Irina L. BOSHKOVA
Natalya V. VOLGUSHEVA
Olexandr S. TITLOV
Ella I. ALTMAN
Igor I. MUKMINOV

V.S. Martynovsky Institute of Refrigeration, Cryotechnologies and Ecoenergetics
Odessa National Academy of Food Technologies 65039
Odessa, Kanatnaya, 112, Ukraine

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PERSPECTIVES OF USING MICROWAVE HEATING OF PETROLEUM PRODUCTS IN THE TANK

Abstract: *The problem of optimizing the heating of petroleum products when draining from railway tanks using microwave heating is considered. It is established that microwave heating can significantly simplify the technological scheme, eliminating all processes and apparatuses associated with the preparation of the coolant. It is determined that currently existing patents and technical solutions proposed for the use of microwave heating for heating petroleum products assume that microwave energy falls on the free surface of the liquid. It is argued that the disadvantage of such schemes is a significant unevenness of heating due to the fact that microwave energy quickly fades out when moving deep into the tank. It is noted that when heated from the surface of the liquid in the tank, the distance from the source to the drain hole is quite large, as a result of which it is impossible to effectively use microwave heating. A method for solving this problem is proposed, which consists in installing a microwave device inside a hollow pipe, which is directly connected to the upper hatch in preparation for pumping and is immersed in the oil product to a depth that correlates with the depth of penetration of the microwave field in a particular product. The depth of penetration of microwave energy into the oil product under study – fuel oil-is estimated, on the basis of which it is recommended to set the distance from the emitter to the drain hole. It is argued that it is advisable to model microwave heating on the basis of the differential equation of thermal conductivity, taking into account internal heat sources. A mathematical model describing the heating of a volume of highly viscous petroleum products as a process of thermal conductivity in an unlimited array under the action of microwave radiation is presented. On the example of fuel oil, calculations were made using the finite difference method, which showed the temperature distribution in the array at different points in time.*

Keywords: *microwave energy, temperature, thermal conductivity, penetration depth, power, oil product drain, tank*

Introduction

When creating resource-saving and energy-saving, environmentally friendly technologies, the use of microwave radiation is one of the most promising areas. Heating in a microwave field is characterized by high speed and high efficiency. The use of microwave energy instead of the heat carriers currently used in most industrial installations can significantly simplify the technological scheme, eliminating all processes and apparatuses associated with the preparation of the heat carrier, as well as harmful emissions into the atmosphere. Conducting research related to determining the optimization of the effect of microwave radiation on the course of a number of chemical and petrochemical processes is an important and relevant direction for intensifying these processes, both at the laboratory level and on an industrial scale. One of the applications of microwave heating is the heating of high-viscosity oils, which provides a significant reduction in the viscosity of the product. The actual task of transporting viscous petroleum products is to unload them from storage tanks or transport them, for example, from railway tanks. Draining is carried out using several methods: a more fluid solvent, by heating the product with saturated water vapor, using microwave installations, by the circulation method using coil heaters, as well as modifications and combinations of these methods. Heating the product with saturated open water vapor is not possible for some products that do not allow waterlogging, for example, fuel oil, because as a result of waterlogging, the efficiency of fuel oil combustion in boiler furnaces decreases. In addition, Steam that does not mix well with fuel oil, as well as boiling water that condenses from Steam, foams the product on cold fuel oil, which can lead to the release of the product into the hatch. It is considered promising to use the energy of the microwave field, but the disadvantage of this method is uneven heating, also associated with the low thermal conductivity of the product and the almost complete absence of convection of petroleum products in the tank.

