe location and spacing on the hydrodynamics and heat transfer of bare pipe bundles. Flat bundles showed higher pressure drops (up to 60%) and low heat transfer rates (up to 30%) than their inclined counterparts. The difference in pressure loss increases with decreasing pipe pitch due to the presence of higher velocity ratios with decreasing pitch.

The work (Gorobets el al., 2019) proposes a new design of shell-and-tube heat exchangers with compact tube bundles, which has a high efficiency, low aerodynamic (1225 Pa) and hydraulic resistances (400 Pa). The heat exchangers of the new design have 1.7–2 times smaller dimensions and 10–15% less weight compared to heat exchangers of traditional designs at the same heat output.

A numerical study was carried out to study the characteristics of heat transfer and pressure drop on the air side of twisted oval tube bundles with a linear arrangement in cross flow (Li el al., 2019). The influence of geometrical parameters on the air side on the characteristics of heat transfer and pressure drop in the range of Reynolds number from 500 to 23,000 is investigated. The results of the studies showed that a swirling oval tube is a streamlined tube that does not depend on the angle of attack. Twisted oval tube bundles provide superior heat transfer compared to other cross-flow tube bundles. And the staggered arrangement of tubes is advantageous for improving heat transfer efficiency compared to a linear arrangement of tubes.

The thermodynamic characteristics of cross-flow tube bundles and annular spaces of shell-and-tube heat exchangers were studied, and the relationship between fluid flow and heat transfer between them was analyzed (Wang el al., 2016). The results show that the degree of pipe inclination does not lead to obvious changes in the fluid flow and heat transfer characteristics of the fluid flowing through the tube bundles. At different angles of inclination, the vertical and parallel components of the velocity of the fluid flowing through the tube bundles are the same. At the same time, the vertical velocity component significantly affects the thermodynamic characteristics of the annulus. The average fluid velocity decreases at lower angles of incidence, which in turn impairs heat transfer.

In the work (Kong el al., 2016), the authors numerically and experimentally analyzed the parameters of the fins of a plastic-finned heat exchanger for heat transfer. The increased thickness of the fin and the outer diameter of the pipe have a positive effect on the heat flow characteristics.

Thus, we can conclude that there are not enough studies in the known literature on the dependence of the thermal-hydraulic characteristics of the heat exchanger on the porosity of the tube bundle packing and the tube diameter. The aim of our work is to numerically simulate heat transfer in a tube bundle and study the influence of the porosity of the tube bundle packing and the tube diameter on the values of the heat flux and pressure drop.

Nomenclature

Q	heat flux
T	air temperature at the outlet
Δp	pressure drop
v	velocity of the air

2. Materials and Methods

The work is aimed at numerical analysis of the influence on the value of pressure drop and heat flux of various pipe diameters and porosity of tube bundle packing in the ANSYS Fluent software package (v.19.2).

In the work a transverse air flow around a tube bundle is considered. The bundle size $d_c = 5$ mm, diameters of pipes in a bundle d_f: 0.1; 0.2; 0.3; 0.4; 0.5 mm. The porosity of the tube bundle was taken equal to $\varepsilon = 0.7$; $\varepsilon = 0.75$; $\varepsilon = 0.8$; $\varepsilon = 0.85$; $\varepsilon = 0.9$; $\varepsilon = 0.95$.

Examples of computational flow regions around a tube bundle are shown in Figures 1-2. The distance of the computational domain from the input boundary to the tube bundle is 5 d_c, from outlet boundary to tube bundle is 15 d_c, from upper boundary to tube bundle is 10 d_c.

