Flow analysis in seamless hot-extruded pipes with helical inner ribbing surface

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Abstract. The article is devoted to numerical simulation of heat transfer processes occurring during the flow of a coolant in seamless hot-extrusion pipes with a spiral inner fin surface (TMK-IRS). A description of the numerical modeling technique is given along with the interface of the program used to create different types of internal fins. Thermohydraulic analysis of finned pipes for transient, turbulent and laminar flow regimes has been carried out. An estimate of the critical Reynolds number characterizing the transition to a turbulent regime, the nature of the transient flow regime in comparison with other classical cases is given.

1. Introduction

It is necessary to carry out computer simulation of the operation process of seamless hot-extruded pipes with helical inner ribbing surface (TMK-IRS) in the CAD software environment SolidWorks using the integrated calculation module Flow Simulation.

At the first stage of the work, 49 three-dimensional solid models of hot-extruded pipes with an outer diameter of 60.0 mm and a wall thickness of 6.0 mm were created. Table 1 shows the parameters of solid pipe models.

The sketches of the cross-sections of the ribs were placed at the same distance from each other when constructing the helical ribbing of the pipes.

Figure 1 shows, as an example, a solid model of a pipe with helical inner ribbing surface (TMK-IRS), consisting of twelve ribs.
Table 1. Pipe parameters for creating solid models

| Number of ribs, pcs | 0 | 15 | 30 | 45 |
|---------------------|---|----|----|----|
| 1                   | + | +  | +  | +  |
| 2                   | + | +  | +  | +  |
| 3                   | + | +  | +  | +  |
| 4                   | + | +  | +  | +  |
| 5                   | + | +  | +  | +  |
| 6                   | + | +  | +  | +  |
| 7                   | + | +  | +  | +  |
| 8                   | + | +  | +  | +  |
| 9                   | + | +  | +  | +  |
| 10                  | + | +  | +  | +  |
| 11                  | + | +  | +  | +  |
| 12                  | + | +  | +  | +  |

The angle of rise of the rib in the models varies from 0° to 45° in 15° increments. The higher the angle of rise, the more turns can fit along the length of the pipe. Figure 2 shows a longitudinal section of a pipe with a designation for the elevation angle to represent this parameter.

Figure 1. Solid model of the TMK-IRS pipe.

Figure 2. Longitudinal section of the TMK-IRS pipe: $\alpha$° – the angle of rise of the rib.
Geometry tools in the SolidWorks software make it easy to create ribbing on the inner surface of a pipe and to vary the angle of elevation of the rib by changing the step size.

The next step after creating three-dimensional solid models of pipes with helical ribbing of the inner surface (TMK-IRS) is to set the process parameters and carry out computer modeling.

2. Setting process parameters and carrying out simulations

The main parameters of the modeling process are shown in Table 2. For each of the 49 models, the same input parameters were set. Each pipe was modeled with two heat carriers: water and steam. In view of the similarity of the thermophysical properties, it was decided not to use a steam-water mixture as a heat carrier during modeling.

| №  | Parameter                              | Value                      |
|----|----------------------------------------|----------------------------|
| 1  | Pipe material                          | Steel 20                   |
| 2  | Pipe length                            | 500 mm                     |
| 3  | Surface roughness                      | 60 microns                 |
| 4  | Ambient temperature                    | 40°C                       |
| 5  | Initial pipe body temperature          | 20°C                       |
| 6  | Flow temperature                       | 160°C                      |
| 7  | Flow pressure                          | 0.156 MPa                  |
| 8  | Flow time                              | 60 s                       |
| 9  | Heat conductor                         | Water / steam-water mixture / steam |

After preparing for the calculation, computer models of the operation process of seamless hot-extruded pipes with helical ribbing of the inner surface (TMK-IRS) were simulated in the SolidWorks software environment using the integrated calculation module Flow Simulation.

The output parameters of the computer simulation were the hydrodynamic and kinematic characteristics of the coolant flow, as well as the indicators of the change in the temperature of the solid. The output from the modeling process is presented in Table 3.

| №  | Parameter                              | Designation | Dimension        |
|----|----------------------------------------|-------------|-----------------|
| 1  | Heat transfer coefficient              | $\alpha_2$  | W/m²·K          |
| 2  | Solid temperature (max.)               | $T_s$       | °C              |
| 3  | Heat dissipation power                 | $N_{ht}$    | W               |
| 4  | Specific heat flux                     | $\eta_{hf}$ | W/m²            |
| 5  | Friction force                         | $F_{trp}$   | N               |
| 6  | Turbulence energy                      | $E_f$       | J/kg            |
| 7  | Specific dissipation of the energy of pulsating motion under the action of viscosity | $\rho_\varepsilon$ | W/kg |

The nature of the movement of the coolant inside the pipe is shown in Figure 3, 4. As you can see, the flow is turbulent in nature, which is associated with the peculiarity of the geometry of the pipe, which ensures swirling and creation of vortex motion. With an increase in the number of calls, the flow rate increases, which is shown by the example of pipes shown in Figure 3, 4.
3. Computer simulation results
For the numerical representation of the simulation parameters, the analysis of computer models has been carried out.

