The study of heart transfer during boiling process of organic fluid

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Abstract. The paper considers the problem of studying heat transfer inside the pipes of an evaporator of an organic Rankine cycle unit during boiling of an organic heat transfer fluid. Recently, the organic Rankine cycle units are increasingly used in various industries for the utilization of low-grade heat of various processing units. One of the main elements of these units is the evaporator in which vaporization takes place. The evaporator is a concurrent boiler. One of the problems in the design of concurrent boilers is the lack of knowledge of heat transfer during the process of boiling fluid. This paper presents a study of the heat transfer process inside a concurrent boiler. This study is carried out by creating a model of boiling organic fluid in the pipes of a concurrent boiler. The boiling model was implemented in the Ansys Fluent software package. Using this model, the values of the heat transfer coefficient were obtained at each point of the evaporator pipe under consideration. After obtaining the values, the dependence of the heat transfer coefficient on the length of the pipe was analyzed. As a result of the analysis, it was determined that starting from the point of 0.6 m, the heat transfer coefficient sharply decreases by 3.5 times. The value of the heat transfer coefficient after the decrease section is at the level of 125 W/m²K over the entire length of the pipe. Thus, it was determined that under given initial conditions, with a pipe length of more than 1 m, heat transfer ceases to be effective.

1. Introduction
The policy of introducing energy-saving technologies implemented in recent years determines the need to maximize the use of waste heat from various enterprises, power plants and boiler houses. The temperature potential of heat discharged into the environment is limited by temperatures of 80÷130°C. Such sources are very common in the oil, metallurgical chemical and other industries. The use of this heat for heating is limited by current regulations requiring the maintenance of water temperature in heating systems above the temperature of sources of secondary energy resources.

Let’s consider the refining industry in more detail. The technological process of oil refining is not perfect in terms of the full use of thermal energy. Thermal energy supplied to oil at oil refineries is used only by 30%. About 35% of it is dissipated into the atmosphere using jacket water or air-cooling units, about 10-15% goes into the atmosphere from the equipment surfaces, and about 15% is released into the atmosphere with flue gases [1]. According to estimates, at refineries with a total capacity of primary oil refining plants of 5-6 million tons of crude oil per year, at least 15 MW of low-grade heat with a temperature of at least 150°C are discharged into the atmosphere.
This low-grade heat can be used to generate electrical energy in small power plants based on the principle of the organic Rankine cycle (ORC).

The unit consists of an evaporator located in the gas duct, a turbine generator, a regenerative heat exchanger, a condenser, and a pump. A distinctive feature of ORC is the use of organic substances boiling at low temperatures and providing a sufficient pressure difference for driving a turbine generator as a working fluid. The evaporator is a direct-flow boiler with minimal aerodynamic drag, in which a liquid working fluid is supplied to the pipe inlet, and saturated steam entering the turbine generator is at the outlet.

One of the problems in this area is the study of heat transfer in evaporator pipes. Its study is complicated by the presence of a phase transition - evaporation of the working fluid in the pipes of this heat exchanger. The aim of the study is to determine the nature of the change in the heat transfer coefficient along the length of the pipeline during the boiling process and to determine the boiling pattern.

A study of heat transfer was given in [2]. In this paper, the criteria equation for calculating the heat transfer coefficient of water during bubble boiling was determined. In [3], a study of changes in the heat transfer coefficient in the boiling process was made. As a result, it was determined that at a certain value of the heat flux density, the heat transfer coefficient begins to decrease due to the formation of a vapor film on the heat transfer surface. However, in this study, the nature of the change in the heat transfer coefficient along the length of the pipe was not noted.

2. Description of the model
The geometry of the studied model is shown in Figure 1. It represents a straight section of the pipe of the heat exchanger with an inner diameter of 32 mm. The length of the straight pipe section and the pipe bending radius are 0.5 m and 0.052 m, respectively. The number of pipes turns \(n\) is 7.

![Figure 1. Geometry of the studied model (inlet - inlet of the working fluid; outlet - outlet of the working fluid; walls - walls of the pipe).](image-url)
Steel was specified as the pipe material. N-pentane was chosen as a working fluid. The saturation temperature of the working fluid is 309 K.

Boundary conditions of the third kind were specified as a boundary conditions for this model. The specified boundary conditions are presented in table 1. The model discretization parameters are listed in table 2.

**Table 1.** Specified boundary conditions.

| Parameter               | Dimension | Value  |
|-------------------------|-----------|--------|
| Heat source temperature | K         | 450.0  |
| Inlet fluid temperature | K         | 308.8  |
| Fluid velocity          | m/s       | 0.1    |
| Wall thickness          | mm        | 4.5    |
| Wall material           |           | steel  |

**Table 2.** Model discretization parameters.

| Parameter              | Value             |
|------------------------|-------------------|
| Momentum               | Second order upwind |
| Volume fraction        | Compressive       |
| Turbulent kinetic energy | Second order upwind |
| Turbulent dissipation rate | Second order upwind |
| Energy                 | Second order upwind |

Thermal energy is transferred to the working fluid from the pipe walls having a temperature of 450 K from the outside. The fluid pressure was equal to atmospheric. The time step was taken 0.001 s. The number of iterations was taken equal to 5000. Thus, 5 seconds of the process of boiling the fluid from the liquid state to the steady state were simulated.

The calculation of parameters in the next step was based on the calculated parameters for the previous step. The calculation was performed in Ansys software (version 19R3) using the Fluent module.

### 3. Obtained results

One of the simulation results is the obtained pattern of the boiling of the working fluid in the heat exchanger pipe. This pattern was obtained for each iteration. The resulting boiling pattern is presented in Figure 2-5.

![Figure 2](image1.png) ![Figure 3](image2.png)

**Figure 2.** The boiling pattern (iteration 100).  
**Figure 3.** The boiling pattern (iteration 200).
Figure 4. The boiling pattern (iteration 300).

Figure 5. The boiling pattern (iteration 500).

Also, during the study, the dependences of the change in the heat transfer coefficient over time were obtained. Examples of these dependencies are presented in Figure 6-7.

Figure 6. Dependences of the change in the heat transfer coefficient in time (change in the heat transfer coefficient in time after the first pipe turn.)
4. Discussion of the results

As can be seen from Figure 2-5, starting from the iteration 3000, the steam almost completely fills the pipe section after 1 turn. Thus, in most of the pipe, heat transfer ceases to be effective. A characteristic indicator of the efficiency of heat transfer is the value of the heat transfer coefficient from the wall to the liquid.

As can be seen from Figure 6-7, the heat transfer coefficient sharply decreases after the first turn of the pipe. It is also possible to notice that in the final sections of the pipe, heat transfer becomes ineffective due to the high degree of dryness of the steam-water mixture. The heat transfer coefficient decreases sharply. These results are consistent with the results given in [2], which states that when the degree of dryness of steam reaches 0.4, the value of the heat transfer coefficient begins to decrease.

The value of the heat transfer coefficient decreases sharply in the area of 0.5 - 1 m. In subsequent sections, the value of the heat transfer coefficient remains at about 121 W/m²K. Thus, the evaporation of water contained in the steam-water mixture at the outlet of the pipe requires more time due to the low thermal conductivity of the steam. Because of this, heat transfer ceases to be effective on most of the heat transfer surface.

5. Conclusions

Thus, this paper shows a picture of boiling an organic fluid in the pipes of an evaporator of an organic Rankine cycle unit. As a result of the study, it was determined that the heat transfer coefficient sharply decreases after a certain section of the pipe. Heat transfer in the pipe section after the section of the decrease in the heat transfer coefficient becomes ineffective.

References
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