Analysis of ribbed tube heating in the cooling system

A F Gizzatullina, O V Mischenkova, F N Pushkarev, A N Terentyev
Kalashnikov Izhevsk State Technical University, 426000, 7, Studencheskaya str., Izhevsk, Russia
gialfi@mail.ru

Abstract. The paper presents the solution of the conjugated heat exchange problem in a cylindrical ribbed tube using the open integrated platform OpenFOAM. The obtained results allow estimating the fluid heating along the channel as well as the temperature difference on the walls of the tube. It is shown that the minimum temperature difference of the fluid is observed in the center of the tube, and the maximum one is closer to the tube walls.

1. Introduction
Nowadays, heat exchangers of different configurations are used [1-4] for reliable and continuous operation of a wide range of technological and technical equipment in various fields (housing and communal services, construction, heavy industry and mechanical engineering, chemical and food industry, transport systems), and their thermal efficiency has a direct influence on operational characteristics of devices in general [5]. A distinctive feature of convective heat exchangers is the heat exchange between two media having different temperatures. In this case, convective heat exchange is important, which depends on the joint effect of thermal conduction and convection.

The work is aimed at the study of thermophysical processes occurring in closed-cycle power plants [6] comprising a cooling module. The cooling system is a package of ribbed tubes with a coolant moving through them.

A detailed study of the heat transfer process in the metal taking into account the conjugate air/aluminum/ethylene glycol heat exchange process is carried out. Given the double conjugation, the mathematical statement requires an account of both properties of these materials and corresponding physical processes. Necessary information on gas-dynamic and thermophysical processes in the cooling system can be obtained as a result of the numerical experiment.

The present work is devoted to the numerical study of the heating process of an aluminum ribbed tube in air flow with the temperature of 253 K. Ethylene glycol with the temperature of 213 K flows through the tube.

2. Study of the heat transfer process in the ribbed tube
We consider the heat exchange between the air flow and the cooled ribbed tube (Figure 1). The presence of an extended heat transfer surface raises a question about heating the coolant inside the tube and the efficiency of air cooling in this case along the whole length of the working element.

The simulation was carried out in the open integrated platform for the numerical solution of continuum mechanics problems OpenFOAM [7-10] based on the chtMultiRegionSimpleFoam solver which allows for solving the conjugate heat transfer problems.
Parameters of the ribbed tube are as follows: the inner diameter is 25 mm, wall thickness – 2 mm, fin radius – 10 mm, fin thickness – 1 mm, fin spacing – 5 mm, and tube length – 25 cm.

![Schematic diagram of the computation domain.](image)

The mathematical model of the conjugate heat exchange process is presented in [11], thermophysical characteristics of the considered media are also given there.

The boundary conditions of the problem were as follows:

- the heated air flow is supplied on the left side with the velocity of 8.5 m/s through the cross-section of more than 1 m²;
- the velocity and temperature of the incoming flow were assigned at the inlet section and upper boundary;
- adhesion conditions for the velocity and zero gradient for the temperature and pressure were assigned at solid surfaces not involved in the heat transfer process;
- boundary conditions of the 4th type including the equality of wall temperatures and heat flows were assigned at conjugation boundaries.

For each material, computational grids were constructed that were meshing with each other in the area of contact surfaces. The results of mesh convergence studies, which were carried out for stationary modes of gas (air) and fluid (ethylene glycol) flows, are presented in [11].

As a result of the numerical simulation, the distributions of the fluid temperature and velocity in the coolant flow and on the inner surface of the tube walls have been obtained (Figure 2).

![Distribution of temperature (a) and velocity (b) along the longitudinal section of the tube](image)
The temperature profile along the length of the cylindrical channel, presented in Figure 2a shows that at the outlet section in the tube center the fluid is heated by 0.7 K. The velocity profile along the length of the cylindrical channel, presented in Figure 2b shows that the velocity at the outlet section is doubled, which fully satisfies the exact solution [12]. All fields of physical quantities and temperature profiles (Fig. 2-4) are presented in the relative (dimensionless) form, the initial temperature (213 K) and initial velocity (1 m/s) of the fluid are taken as basic quantities.

Figure 3 shows that the smallest temperature difference along the channel is observed in the tube center, while close to the tube walls the temperature difference is insignificant and equal to 2 K. According to the Poiseuille profile, the velocity reaches its maximum in the central axis of the channel.

Figure 4 shows diagrams of dimensionless velocity and temperature in the cross-section of the tube (1 corresponds to the inlet section, 2, 3 – intermediate sections, 4 – outlet section). The dimensionless temperature and velocity are defined by dividing by the fluid temperature and the mean fluid velocity. Figure 4 illustrates that profiles moving along the flow (-OZ) are rearranged to classical parabolic ones [12].

In the laminar flow, the heat transfer from one fluid layer to another in the direction normal to the wall is carried out by thermal conduction. At the same time, in the general case, each layer has a different longitudinal velocity. Therefore, along with the transverse heat transfer by thermal conduction, there is also a convective heat transfer in the longitudinal direction. As a consequence,
heat transfer in the laminar flow mode depends on the hydrodynamic motion pattern. At the inlet section, the fluid temperature is constant and equal to 213 K, and it differs from the tube wall temperature of 253 K. As the flow proceeds between the fluid and the wall, heat transfer occurs and the temperature of fluid liquid gradually varies. Initially, near the inlet section, the temperature variation occurs only in a thin layer near the surface. Then, as moving away from the inlet section, more and more of the flow is involved in the heat exchange process. Figure 2b shows that viscous boundary layers disappear at about 0.3x/l from the inlet, while thermal boundary layers are not stabilized even at the end of the tube – Figure 2b. Thus, to obtain a stabilized thermal flow, it is necessary to increase the length of the tube.

Figure 5. Temperature variation at the tube fins

Figure 5 shows the temperature variations for the tube fins in sections along the coolant flow. The maximum heating of fins is observed in the middle of the tube and it is equal to 6 K. The minimum heating occurs in fins located at the inlet and it is equal to 5 K.

Figure 6 shows the dimensionless temperature variation along the channel inside the wall from the front and aft sides of the tube.

Figure 6. Temperature distribution inside the tube wall
The closeness of curves is caused by peculiarities of the problem statement, namely the essential predominance of the volume occupied by hot gas over the volume occupied by a single ribbed tube.

3. Conclusions
The distribution of metal temperature in the longitudinal section of the tube, in particular, in the cylindrical part of the tube and its finning elements has been studied taking into account the heating of the coolant and the temperature of the incoming air flow.
Along the channel axis, the temperature difference of the coolant along the length of the tube is minimal. The intensity of liquid heating near the wall increases by 3 times (along the length).
Since the coolant in the tube is supplied from top to bottom, the fluid velocity in the core of the flow increases twofold, due to the action of gravity. The increase of the velocity head is accompanied by the increase of the viscous sublayer near the tube walls at 0.2-0.25 m section of the tube. The mutual influence of the velocity head and viscous layer thickness at the uniform air flow by the cooled air leads to the appearance of a saturation zone on longitudinal temperature profiles and the decrease in the heat transfer intensity. The maximum heat transfer intensity is observed at the tube length of 0.18-0.2 m.

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