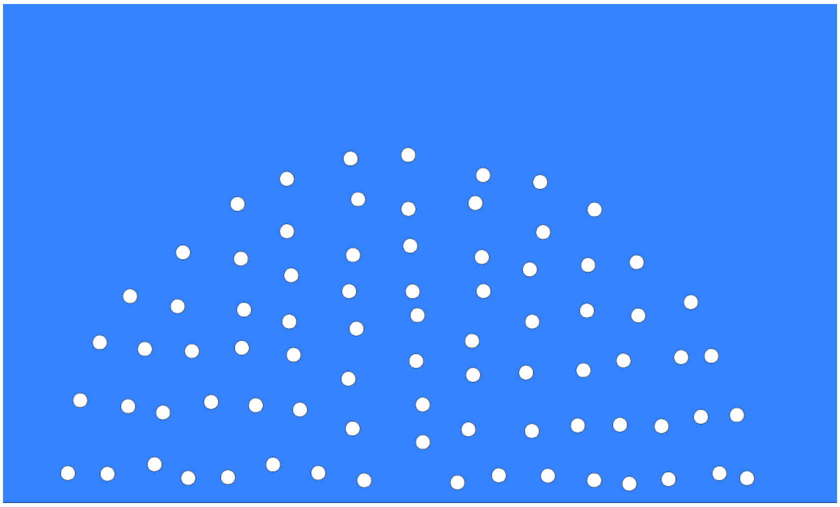

Fig. 1. An example of a computational domain with a pipe diameter $d_f = 0.2$ mm and tube bundle porosity $\varepsilon = 0.9$.

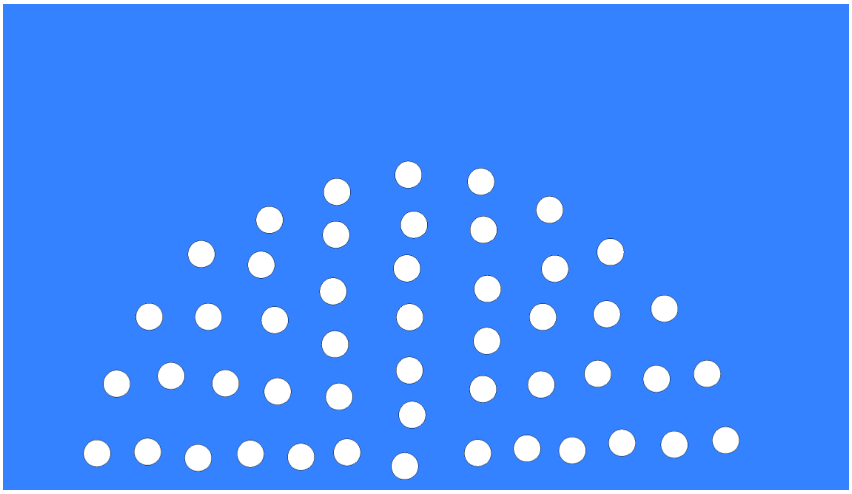

Fig. 2. An example of a computational domain with a pipe diameter $d_f = 0.4$ mm and tube bundle porosity $\varepsilon = 0.75$.

At the inlet to the computational domain, the air temperature was set to 293K, the pipe wall temperature was 373K, and the symmetry conditions were set at the upper and lower boundaries. The air velocities at the inlet were 0.001 and 1 m/s, which generally corresponded to the laminar flow regime in the computational domain.

3. Results

Figure 3 shows a graph of the change in the surface area of pipes of different diameters depending on the porosity of the tube bundle packing.

