TEMPERATURE FIELD DISTRIBUTION ANALYSIS FOR CARGO OIL ON MICROWAVE HEATING PROCESS

by

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Original scientific paper
https://doi.org/10.2298/TSCI191226133W

This paper uses microwave technology to study the heating process of cargo oil in tanker side cabin under the static environment. The research is aimed to improve the heat transfer efficiency of cargo oil and solve the problems of uneven temperature distribution and energy consumption during the heating process of traditional crude-oil in oil tank. Based on the theory of microwave heating and heat transfer, the finite element simulation software is used to couple the microwave and temperature field during the cargo oil is heated to simulate the changing characteristics of the temperature field in static environment, and then verify the numerical results of the existing experiments. The simulation results show that the numerical results of this model agree well with the experimental data, and the error is in the range of 6.21-13.84%. Therefore, the accuracy of the numerical method can be verified. During the heating process, the absorption of microwave energy has a positive correlation with the electric field intensity distribution. The microwave field shows a "strong point" distribution characteristic. Heat transfer is accompanied by natural-convection and heat conduction, and the oil temperature distribution is more balanced under the combined effect, which shows that the microwave heating of oil tankers have certain feasibility. The results of this study can provide a theoretical basis for studying the heat transfer law of oil tanker cargo steam and microwave combined heating process.

Key words: *microwave heating, temperature field, microwave energy, numerical simulation, crude-oil*

Introduction

In the marine transportation of crude-oil tankers, tankers are mostly filled with crude-oil with higher viscosity. In the whole transportation process, the crude-oil must be heated to be able to transport cargo oil with higher efficiency and lower cost, so as to ensure that the temperature in the oil tank can be maintained above the freezing point of the cargo oil. The purpose is to prevent its natural cooling below the freezing point, make it difficult to unload, and increase the risk of oil tanker transportation [1]. At present, the heating and insulation control of cargo oil is mainly based on the experience of the crew, but there is often a problem of overheating of the cargo oil, which in turn causes the temperature of the actual heated cargo oil

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to be much higher than the theoretical temperature when unloading. It may lead to the inability to unload the oil, greatly increasing the risk of oil tank explosion. The aforementioned approach is neither economical nor environmentally friendly, and has gradually moved away from the concepts of *low-carbon tankers* and *green tankers* [2].

Researchers have done a lot of research on the heating and insulation process of oil in cargo tankers. Akagi and Kato [3] studied the influence of convective heat transfer coefficient on heat transfer and temperature distribution during cargo oil heating. Wei *et al.* [4], Macagnan *et al.* [5], Hu [6], and Zhu *et al.* [7] studied the change characteristics of temperature and flow field by numerical simulation methods and obtained the flow characteristics and transmission characteristics of oil thermal mechanism. Although large engineering researches have been done on the heating and thermal insulation of crude-oil tankers, there are relatively few studies on how to use more energy-saving methods to improve the heating efficiency of cargo oil, shorten the heating time and reduce energy loss. As we all know, microwave heating technology has the characteristics of fast heating, uniform heating temperature and high efficiency. Therefore, it is widely used in food heating and drying, oil viscosity reduction, oil-water emulsification separation and other fields [8-12]. Chen *et al.* [13] used numerical simulation simulate the distribution of microwave fields in water, and obtained from the comparative experiments agree well with the experimental results. Wang [14] used the FDTD method to solve the average temperature inside the heating cavity, and concluded that the heavy oil temperature distribution in different locations was uneven. Song [15] designed the microwave heating experiment, using water and oil as experimental objects, and finally obtained theoretical values of microwave absorption power under different conditions, but did not use numerical simulation analyze the relationship of the microwave and temperature fields in the cabin.

This paper establishes a 3-D finite element model of microwave and temperature fields. It studies the dynamic changes of cargo oil temperature under the coupling of electromagnetic and heat flow, and analyzes the distribution characteristics of cargo oil temperature heating process under static environment. It provides theoretical guidance for the further study on the feasibility and safety of the combined heating of steam and microwave by oil tanker cabin.

Numerical model

Physical model

Taking a side tank of a certain VLCC as the research object, as shown in fig. 1. According to the scale ratio of 40:1, the cargo tank with a length × width × height of 20×22×30 m is simplified into a model of 0.55×0.5×0.75 m. The specific geometric parameters are shown in fig. 2.

