Study of heat transfer in the disk of a regenerative crystallizer

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Abstract. The study is devoted to the research of the heat transfer process at different numbers and locations of labyrinth passages of the regenerative mold disk design by numerical modelling. The designs of the cooling disk with 6, 12 and 18 labyrinth passages are considered. It was found that the number increasing of labyrinth passages to twelve passages allows increasing the average heat transfer coefficient by 1.3 times and providing 2-fold increase in the uniformity of heat transfer. Analysis of the dependence of heat transfer in a disk with twelve labyrinth passages on the refrigerant flow showed that the greatest uniformity of temperature distribution over the disk surface is achieved when the refrigerant flow rate is 100 m³/h. An equation for the dependence of the average heat transfer coefficient from the refrigerant to the disk wall on the flow rate is obtained. It can be used to find the required flow rate of the refrigerant in order to achieve a certain average temperature when regulating the crystallization process. Thus, an improved version of the cooling disk design is proposed for the regenerative disk type mold, which provides a more efficient heat transfer compared to existing analogues, which is confirmed by the results that were obtained.

1. Introduction

The dewaxing process is the most complex and multi-stage process in the production of petroleum oils. The main stage of this process is crystallization, which determines the quality and speed of subsequent separation of the oil phase [1, 2, 3]. Disk regenerative crystallizers (DCR) have a number of advantages in comparison with devices of the "pipe-in-pipe" type. The use of this form of apparatus provides an increase the deparaffinizing oil output, increasing the filtration rate of the suspension, reducing the ratio of solvent to raw material and reduction in specific energy consumption for the regeneration of the circulating solvent [1, 4, 5].

However, disk crystallizers are used in production rather recently and they are of interest for research and improvement. For example, the problem of increasing the efficiency of DCR by intensifying heat exchange due to the optimized design of the mixing device and the implementation of distributed solvent input was solved in studies [6, 7].

The disk regenerative crystallizer is a horizontal cylindrical vessel which is divided by means of hollow cooling disks into separate sections-inter-disk chambers (figure 1). Inside the hollow two-chamber disks 2, connected by a system of overflow pipes 4, the refrigerant-filtrate – dewaxed oil III solution is fed. The refrigerant flows in two independent parallel streams through a system of labyrinth channels inside each disk. The raw material mixture I, consisting of paraffin-containing raw materials and a solvent, moves in a countercurrent direction to the refrigerant III inside the housing 1, flowing through the peripheral or central ring gaps [1, 4, 5].
Figure 1. Schematic diagram of a regenerative disk crystallizer [4, 5]: 1-cylindrical body; 2-cooling disk; 3-drive shaft; 4-overflow pipes; 5-scraper device; 6-Central seal; 7-peripheral seal; 8-frame agitator; 9-scraper element; I - input of raw mixture; II-output of suspension; III, IV-input and output of refrigerant-filtrate.

Paraffin crystallization occurs on the surfaces of the cooling disks 2, as well as in the volume of the supercooled solution in each inter-disk section, which has a positive effect on the quality of the resulting crystals. All disks 2 are equipped with two scraper devices (SD) 5, which are fixed on both sides of the disks 2 on a low-speed shaft 3, which is driven by a two-speed geared motor. Rotating SDs 5 remove paraffin crystals from the surfaces of disks 2 using bronze scraper elements 9 [1, 4, 5].

We are interested in the effect of the design of cooling disks with labyrinth channels on the heat transfer process. The study of the heat transfer process for different numbers and locations of labyrinth passages in the DCR disk structure was performed for this purpose.

2. Influence of the number of moves on the heat transfer process

The study of heat transfer between the disk and the cooled environment was carried out using a numerical simulation method using the ANSYS Workbench software package.

Three variants of disks were performed for the study: the design with 6 passages in each section, as in the original device - is an option 1, the design with 12 passages in each section - is an option 2 and the design with 18 passages - is an option 3 (figure 2).