Analysis of existing research

To develop the method of microwave heating of oil, the thermal effects and temperature fields in the product are studied. The research [1] is aimed at improving the efficiency of heat transfer of viscous oil and solving the problems of uneven temperature distribution and energy absorption during oil heating in an oil reservoir. The temperature distribution of petroleum products is more balanced under the combined influence of heating sources. The results of this study can provide a theoretical basis for studying the law of heat transfer in the process of combined steam heating of oil tanks and microwave heating. In [2], the features of heating petroleum products in a microwave field are considered and the basic theory of effective heating is presented. At the same time, it is necessary to avoid overheating of oil in its local areas [3], which increases the risk of explosion. Akagi and Kato [4] studied the effect of the convective heat transfer coefficient on heat exchange and temperature distribution during heating of viscous oil. Wei and others [5], Makanyang and others [6], Hu [7], Zhu and others [8] investigated the change in the characteristics of the temperature field and flow rate by numerical modeling methods and obtained the characteristics of the heating process of petroleum products. The developed microwave heating technologies are characterized by high intensity and efficiency. These advantages make it possible to use microwave heating when drying food products, reducing the viscosity of oil, separating the emulsification of oil and water, etc. [9, 10]. According to the analysis of the temperature field of viscous oil, an uneven distribution of the microwave field in the oil tank will cause regional differences in the distribution of the temperature field. From the point of view of analyzing the heat transfer process [1], during microwave heating, oil molecules move rapidly and begin to quickly penetrate other areas. Macroscopically, a hot oil product transfers energy to a region with a lower temperature due to thermal conductivity. At the same time the effect of thermal conductivity is decisive in comparison with natural convection. It was determined [1, 11, 12] that microwave energy is intensively absorbed by a viscous petroleum product. Analysis of literature data shows that the method of microwave heating of oil tankers is feasible and it is advisable to study it for further application in industry. However, there is a need to conduct analytical and experimental studies of the process of heating petroleum products in a microwave field to solve certain problems, one of which is the intensification of draining high-viscosity petroleum products from railway tanks.

Analytical study of the process of microwave heating of high-viscosity petroleum products

To describe the heating process of a cylindrical tank with petroleum products exposed to high-frequency electromagnetic radiation, the equation of thermal conductivity in cylindrical coordinates is applied in [13]. The analysis of the work allows us to conclude that the proposed method of mathematical modeling of microwave heating of petroleum products can be taken as a basis. Modeling of microwave heating of high-viscosity petroleum products should be carried out on the basis of the differential equation of thermal conductivity, taking into account internal heat sources. However, it is impossible to use the proposed results directly, since this paper considers the process of heating a large volume, which cannot be described by cylindrical coordinates.

The mathematical model of heating petroleum products in a tank from the action of a microwave source is based on the assumption that heat propagation is carried out in an unlimited array during thermal conductivity under conditions of internal energy sources. Assuming that the thermophysical properties are constant and the power of the microwave field is determined by the action of internal heat sources q_v, the differential equation of thermal conductivity takes the following form:

$$\frac{\partial t}{\partial \tau} = a\nabla^2 t + \frac{q_v}{\rho c_p} \tag{1}$$

where:

a – coefficient of thermal conductivity;

ρ – density of the petroleum product;

c_p – heat capacity.

The conditions for unambiguity are as follows:

- petroleum product represents an unlimited array;
- the initial temperature distribution of the array is uniform.

The problem was solved in spherical coordinates, for which the Laplace operator ∇^2, provided that the temperature changes only along the radius *r*, has the following form:

$$\nabla^2 t = \frac{\partial^2 t}{\partial r^2} + \frac{2}{r}\frac{\partial t}{\partial r} \tag{2}$$

The boundary condition is $\left(\frac{\partial t}{\partial r}\right)_{r=\infty} = 0$, where $r = \sqrt{x^2 + y^2 + z^2}$ (The origin is placed in the volume under consideration).

The finite difference method was used to calculate temperatures.

The following values of physical characteristics were used in the calculations: ρ = 950 kg/m³, c_p = 3 KJ/(kg·K), L = 300 KJ/kg, λ = 0.125 V/(m·K) [13]. According to [14], for fuel oil, the relative permittivity ε'= 3.5-4.5 and penetration depth tgδ = 0.013-0.03, this is typical for dielectrics, which absorb microwave energy quite efficiently.

When modeling the microwave heating of petroleum products for this scheme, it is necessary to estimate the distance from the microwave emitter to the drain hole. Since the microwave radiation must be almost completely absorbed, it was necessary to estimate the penetration depth, which, in turn, depends on the absorption coefficient:

$$\alpha = \frac{2\pi}{\lambda_0}\left[\frac{1}{2}\cdot\varepsilon'\left[\sqrt{1+\mathrm{tg}\delta^2} - 1\right]^{1/2}\right] = \frac{2\pi}{12.24\cdot 10^{-2}}\left[\frac{1}{2}\cdot 4.5\left[\sqrt{1+0.03^2} - 1\right]^{1/2}\right] = 2.45\ \mathrm{m}^{-1} \tag{3}$$

then the penetration depth:

$$\Delta = \frac{1}{2\alpha} = \frac{1}{2\cdot 2.45} = 0.20\ \mathrm{m} \tag{4}$$

At this distance, the flow of electromagnetic energy will decrease by e times. We assume the distance to the drain hole equal to one and a half values of Δ – 30 cm.

