Intensification of heat transfer by mixing in pyrolysis units during oil waste disposal

O A Kolenchukov¹, E A Petrovsky¹, A Yu Mikhaylov², K A Bashmur¹ and N A Smirnov³

¹Siberian Federal University, 79, Svobodny Av., Krasnoyarsk, 660041, Russia
²LLC «RN–Vankor», 78, Dobrovolskoye, 15, Krasnoyarsk, 660077, Russia
³Reshetnev Siberian State University of Science and Technology, 31, Krasnoyarsky Rabochy Av., Krasnoyarsk, 660037, Russia

E-mail: OlegAndrenalin.ru@mail.ru

Abstract. This article provides an overview of the most common mixing devices. Their advantages and disadvantages are presented, as well as a mathematical description of the heat transfer process. Revealed the most promising designs for mixing oil waste. The design of the developed mixing device is shown.

1. Introduction

Mixing is one of the most common processes in chemical technology. Aggregates with mixing devices are used to carry out various technological processes, such as carrying out quick reactions, mixing abrasive suspensions, preventing sedimentation of particles, etc. When disposing of liquid hydrocarbon waste using a promising pyrolysis method it is important to ensure uniform heating of raw materials for quality control of final products [1-2]. To this end, various types of mixing devices are used. The optimal mixer design is selected depending on the type of mixing fluid. The mixing efficiency is evaluated using a heat transfer coefficient or Nusselt criterion.

2. Types of agitator devices

Consider the main types of agitators. We will single out the most promising of them; we will also highlight the advantages and disadvantages in them [3].

2.1 Turbine agitators

Turbine agitators are high-speed electric mixing devices of the turbine type with a rigid attachment of the agitator shaft to the drive shaft used for the formation of suspensions, dissolution, during a chemical reaction, gas absorption and heat transfer intensification (Figure 1). Turbine agitators provide intensive mixing throughout the entire volume of the device [4].

At large values of height to the diameter of the device, multi-row turbine agitators are used. Turbine agitators are used for stirring up precipitation in liquids containing 60% or more of the solid phase. The permissible sizes of solid particles are up to 1.5 mm for open agitators and up to 25 mm for closed agitators. Turbine agitators are in the form of wheel water turbine with an inclined flat or curved blades. In devices with turbine agitators, mainly radial flows are created along with axial flows. At high speeds,
the formation of craters. Viscosity of the liquid used in turbine agitators up to 5000 cP. Turbine agitators operate at a speed of 100-380 revolutions per minute and a circumferential speed of 1.8-13 m/s.

The heat transfer from the vessel wall to the liquid, in this type of mixing, is determined by the following equation:

$$Nu = 0.40 \cdot Re^{0.25} Pr^{0.5} \left(\frac{\mu}{\mu_s}\right)^{0.14}$$  \hspace{1cm} (1)

$$Nu = 1.01 \cdot Re^{0.62} Pr^{0.5} \left(\frac{\mu}{\mu_s}\right)^{0.14}$$  \hspace{1cm} (2)

Figure 1. Turbine agitator.

Figure 2. Milling agitator.

Heat transfer from the liquid to the coil wall is expressed as follows:

$$Nu = \frac{\alpha D_i}{\lambda}$$  \hspace{1cm} (3)

The advantages of turbine agitators are: speed; high efficiency; low starting torque. Disadvantages: comparative complexity; high cost of manufacturing.

2.2 Milling agitators

Milling agitators are universal, which makes it possible to use them to create homogeneous suspensions, emulsions, and to mix liquids and solid components of the mixture in various combinations. The basic design of such a stirrer is shown in figure 2.

Milling agitators favorably differ in their versatility and are successfully used in the processes of fine grinding and mixing of solids and liquids in various combinations, which allows you to obtain suspensions, emulsions and pastes of a high degree of uniformity. Examples of such processes are mixing solid, crystalline, or granular particles with liquids, including those of high viscosity (making paints, adhesives, salt solutions, fertilizers, and detergents); and breaking fibrous particles (making fruit pastes, ketchups, and so on. in food production), weighing and insoluble liquids (production of cooling lubricants) and many other processes in the chemical, food and other industries [5].