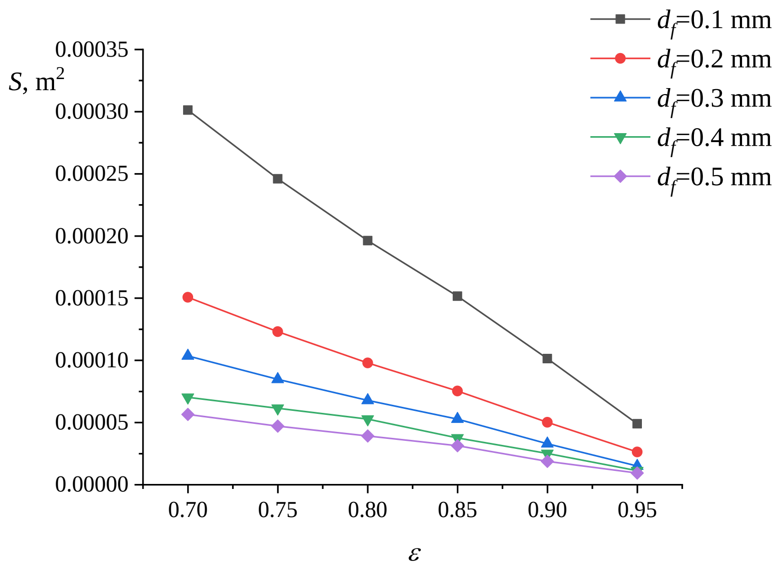

Fig. 3. Changes in the surface area of pipes of different diameters depending on the porosity of the tube bundle packing.

Figure 4 shows graphs of changes in heat flux depending on porosity for a tube bundle with different pipe diameters at air flow velocities of 0.001 and 1 m/s. From the graphs, we see that the highest value of the heat flux for the studied porosities is demonstrated by a tube bundle with a diameter of each tube of $d_f = 0.1$ mm. The smallest value of the heat flux corresponds to a tube bundle with a diameter of each tube of $d_f = 0.5$ mm. In this case, the highest value of the heat flux is demonstrated at the porosity of the package $\varepsilon = 0.7$, and the smallest – at the porosity $\varepsilon = 0.95$. The intensity of heat transfer is affected by hydrodynamics and surface area. Note that in this case, the surface area is the determining factor: the larger the area, the greater the heat flux.

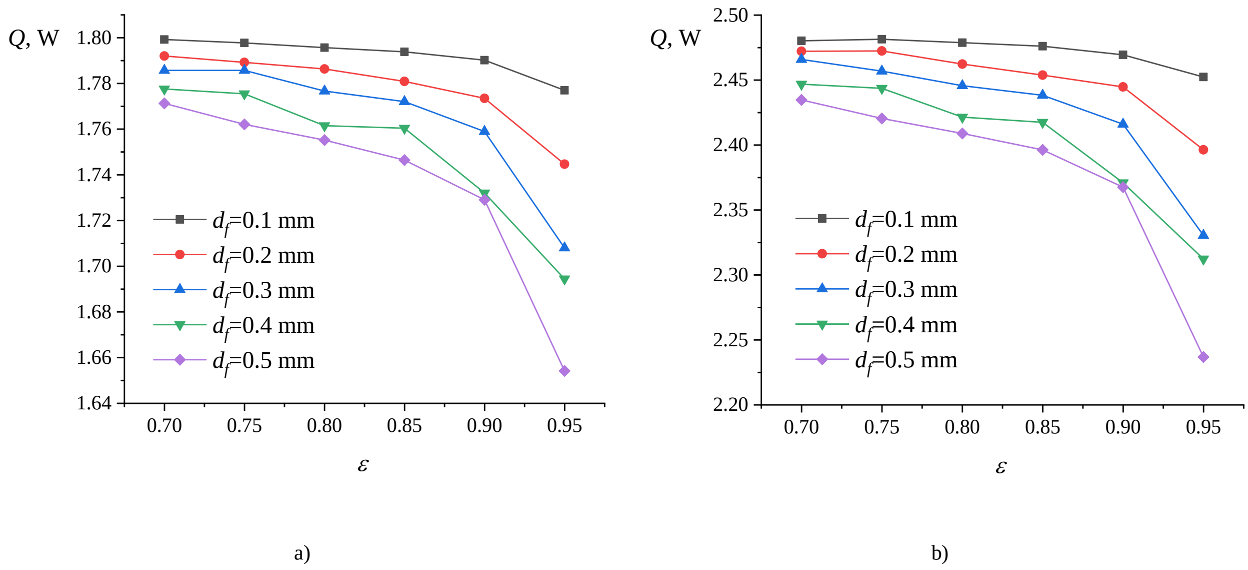

Fig. 4. The change of heat flux depending on the porosity for a tube bundle with different tube diameters at air velocity: a) 0.001 m/s; b) 1 m/s.