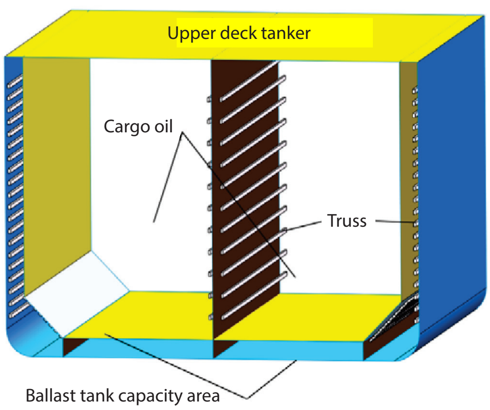


Figure 1. Partial schematic diagram of cargo tanks of a double hull oil tanker

The heat exchange is more complicated in the actual heating process and it is necessary to simplify the model solving process. The following assumptions are made for the model.

It is assumed that the heating process was maintained in a still static environment, and the input power of the waveguide was maintained at a constant value. Considering the influence of a single microwave source on heat transfer, the waveguide was set at center of the upper end of the tank which its long side was consistent with the length.

It is assumed that the changes in oil concentration and chemical changes were ignored after heating in a static environment, and only considered the effects of flow heat transfer caused by temperature differences.

Ignoring the heat generated by volatilization and condensation of oil and gas when phase change occurred during the heating of cargo oil.

It is assumed that the relative dielectric constant of the oil did not change with temperature, and that the oil was isotropic.

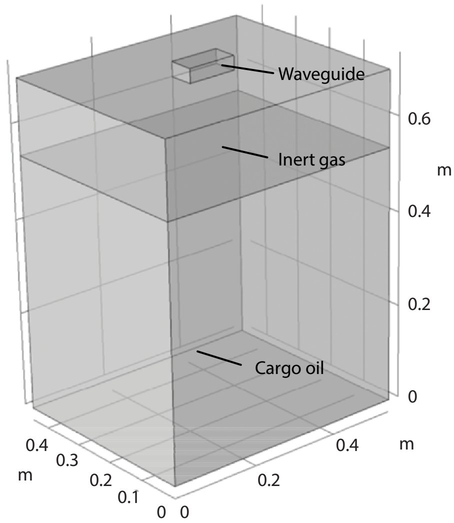


Figure 2. Schematic model of coupled electromagnetic and thermal flow of cargo oil

Mathematical model

The temperature of cargo oil gradually rises under the action of the microwave field, and the distribution of the electric field intensity is given by the Helmholtz equation. The solution equation:

$$\nabla \times \mu^{-1}(\nabla \times E) - k_0{}^2(\varepsilon_\mathrm{r} - \frac{j\sigma}{\omega\varepsilon_0})E = 0 \tag{1}$$

where E is the strength of the electromagnetic field, μ – the permeability of the medium, ε_r – the relative dielectric constant of the medium, ε_0 – the dielectric constant of the vacuum, k_0 – wave number, ω – the angular frequency, σ – the electrical conductivity, and μ – the magnetic permeability of free space, respectively.

The closed oil tank is equivalent to a microwave-heated resonant cavity. The boundary condition of the bulkhead is defined as a perfect electrical conductor, and the electromagnetic wave propagates to cause full emission in the cavity. The ideal boundary condition:

$$nE = 0 \tag{2}$$

Under the action of a microwave field, the cargo oil absorbs microwave energy and converts it into internal energy, which increases its internal temperature. Without considering the real sloshing sea conditions, the numerical heating process satisfies the energy conservation, continuity equation and momentum equation. The corresponding equations are shown in eqs. (3)-(5), respectively:

– the equation of energy equatio

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P u \nabla T = \nabla(k\nabla T) + \frac{1}{2}\omega\varepsilon_0\varepsilon''|E|^2 \tag{3}$$

– the equation of continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u) = 0 \tag{4}$$

– the equation of mass conservation

$$\rho\frac{\partial u}{\partial t} + \rho(u\nabla)u = \nabla\{-p\mathbf{I} + \mu_l[\nabla u + (\nabla u)^T]\} + \rho \mathrm{g} + \mathbf{F} \tag{5}$$

where C_p is the constant pressure heat capacity, k – the thermal conductivity, ε'' – the relative dielectric loss, u – the velocity tensor, p – the fluid pressure, **F** – the fluid domain stress tensor, and **I** – the unit tensor.