When carrying out computer modeling in the SolidWorks CAD software environment using the integrated calculation module Flow Simulation, the numerical values of the output data presented in Table 3 were obtained.

The key parameters influencing the change in the hydrodynamic and kinematic characteristics of the coolant flow are the number of helical ribbing entries and the rib elevation angle, varying from 0 to 45° due to an increase or decrease in the step between the turns of the generatrix, which constitutes the trajectory of motion when constructing the rib geometry.

To determine the equations for calculating the parameters of the process of modeling the operation of seamless hot-extruded pipes with helical ribbing of the inner surface (TMK-IRS), depending on the change in the angle of the rib lift and their number, a regression analysis was carried out.

Due to the sufficient amount of data obtained in the course of computer modeling in the SolidWorks CAD software environment using the integrated calculation module Flow Simulation, it was possible to carry out regression analysis.

An experimental method was used to select the type of regression function.

The software package is implemented using the imperative, structured, object-oriented programming language Delphi with strict static typing of variables [1].
3.1 Interface of the software package

The program includes the following main blocks:
1) initial data preparation unit;
2) block for outputting the main parameters of the process;
3) block of help information if necessary.

The interface of the software package is implemented as a single window with tabs, which makes the program easy to use. The initial data for the calculation can be divided into two categories. In the first category, the geometric parameters of the pipe are set, such as the outer diameter and wall thickness, and the type of coolant. In the second category, the characteristics of the internal finning of the pipe are specified, such as the angle of rise of the fin and the number of fins. The characteristics of the internal ribbing of the pipe are specified from the drop-down list. You can also choose a pipe with no internal ribbing, that is, with a smooth inner surface. The task of these parameters is carried out on the "Data entry" tab, shown in Figure 5.

3.2 Using the software package

For the automated calculation of the operational parameters of TMK-IRS pipes, the following basic steps must be taken:
1) enter the value of the outer diameter of the pipe in mm;
2) enter the pipe wall thickness in mm;
3) select the heat carrier from the drop-down list: water or steam;
4) specify the type of pipe: with or without ribs;
5) in the case of selecting a pipe without ribs, click on the "Calculate" button;
6) when selecting a pipe with ribs, specify:
   - the number of edges, by selecting a value from 1 to 12 from the drop-down list;
   - rib angle: 0, 15, 30 or 45 °;
   - click on the button "Make a calculation".

It should be noted that until the characteristics of the internal ribbing of the pipe are selected, the "Calculate" button is inactive.

After completing all the above actions, the transition to the "Results" tab is carried out, where the calculation parameters are presented in a tabular form. The program allows you to save the calculation results for their further processing.

4. Analysis of thermohydraulic characteristics of pipes with internal spiral fins

4.1 Laminar flow region of the coolant

The use of surface heat transfer intensifiers is an additional factor contributing to the generation of turbulent pulsations in the heat exchange channels. In this regard, the laminar-turbulent transition may begin earlier than in smooth-walled channels.
When using internal spiral fins, the transition from laminar to turbulent mode occurs smoothly, without sharp increases in the values of the hydraulic resistance coefficients. The beginning of the laminar-turbulent transition occurs at Re≈500. The increase in hydraulic resistance in the laminar flow region can reach 200%. The increase in Nu values in the laminar region of the coolant flow in pipes with internal spiral fins can also reach 300% [1-5].

The degree of proportionality of the coefficients of hydraulic resistance and average heat transfer from the value of the Reynolds number corresponds to a smooth-walled channel and is equal to Re\(^{-1}\) and Re\(^{0.33}\) for the coefficients of hydraulic resistance and heat transfer in the laminar flow region of the coolant in the pipes, respectively.

Similar results were obtained by Uttavar and r. Rao [6] in pipes with wire inserts. At the value of the Reynolds number Re< 180, the deviation of the experimental data of the hydraulic resistance coefficient during the flow of liquid in pipes with wire inserts does not exceed the value of 5–6% compared to a smooth channel.