Figure 5 shows curves of pressure drop versus bundle porosity for a tube bundle with different tube diameters at air flow velocities of 0.001 and 1 m/s. The smallest value of the pressure drop corresponds to a tube bundle with a diameter of each tube d_f = 0.5 mm. The largest value of the pressure drop is shown by the tube bundle with the diameter of each tube d_f = 0.1 mm. Due to the more difficult passage of air through the dense packing of the tube bundle, the largest value of the pressure drop is observed at the porosity $\varepsilon = 0.7$.

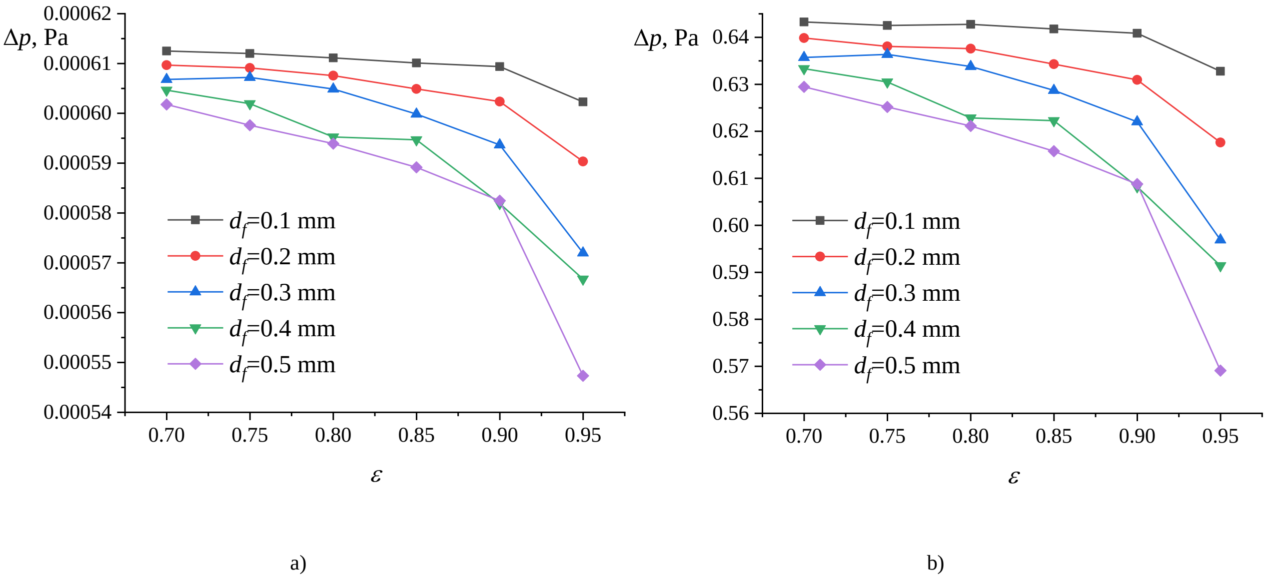

Fig. 5. The change of pressure drop depending on the porosity for a tube bundle with different tube diameters at an air flow velocity: a) 0.001 m/s; b) 1 m/s.

4. Conclusion

In this work, the influence of the pipe diameter and the porosity of the tube bundle packing on the values of the heat flux and pressure drop in the case of air flow around the tube bundle is studied. The bundle size $d_c = 5$ mm, diameters of pipes in a bundle d_f : 0,1; 0,2; 0,3; 0,4; 0,5 mm. The porosity of the tube bundle was taken equal to $\varepsilon = 0.7$; $\varepsilon = 0.75$; $\varepsilon = 0.8$; $\varepsilon = 0.85$; $\varepsilon = 0.9$; $\varepsilon = 0.95$. The results of the study showed that the highest values of heat flux and pressure drop have a tube bundle with a diameter of each tube d_f =0,1 mm and packing porosity $\varepsilon = 0.7$. The smallest values of heat flux and pressure drop correspond to a tube bundle with a diameter of each tube $d_f = 0.5$ mm and packing porosity $\varepsilon = 0.95$. A heat exchanger of this size can be used to cool microelectronics.

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