Thermophysical properties off cargo oil

To ensure that the heating process is consistent with the prototype in the numerical simulation, taking into account that the difference in viscosity forces will cause a scaling effect. According to the Grachev number [16], a certain type of lubricant with similar viscosity change is selected as the oil for numerical experiments. Table 1 shows the physical parameters of a certain type of lubricant selected when the oil temperature is 30 °C.

Table 1. Physical properties of a certain type of lubricant

Temperature [°C]	Density [kgm^{-3}]	Thermal conductivity [Wm^{-1}k^{-1}]	Dynamic viscosity [Pa×s]
30	887.4	0.1471	0.79

Boundary conditions

In the numerical experiments, the model set the oil loading rate to 80%, which means that the liquid depth was 0.552 m. The initial lubricating oil temperature was 30 °C, while ambient temperature is 20 °C. The initial pressure in oil tank is set to 0.101 MPa, and the oil conductivity is $2.03416 \cdot 10^{-3}$ S/m. In addition, it is stipulated that rectangular waveguide port is fed with a microwave with power of 1500 W, a frequency of 2.45 GHz, and a modulus of TE_{10}. According to the third type of boundary conditions of convective heat transfer, we set the heat transfer coefficient of the bulkhead to 10 W/m^{2}K, while cargo oil in contact with air to 30 W/m^{2}K.

Numerical results and analysis

Model validation

This paper, in order to verify the accuracy of this numerical method, compared the temperature change in numerical simulation with the experimental data in thesis [15]. The size of the model is 0.39 × 0.34 × 0.6 m, and the waveguide was placed at the bottom of the heating cavity. The heating tank chamber was filled with lubricating oil with depth of 0.27 m and volume of 36 L. We set the initial lubricant oil temperature to 22.1 °C. Numerical experiments monitored the oil temperature changes of monitors 2 and 3 at 25 cm and 15 cm from the bilge. In addition, the number of degrees of freedom of the model grid was 1852777, and the oil was heated for 3600s in a transient state, as shown in fig. 3.

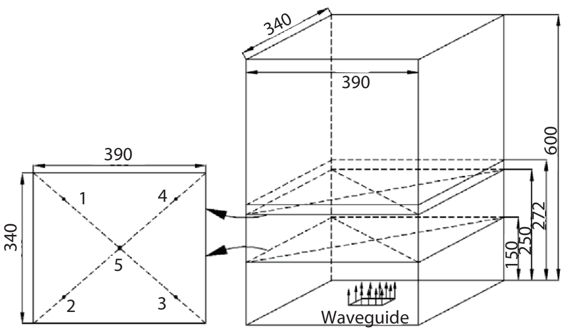


Figure 3. Distribution of temperature monitoring points

Figure 4 shows the comparison between the numerical simulation data and the data in [15]. We can see that the numerical results are in good agreement with the data in [15], and the error remains between 6.21-13.84%. This preliminary verification shows that the numerical method can accurately simulate the change of temperature field during heating. The reason for