Calculation of heat transfer in the mold disk was performed in ANSYS FLUENT, the viscosity model was adopted according to the K-ω standard (Viscous – Standard k-omega). The properties of the environment in the disk (filtrate) at 20 ºC were set according to the data presented in [4-7], and are shown in table 1.

| Environment | T,ºC | n, PA·s | c, j/(kg·K) | p, kg/m³ | λ, W/(m·K) |
|-------------|------|---------|-------------|---------|------------|
| III oil fraction 350-420 ºC | 20 | 0.0749 | 2514.20 | 878.00 | 0.16 |

The following boundary conditions were set during the calculation:
- at the filtrate input to the disk (inlet1, inlet2): type-pressure-inlet, inlet overpressure – 1.5 MPa, temperature – 19 ºC (Gauge Total Pressure/1500000, Thermal/Total Temperature/19);
- at the output of the filtrate from the disk (outlet1, outlet2): type – pressure-outlet, the excess output pressure is 0 (Gauge Pressure/0);
- the wall disk: type-wall, thermal conditions-temperature equal to 41 ºC, which corresponds to the oil temperature at the entrance to the mold body, wall thickness – 0.012 m, material name-steel (Edit/Thermal/Thermal Conditions/Temperature, Temperature/41, Wall Thickness/0.012, Material Name/steel) [6, 8].
The results of calculating of the disk model for options 1, 2, and 3 are shown in figure 2. The output parameter in the postprocessor is the temperature of the liquid at the boundary with the wall.

![Figure 2](image_url)

**Figure 2.** The result of the calculation models of the cooling disk: a - design with 6 passages in each section, b - design with 12 passages in each section, c - design with 18 passages.

It is necessary to ensure the most uniform supercooling of the solution in order for the mass crystallization process to take place in the entire volume of the raw mixture. In other words, the more uniform the surface temperature of the cooling disk is, the more efficient the process will be. In addition to the efficiency of heat and mass transfer, temperature uniformity affects the rate of crystallization of paraffin on the outer surface of the disk. The more uniform the layer of paraffin crystals, the more durable the scraper elements of the device will be. A summary histogram was constructed to estimate the temperature distribution. The values of the refrigerant temperatures were considered at 5000 points on the "filtrate-wall" boundary which were evenly distributed over the entire contact surface. A summary histogram of the distribution of the points number by temperature is shown in figure 3.

![Figure 3](image_url)

**Figure 3.** Summary histogram of the distribution of the points number by temperature at the "filtrate-wall" boundary.

Analysis of the histogram shows that in the disk for option 2, the liquid temperature at most points (76.8 % of the total) is 22 °C. It is obvious that this option is characterized by the most uniform temperature field. In options 1 and 3, the temperature of the liquid is in a wider range. Although there are local areas with high temperatures in figure 3, this phenomenon is explained by a design feature. In places where the partition divides the input and output streams, a stagnant zone is formed. The size of this zone is quite small, so the presence of this local temperature increase can be neglected. From the foregoing, we can conclude that with an increase in the number of passages in the cooling disk, the uniformity of the temperature field increases and, as a result, the cooling of the raw
mixture and the growth of paraffin crystals are more uniform. These factors have a positive effect on the speed of suspension filtration and on the overall installation performance.

Statistical analysis of the data showed that the smallest variance in temperature readings is observed in the disk with option 2, and the largest-in the disk with option 1. The lower the dispersion value, the smaller the temperature difference of the liquid in different areas and over the entire surface area of contact between the raw material and the disk. The value of the temperature dispersion in the disk with 12 labyrinth passages was 2 times lower than in the option 1.

To increase the efficiency of the mold, it is important to improve the characteristics of heat transfer which can be achieved by increasing the total heat transfer coefficient $K$ between the flows of raw materials and the refrigerant, the value of which is determined by the heat transfer coefficients of the flows $\alpha_{ref}$, $\alpha_{r,m}$, the thermal resistance coefficients of the environment $R_{ref}$, $R_{r,m}$ and the wall material $R_w$. The thermal resistance coefficients are constant, since they are determined by the properties of the process media, and also depend on the thickness of the disk wall, which is determined by the strength calculation. However, we can influence the values of the heat transfer coefficients of the $\alpha$ flows, which depend on the geometry of the flow part, the flow rates and the thermophysical properties of the process flows [5, 6, 7, 9].

We change the geometry of the flow part by changing the configuration of labyrinth passages. Therefore, to assess the effect of the design of cooling disks on the heat transfer characteristics, we should determine the heat transfer coefficient from the disk wall to the coolant flow $\alpha_{ref}$.

The equation shown in the studies [5, 6, 9] should be used to determine the average heat transfer coefficient from the disk wall to the refrigerant-filtrate flow:

$$\bar{\alpha} = \frac{\bar{q}}{\Delta t_c}, \quad (1)$$

where $\bar{q}$ is the average surface heat flux density, W / m$^2$;

$\Delta t_c$ - average calculated thermal head, °C.

The value $\bar{q}$ is determined by averaged measurements on the inner walls of the cooling disk of 5000 points across the entire surface of the disk heat transfer.