When performing calculations, it was assumed that at the initial stage no draining is carried out, the stationary volume of petroleum product (fuel oil) is heated. When the fuel oil temperature reaches 60°C (recommended for draining) near the drain hole, its pumping begins. At the same time, streams of unheated product begin to approach the emitter. The heating process can continue until the oil drops to the level of the drain hole. There are recommendations [15], according to which when the volume of heated material exceeds 20 m^3 and the ambient temperature is below 10°C, it is advisable to use microwave installations with a capacity of at least 50 kW. In contrast to these recommendations, when installing the magnetron at a low height relative to the drain hole, the power of the magnetron can be significantly reduced, since there is no need to heat the entire volume of petroleum product.

Fuel oil temperatures were calculated at a distance from 0 cm (microwave energy source) to 30 cm (drain hole). In Figure 1 shows the temperature field in the oil product for different time intervals.

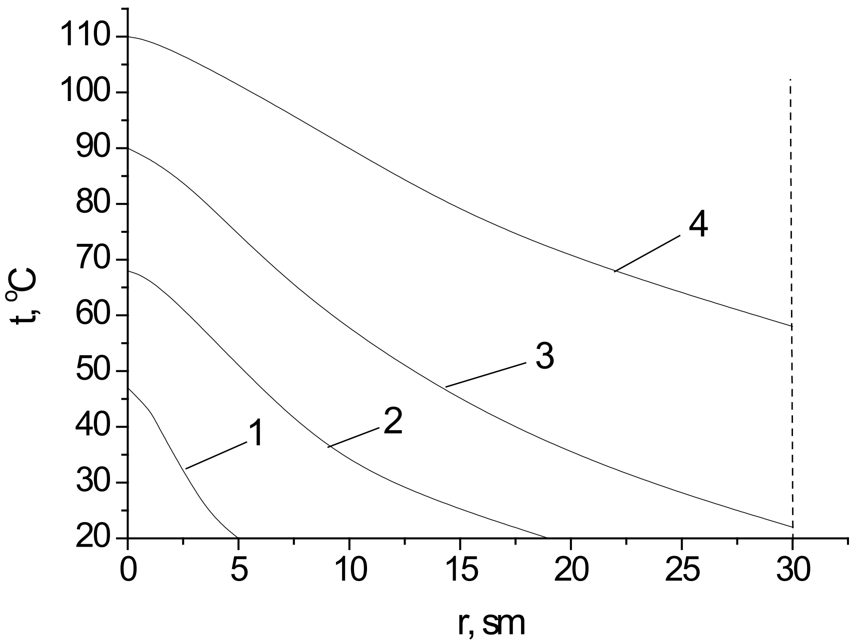

FIGURE 1. *Calculated change in the temperature of fuel oil in the tank during microwave heating: 1 – τ = 1 min, 2 – τ = 10 min, 3 – τ = 65 min, 4 – τ = 116 min*

The temperature of fuel oil increases over time, and the front of the heated area expands. After 65 minutes, this front reaches the drain hole, but the oil temperature is insufficient to start the pumping process. From Figure 1 it can be seen that the fuel oil temperature of 60°C at the drain hole will be reached in 116 minutes. To increase the flow rate, ensuring that the required temperature is reached at the drain hole of 60°C, you can install a magnetron of greater power, for example, 15 kW. Then the consumption will increase to 0.93 kg/s.

When developing a device for microwave heating, the following should be taken into account [15]: the volume of product in tanks can vary widely, and, accordingly, the load resistance (heated volume) changes, so it becomes necessary to coordinate the latter with the microwave generator in order to avoid damage to the magnetron, which must be reliably protected from load mismatch.

Analysis of the applicability of microwave heating to the intensification of draining high-viscosity petroleum products

Existing patents and technical solutions proposed for the use of microwave heating for heating petroleum products assume that microwave energy falls on the free surface of the liquid. An example of such a circuit solution is shown in [15]. In this patent, the subject of the invention is an emitter in the form of a directional antenna installed obliquely to the surface of a thickened or frozen petroleum product, while the transmitting line is equipped with an additional direct waveguide installed between the waveguide break and the cover-screen. The design provides for heating the product in the tank by a stream of microwave radiation formed at an acute angle to the product in the opposite direction from the internal stairs, which increases the efficiency of heating the product, the reliability of the magnetron and the microwave generator as a whole.