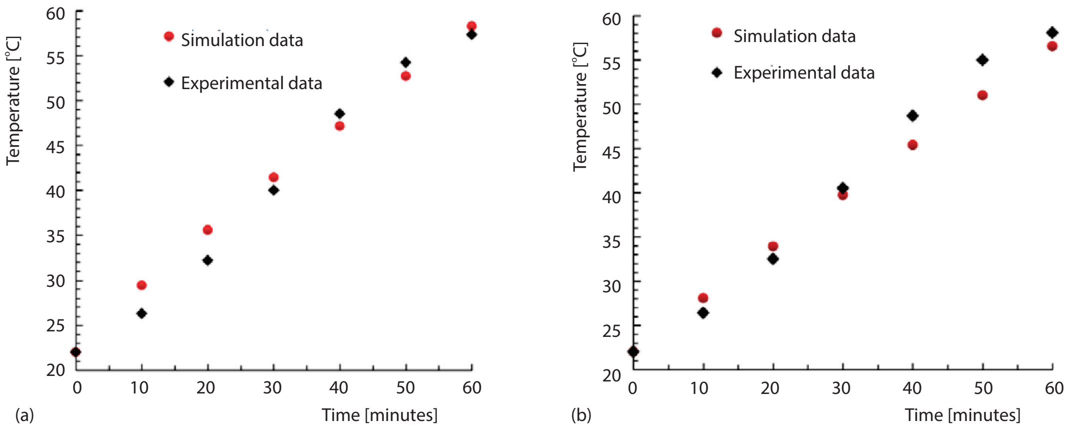


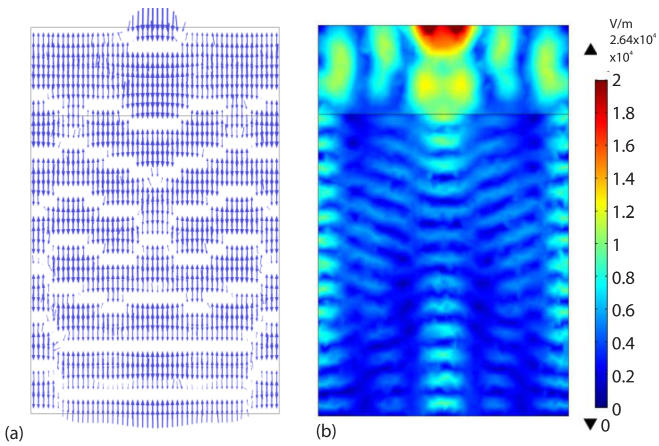
Figure 4. Comparison of simulated data and experimental data; (a) temperature monitoring point 25 cm from the bilge 2 (b) temperature monitoring point 15 cm from the bilge 3

the speculation error may be that the boundary of the bulkhead surface is idealized by numerical experiments, and the microwave energy is completely absorbed by the oil. In addition, the influence of the relative dielectric constant of the oil medium with temperature is not considered in the simulation.

Distribution of microwave field in heating cavity

Figure 5(a) shows the change of the electric field vector in the heating chamber. When the microwave enters the heating cavity, the vertical microwave and the reverse microwave along the *Z*-axis direction interfere with each other to form a standing wave, and then an electric field distribution is formed in the cabin. For different media, different wavelengths will cause different electric field intensity distributions after mutual interference [13]. From the simulation results in fig. 5(b) and fig. 6, it can be seen that the microwave field is symmetrically distributed when heated by a single microwave source, and the electric field intensity shows a *strong point* distribution characteristic. As shown in eq. (3), it can be seen that the intensity of the electric field is an important factor that affects the heated medium's absorption of microwave energy and converts it into thermal energy. As a result, the amount of heat generated by the medium

Figure 5. Middle section in the heating chamber X = 0.22 m; (a) electric field intensity distribution, (b) electric field vector



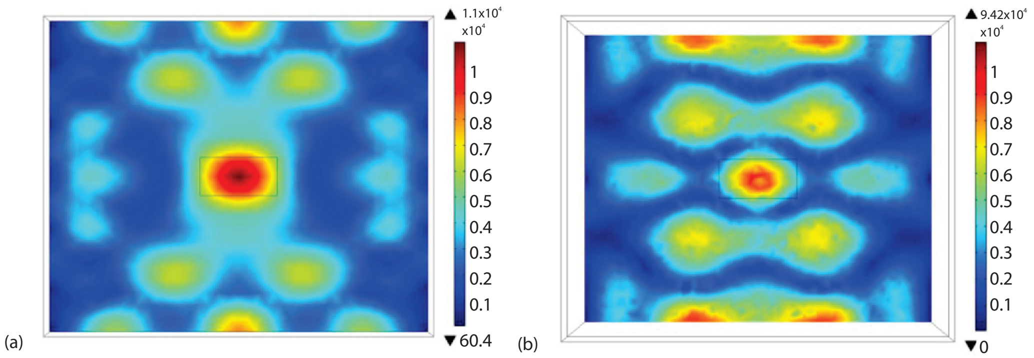


Figure 6. Distribution of electric field strength in the heating chamber; (a) *Z* = 0.54 m on the upper surface (b) *Z* = 0.02 m on the bilge

after absorbing microwave energy is directly proportional to the square of the electric field strength, which shows that the more microwave energy the medium absorbs, the more heat is generated. Therefore, the heating rate of oil cargo in different *strong point* areas is relatively significant, and a large amount of heat will be obtained when microwave power is lost.