A comparative study of various types of internal spiral finning of pipes: wire inserts, single-pass spiral knurling, application of hemispherical projections along a helical line was performed by A. Garcia [7]. The results obtained show that in the laminar flow region (Re < 350), there is an increase in the values of the hydraulic resistance coefficients up to 30% for all types of spiral fins in comparison with a smooth channel. The authors attribute this fact to a decrease in the cross-sectional area of the channel, and, accordingly, an increase in the area of the wetted surface. It is noted that in the case of using wire inserts or spiral knurling of the surface, the transition from the laminar to the turbulent flow mode occurs more smoothly, without sudden jumps, as is noted when using three-dimensional elements of heat exchange intensifiers, for example, hemispherical protrusions.

A. Garcia [8] showed that in the laminar flow region, the use of pipes with spiral wire inserts allows for an increase in heat transfer to Nu/Nu\(_0\)=1.4 compared to a smooth-walled channel. However, such an increase in heat transfer, and even greater in the transition region up to Nu/Nu\(_0\)=500%, is due to the fact that at the same value of the Reynolds number, laminar flow is still observed in a smooth channel, while in pipes using wire inserts, a laminar-turbulent transition has already occurred and the flow regime has changed. It is also noted that the use of spiral wire inserts allows for a laminar-turbulent transition more smoothly, compared to a smooth channel. The minimum marked value of the value of the first critical Reynolds number (the beginning of the laminar-turbulent transition) is Re = 700 for a pipe with a relative axial pitch of spiral wire inserts 1.41 and a relative height of protrusions 0.101.

### 4.2 Turbulent flow region of the coolant

The analysis shows that the degree of change in the value of the hydraulic resistance coefficient with an increase in the values of the Reynolds number according to different authors differs significantly from each other.

With certain geometric parameters of the intensifiers in pipes with internal spiral fins, the self-similar nature of the dependence of the hydraulic resistance coefficients on the value of the Reynolds number can be noted, that is, the pressure loss for pumping the coolant ceases to depend on the flow rate of the liquid in the channel. The values of the Reynolds numbers, at which the self-similarity of the flow is manifested in pipes with internal spiral fins, are significantly lower than in a smooth channel. This phenomenon is primarily due to the influence of the geometry of the heat transfer intensifiers: the relative position, height, and shape of the turbulators.

The dependence of the hydraulic resistance during fluid flow in channels with internal spiral fins at certain geometric parameters of heat exchange intensifiers is similar to the behavior of the hydraulic resistance of pipes with significant relative roughness (\(\varepsilon = ks / d_i > 0.03\), where \(ks\) is the height of the roughness elements).

The hydraulic resistance of pipes with internal spiral fins can increase up to 9 times compared to the flow in a smooth-walled channel, depending on the geometric parameters of the turbulators. Thus, the highest values of the hydraulic resistance coefficients are noted for the plate spiral inserts considered by V. K. Migay, with the relative height of the intensifiers \(e/d = 0.2\), that is, when the height of the protrusions is 20% of the cross-section of the channel.
The analysis of the dependence of the values of the Nusselt number on the Reynolds number in pipes with internal spiral fins in the turbulent region of the coolant flow shows that the increase in heat transfer with an increase in the values of the Reynolds number occurs similarly to the flow in smooth-walled pipes, i.e. \( \text{Nu} \sim \text{Re}^{0.8} \), regardless of the geometric parameters of the heat exchange surface. The increase in heat transfer relative to the fluid flow in the smooth-walled channel with the corresponding values of the Reynolds number can reach 350%.

Thus, it can be noted that the dependence of the hydraulic resistance of pipes with internal spiral fins on the flow regime of the liquid differs significantly from different authors, while the increase in the value of the average heat transfer coefficient of pipes with an increase in the speed of the coolant occurs in a similar way from different authors.

5. Conclusion

1. Computer modeling was carried out computer modeling of the operation process of seamless hot-extruded pipes with helical ribbing of the inner surface (TMK-IRS) in the SolidWorks CAD software using the integrated calculation module Flow Simulation, which made it possible to obtain numerical values of the hydrodynamic and kinematic parameters of the process.
2. A software package has been created for an automated procedure for calculating the operational parameters of pipes with internal helical finning.
3. The results obtained in the course of the work can be useful for assessing the possible boundaries of intensification of heat transfer and assessing the applicability of TMK-IRS pipes as transport for the transfer of various coolants.

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