The average arithmetic thermal head can be found by the formula [5, 6, 9]:

$$\Delta t_c = \bar{\theta}_w - 0.5(\bar{\theta}_{in} + \bar{\theta}_{out}), \quad (2)$$

where $\bar{\theta}_w$ is the average wall temperature of the heat transfer surface, °C;

$\bar{\theta}_{in}$, $\bar{\theta}_{out}$ - the average mass temperature of the environment at the beginning and end of the flow around the heat transfer surface, °C.

The temperature of the heat transfer wall of the disk is measured at 5000 points on the inner surface, after which the arithmetic mean value of the temperature is determined $\bar{\theta}_w$. The results of calculating the average heat transfer coefficient from the disk wall to the refrigerant-filtrate flow for three options of labyrinth channels are shown in table 2.

| Disk option | Average heat transfer coefficient $\bar{\alpha}$, W/(m$^2$·K) |
|-------------|---------------------------------------------------------------|
| Option 1    | 825.02                                                        |
| Option 2    | 1040.51                                                       |
| Option 3    | 865.80                                                        |

**Table 2.** Average heat transfer coefficient from the disk wall to the refrigerant-filtrate flow for three options of labyrinth channels.
The analysis of the obtained data shows that the average coefficient of heat transfer from the disk wall to the flow of the refrigerant-filtrate for the labyrinth channel option 2 is 1.3 times higher compared to option 1 and 1.2 times higher compared to option 3.

Thus, based on all the previously obtained results of comparative analysis, the design of the cooling disk with the execution of labyrinth channels according to option 2 proved to be more effective in comparison with the options of the disk according to option 1 and 3. This option showed a more uniform temperature distribution and an increase in the average heat transfer coefficient, which has a positive effect on the crystallization process.

3. The influence of the flow rate of the filtrate on heat transfer

The cooling disk design option 2 was selected for further studying the effect of the filtrate flow rate on heat transfer.

During the study, calculations for disks with volume flow rates of 25, 50, 75, 100 and 125 m$^3$/h were made. The pictures of temperature fields obtained as a result of the calculation are shown in figure 4.

![Image](image.png)

**Figure 4.** The distribution of temperature field in the flow rate of the refrigerant: a - 25 m$^3$/h, b - 50 m$^3$/h, c - 75 m$^3$/h; d - 100 m$^3$/h.

The changes of the average heat transfer coefficient from the disk wall to the flow of refrigerant-filtrate when its flow rate alters should be estimated. A summary table of the calculation results for different flow rates is shown in table 3.

**Table 3.** Summary table of results for calculating the heat transfer coefficient for different flow rates.

| Volume flow, m$^3$/h | 25   | 50   | 75   | 100  | 125  |
|----------------------|------|------|------|------|------|
| Heat transfer coefficient, W/(m$^2$·K) | 387.98 | 809.54 | 1222.63 | 1759.07 | 2435.73 |
It can be noticed that as the refrigerant flow rate increases, the heat transfer coefficient from the disk wall to the refrigerant-filtrate flow increases. Accordingly, the flow rate can be controlled to achieve the required temperature. On the basis of data on values of heat transfer coefficient of 5000 points uniformly distributed on the surface of contact of the liquid with the wall, obtained in the course of calculation models with different value of the input mass flow rate have been found average values of heat transfer coefficient and the equation of the average heat transfer coefficient $\bar{a}$ from the refrigerant to the wall of the disc, flow-rate $Q_m$, which has the form:

$$\bar{a} = 10.17 \cdot Q_m^{1.1225}.$$\hspace{1cm}(3)

The resulting equation can be used to find the required refrigerant flow rate in order to achieve a certain average temperature when regulating the crystallization process.

4. Conclusion

The influence of the cooling disk design on the heat transfer parameters of the disk regenerative crystallizer for the process of oil dewaxing was studied. It was found that the number increasing of labyrinth passages to twelve passages allows increasing the average heat transfer coefficient by 1.3 times and providing 2-fold increase in the uniformity of heat transfer.

Analysis of the dependence of heat transfer in a disk with 12 labyrinth passages on the refrigerant flow showed that the average temperature of the wall of the heat transfer surface decreases with increasing flow. The greatest uniformity of temperature distribution over the disk surface is achieved when the refrigerant flow rate is 100 m$^3$/h.

Thus, an improved version of the cooling disk design is proposed for the regenerative disk type mold, which provides a more efficient heat transfer compared to existing analogues, which is confirmed by the results that were obtained.

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