Analysis of distribution characteristics of temperature

In order to obtain the distribution of the cargo oil temperature field during heating, we consider the influence of a single microwave source on the temperature field of the oil. Therefore, comparing the distribution characteristics of the microwave field in the heating cavity, five temperatures were set along the Z-axis Monitoring planes: Z = 0.02 m, 0.1 m, 0.2 m, 0.3 m, 0.4 m, and 0.5 m. We analyze the oil temperature at two monitoring points $P1$ (high) and $P2$ (low) where the electric field strength distribution is greatly different. As shown in fig. 7, the time-domain changes of the oil temperature at the monitoring points $P1$ and $P2$ in different areas along the Z-axis direction. It can be seen that with the progress of heating time, the overall cargo temperature rises synchronously. In addition, in the same heating process, the temperature distribution at the points in each region along the longitudinal direction shows that the temperature is higher in the region closer to the upper surface of the cargo oil. On the contrary, the temperature is lower as it is closer to the bottom of the tanker. As shown in the fig. 7, when the cargo oil is heated to 1200 seconds, the temperature at the $P1$ and $P2$ points has a large difference in the Z = 0.02 m plane area, which is specifically shown in the following: the average temperature rise rate of the point $P1$ area is 0.28 K per minute, which is about 1.25 times that of the point $P2$. Furthermore, because of the uneven electric field strength in the cabin, there is a certain difference in oil temperature in the upper and lower tank areas. The temperature at the same point $P1$ differs by 2.3 K in two areas. It can be seen that the uneven distribution of the electric field strength in the cabin results in regional differences in oil temperature under the upper and lower tanks, which is specifically reflected by a temperature difference of 2.3 K at the same $P1$ point in the area. At the same time, due to the difference in the electric field intensity distribution in the same plane area, there is also a regional difference in oil temperature. Among them, the oil temperature difference between $P1$ and $P2$ is 1.2 K in the Z = 0.5 m plane, and in the Z = 0.02 m plane differs by 1.5 K. The reason is that microwave will have load loss in the medium [17]. When the microwave penetrate to the same depth, the cargo temperature rises relatively quickly in the area with a large electric field intensity distribution.

Figure 8 shows the distribution of the cargo oil temperature field and temperature gradient at the middle section of $X = 0.22$ m. Comparing the electric field intensity distribution cloud diagram, it can be seen that the oil temperature field and the electric field distribution are basically consistent. Along the Z-axis, the difference in the temperature rise of cargo oil in different areas is mainly related to the distribution of the electric field in the cabin, which is reflected in the faster the temperature of the cargo oil, the greater the ability of the medium to absorb microwave energy.

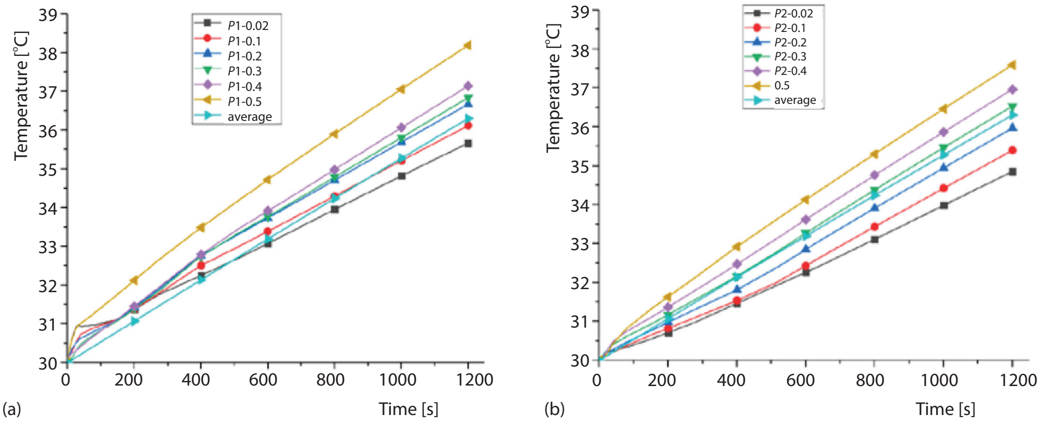
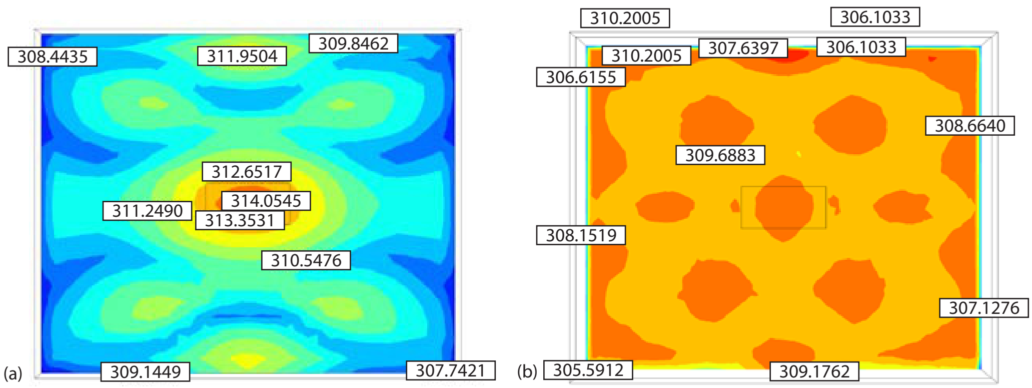