The heat transfer coefficient is calculated for such a structure using the following equation:

$$Nu = 0.18 \left(\frac{d_o}{t}\right)^{0.54} \left(\frac{h}{t}\right)^{-0.14} Re^{0.65} Pr^{0.4}$$  \hspace{1cm} (4)
where: $d_o$ – outer diameter; $t$ – step between ribs; $h = 0.5(D - d_o)$ – edge height; $D$ – rib diameter.

Advantages of milling agitators: low manufacturing cost; easy to manufacture; reliability. The main drawback is a small range of uses.

2.3 Frame agitators

Frame agitators are used for mixing liquids with a dynamic viscosity of up to 20,000 cP, including in heated containers, when precipitation or contamination of the heat transfer surface is possible. The frame agitator is most often used for liquids with a dynamic viscosity of more than 10000 cP. The design of such a stirrer is shown in the figure 3.

![Figure 3. Frame agitator.](image1)

![Figure 4. Screw agitator.](image2)

Agitators have a shape corresponding to the internal shape of the container and a diameter close to the internal diameter of the container (the gap between the blade and the wall is within 0.005 – 0.1 D). When rotating, the agitators clean the walls and bottom of the tanks from adhering deposits. Frame agitators are characterized by a low number of revolutions (20-60 rpm) at a circumferential speed of 0.5-1.5 m/s [6].

When solid substances are dissolved in a liquid, the loading of the powder should be uniform and gradual in order to avoid the formation of lumps, and as a result of this beating and failure of the agitator. The heat transfer coefficient is determined by the equation:

- to the outer wall: at

$$\frac{Re \cdot D}{H} \leq 21; \quad Nu = 7.6 \left(\frac{\mu}{\mu_i}\right)^{0.14}$$

(5)

- in another case:

$$Nu = 2.76 \left(\frac{Re \cdot D}{H}\right)^{0.33} \left(\frac{\mu}{\mu_i}\right)^{0.14}$$

(6)

- to the inner wall: at

$$\frac{Re \cdot D}{H} \leq 21; \quad Nu = 3.6 \left(\frac{\mu}{\mu_i}\right)^{0.14}$$

(7)

- in another case:
The advantages include: simplicity of the device; low cost of production. Disadvantages: low pumping action of the agitator (weak axial flow); blade agitators stir only those layers of liquid that are in close proximity to the agitator blades [7].

2.4 Screw agitator

Screw agitators have found application and are used in the chemical industry for dosing and transporting products. The design scheme is shown in figure 4. Performing technological operations such as mixing high-viscosity media and chemical reactions in them, melting, compaction, dissolution, drying of bulk materials, etc. [8].

Technologies where the extruder-reactor is used usually combine separate processes: mixing, product forming and chemical reactions. In this regard, new problems arise related to the removal of heat released during processing, changing the flow structure, etc. Ensuring the optimal conditions of the processes that accompany the above operations is impossible without knowledge of the flow of hydrodynamics and thermal conditions in screw machines, which are the basis for the analysis of mixing processes, temperature homogenization of the mass and dispersion.

The heat transfer from the vessel wall to the liquid is determined by the following equation: [9]

$$Nu = 0.74 \cdot Re^{0.33} Pr^{0.14} \cdot \left( \frac{\mu}{\mu_s} \right)^{0.14}$$

(8)

Heat transfer from the liquid to the coil wall is expressed by the ratio:

$$Nu = 1.19 \cdot Re^{0.62} Pr^{0.14} \cdot \left( \frac{\mu}{\mu_s} \right)^{0.14}$$

(9)

The heat transfer coefficient is determined by the equation:

$$\alpha = \frac{0.267 \cdot \rho C_p \cdot \left( \frac{N}{\rho V} \right)^{0.25}}{Pr^{0.75}}$$

(10)

where: $C_p$ – heat capacity of the medium J/kg·deg; $Pr = \nu \rho C_p \lambda$ – Prandtl number; $\lambda$ – thermal conductivity of the medium.

The advantage of screw agitators is the uniform distribution of raw materials throughout the volume. The disadvantage is the complexity of the design.