The disadvantage of such schemes is that the microwave energy falling on the surface of the oil product quickly fades due to its conversion into heat when moving deep into the tank. As shown above, the penetration depth for fuel oil is 20 cm, and this value is comparable to the penetration depth of other high-viscosity petroleum products. Since the diameter of the railway tank is 3 M, it is clear that at a relatively short distance from the surface, the oil product will not be heated. This problem is partially solved in [16]. To ensure more uniform heating, it provides for the extraction of cold oil product from the bottom part of the tank, heating it in an external heat exchanger and feeding the heated oil product by means of a pump to the bottom part of the tank using nozzles, the use of preheated oil product on the initial cold oil product extraction cycle, and continuous circulation of oil product. Microwave heating [17] of heavy oil shows that the viscosity is significantly reduced, which ensures a significant intensification of its inflow. The specific nature of the volume absorption of microwave energy is also expressed in the fact that it is difficult to ensure the uniformity of heating, especially for large volumes. It is proposed to use high-power magnetrons to ensure the mobility of layers far from the source. However, the distance from the source to the drain hole is quite large, which does not allow efficient use of the features of microwave energy conversion by dielectric materials. Therefore, one of the tasks of this work was to find the ability to place the radiation source in close proximity to the drain hole. The problem was made easier by the fact that the tank refueling Hatch is located directly above the drain hole. Therefore, it is possible to lower the radiator through the hatch to the drain hole. To do this, you can make a hollow pipe that can be connected to the upper hatch, and in which the microwave device will be located. As calculations have shown, the output power of the magnetron should be at least 3 kW. Then a water cooling system must be provided to cool the anode block of the magnetron. A magnetron is placed in a hollow pipe, the emitter of which comes out of the base of the pipe and is located directly above the drain hole. The air channel also contains the main components of the microwave device: a high-voltage capacitor and transformer, control system elements. Schematically, the location of a removable air pipe for a microwave device in a railway tank is shown in Figure 2.

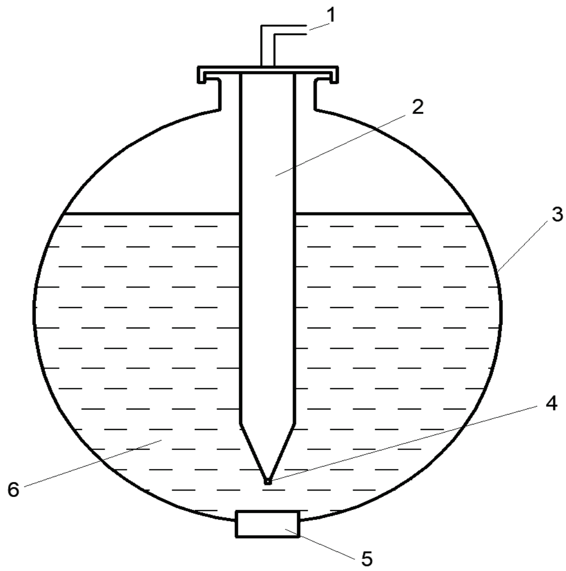

FIGURE 2. *Diagram of the longitudinal section of a tank with a microwave device: 1 – channel for the device of the magnetron control system and the magnetron cooling system, 2 – air Channel, 3 – tank with petroleum product, 4 – microwave energy emitter, 5 – outlet, 6 – petroleum product*

To avoid contact with petroleum products, it is proposed to cover the electromagnetic energy emitter with a radio-transparent cap. Thus, the method of microwave heating of oil in the immediate vicinity of the drain hole can be practically implemented using the proposed scheme. With this location of the source (Fig. 2) relative to the drain hole, heating, and, accordingly, a decrease in the viscosity of the oil product, will be observed in the drain zone, which can significantly intensify the process and reduce energy costs for heating.

Conclusions

An analytical study of the process of microwave heating of petroleum products is carried out on the example of fuel oil. It is obtained that the temperature of fuel oil increases over time, and the front of the heated region expands. For an initial temperature of 20°C after 65 minutes. the hot front reaches the drain hole, but the oil temperature is not sufficient to start the pumping process. Under the specified conditions (initial temperature 20°C, magnetron output power 3 kW, relative permittivity ε'= 4.5 and loss angle tangent tgδ = 0.03), the fuel oil temperature of 60°C at the drain hole will be reached in 116 minutes. To increase the flow rate, ensuring that the required temperature is reached at the drain hole of 60°C, you can install a magnetron of greater power, for example, 15 kW. In this case, the consumption will increase to 0.93 KG/s.

The circuit solution for a microwave device allows you to place the radiation source in close proximity to the drain hole. It is suggested to place the microwave device in a hollow pipe that can be connected to the upper hatch. The microwave energy emitter comes out of the lower base of the pipe and is located directly above the drain at a distance of 1.5 penetration depth. With this location of the source relative to the drain hole, heating, and, accordingly, a decrease in the viscosity of the oil product, will be observed in the drain zone, which can significantly intensify the process and reduce energy costs for heating.

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