Figure 7. Time-domain changes of oil temperature at different monitoring points; *P*1 (a) and *P*2 (b) in the longitudinal direction



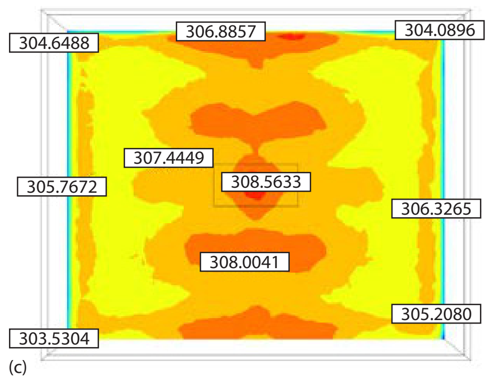


Figure 8. Cloud diagrams of oil temperature gradient distribution in different planes; (a) $Z = 0.54$ m, (b) $Z = 0.28$ m, and (c) $Z = 0.02$ m

According to the analysis of the cargo oil temperature field, the uneven distribution of the microwave field in the oil tank will cause regional differences in the distribution of the cargo oil temperature field in the entire oil tank. From the perspective of heat transfer, we can analyze that during the microwave heating process, the oil molecules move violently and begin to rapidly spread to other areas. Macroscopically, the hot oil, in the upper layer area, transfers energy to the lower oil temperature area through heat conduction. At this time, the heat conduction effect is the strongest. The cargo oil temperature distribution in the middle layer is relatively uniform, and the temperature difference between adjacent regions is small. At this time, the natural-convection intensity is weak and there is no obvious flow phenomenon. The microwave energy absorbed by the cargo oil at the bottom of the tank is relatively small, and its heating is relatively slow. The temperature difference of the cargo oil in a local area causes the density of the oil to change. It is driven by the buoyant force to cause the surrounding hot oil to flow upwards, and to conduct natural-convection with the cargo oil above for heat transfer. Under the combined effects of natural-convection and heat conduction, the overall temperature field distribution of cargo oil in the tank is more balanced.

Conclusions

In this paper, by establishing a 3-D scale model of microwave heating of cargo oil, the distribution and variation characteristics of the microwave field and temperature field of cargo oil under static environment are analyzed, and the following main conclusions are obtained.

- Firstly, the finite element method is used to simulate the temperature field distribution during cargo oil heating, and the accuracy of the numerical method is verified with experimental data.
- Secondly, the numerical simulation results show the changing characteristics of the temperature field during the microwave heating process. It is obtained that the microwave heating of cargo oil under static conditions is conducted by heat conduction and natural-convection.
- Finally, It can be obtained that the microwave energy absorbed by the cargo oil along the direction of gravity is gradually lost under the action of the microwave field. During the heating process, the temperature rise rate of the cargo oil decreases as the ability of the medium to absorb microwaves decreases.
- Generally speaking, the cargo oil temperature field is evenly distributed during the heating process, which shows that the method of microwave heating for oil tanker cargo oil is feasible.

The aforementioned research can provide guidance for exploring the feasibility and safety of oil tanker cargo oil steam and microwave combined heating in practical application from the perspective of microwave heating.

Acknowledgment

The authors would like to express great thanks to School of Port and Transportation Engineering, Zhejiang Ocean University for financial support.

This work was financially supported by Provincial colleges and Universities Scientific Research Business Expense Project in Zhejiang Province (2019J00029), Basic Public Welfare Research Project in Zhejiang Province(Y18E090022), General Research Project of Zhejiang Provincial Department of Education (Y201942524) and University Students Science and Technology Innovation Activity Plan Project in Zhejiang Province (2019R411030).

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Paper submitted: December 26, 2019
Paper revised: January 30, 2020
Paper accepted: February 15, 2020