2.5 Combined precession agitator

Electric agitator combined with a three-blade impeller and a turbine (figure 5). The agitator is equipped with a hook joint, an oil seal, a frequency Converter, and a General-purpose gear motor. Material of production of the working part of the agitator stainless steel [10].
The coefficient of heat transfer to the device body can be calculated using the equation:

\[
Nu = 1.1 \cdot \left[ \left( 1 - \frac{r_p}{r_e} \right) \left( 1 - \frac{r_p}{r_e}^2 \right) \left( 1 - \frac{r_p}{r_e}^2 \right)^{1/3} \cdot Re \cdot \frac{d_e}{H \Omega} \right]^{1/3} \cdot \left( \frac{K}{K_r} \right)^{0.14} \cdot \left[ 1 + 0.12 \left( \frac{l}{H} \right)^{0.6} \right]
\] (12)

where: \( d_e = 2R_e \cdot (1 - r_m) \); \( K \) – consistency; \( M \) – behavior index of a non-Newtonian power fluid.

The agitator is designed for mixing industrial slurries. Even distribution of the sludge in the tank is provided by a two-level agitator: a blade in the middle part and a turbine in the lower part [11].

The advantages of this agitator include: precession based on the hook joint; uniform distribution of sludge throughout the tank volume; prevention of the formation of stagnant zones and bottom sediment. The main drawback is the complexity of the design.

### 2.6 Caustic agitator

The SMX type agitator (Figure 6) is best suited for ideal mixing of resins, additives, dyes and catalysts. It is used in the production of resins and sealants, as well as in the introduction of additives, and due to its exceptional mixing characteristics, it is also effective in mixing masses with very difficult mixing characteristics [12].

Heat transfer from the vessel wall to the liquid is determined by the equation: [13]

\[
Nu = 0.27 \cdot Re^{2/5} Pr^{1/3} \left( \frac{\mu}{\mu_s} \right)^{0.14}
\] (13)

Heat transfer from the liquid to the coil wall is expressed by the ratio:

\[
Nu = 1.04 \cdot Re^{0.62} Pr^{1/3} \left( \frac{\mu}{\mu_s} \right)^{0.14}
\] (14)

where

\[
Nu = \frac{\alpha D_{kr}}{\lambda}
\] (15)

The advantages of SMV agitators are as follows: the SMV configuration can be adjusted to the pressure drop and drop size, as well as the drop distribution expectations; low acid and caustic transfer protects the downstream columns; acid flushing and product neutralization static SMV mixers increase the overall efficiency of the plant; longer plant operation time; less maintenance work, ensuring
operational reliability; the pressure drop is usually from 0.3 to 0.5 bar, which ensures low energy demand. The disadvantages include: a larger volume in the reactor; heavy construction.

2.7 Other types of agitators
In addition to all the above, all types of agitators have a disadvantage that reduces the stability of their operation and reliability. This disadvantage is due to the lack of additional support points in the mixing mechanism. At the Department of Technological machines and equipment, Institute of oil and gas of the Siberian Federal University, a design of a mixing device containing at least two points of support and driven by an electric motor was proposed (Figure 7). In addition, the mixing device consists of blades located along the shaft at a predetermined distance. At the same time, the blades themselves can be made of various shapes, are quick-detachable, with the ability to adjust the mixer to the desired environment. The blades themselves, in turn, have the ability to adjust the angle of rotation from 0° to 90°. Thus, we managed to develop a universal device. As a result of research, it was found that the heat transfer is at a high level, comparable to screw agitators. The next step of the research will be mathematical modeling, as well as practical research aimed at determining the main parameters of the mixing device to increase its efficiency.

![Figure 7. Universal agitator for oil waste: 1 – electromotor; 2 – working blades; 3 – bearing unit; 4 – space for the speed controller.](image)

3. Conclusion
Screw and combined precession agitators are the most optimal for oil sludge utilization. Their design features allow efficient mixing of highly viscous liquids.

In order to ensure high performance of the mixing device, it is necessary to select a material with high corrosion resistance, since oil waste is a fairly aggressive environment.

To ensure stability at high speeds, as well as the reliability of the bearing units and the entire structure as a whole, it is advisable to increase the number of reference points. A minimum of two support points must be inserted into the structure, and when the drive is moved to the center of the mixer shaft, it must be increased to four.

The developed mixer has equal efficiency with the most optimal technical solutions, and in some parameters (the ability to adjust the angle of the blades, speed and torque) exceeds existing designs.

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