The influence of compound heating power distribution on heat transfer

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Abstract. With the continuous deepening of oil and gas resource development, the number of large cargo tankers is increasing rapidly, and the tankers need to heat and keep the cargo oil in the tanks during navigation. However, the traditional steam coil heating method has many problems, such as low thermal efficiency and large total fuel consumption, which will cause energy waste and increasing oil tanker transportation costs. Microwave heating technology has the characteristics of fast, uniform and efficient heating, and is widely used in petroleum extraction and viscosity reduction of heavy oil. This paper proposes a new heating method of steam-microwave composite heating to heat the cargo in the tanker cabin. Taking a VLCC side cabin as a prototype, a three-dimensional numerical scale model is established through COMSOL software to study the influence of thermal efficiency under different power distribution between steam and microwave. The research results show that when the total power is constant, the smaller the proportion of microwave power, the more beneficial it is to improve the heat transfer efficiency in oil heating. This research has important guiding significance for improving oil heating efficiency and saving energy consumption.

1. Introduction
In the process of oil tanker transportation at sea, some waxy crude oils with higher viscosity usually have higher freezing points. In order to ensure safety during the voyage, it is necessary to heat the cargo oil in the oil tank to prevent it from solidifying or deteriorating, which will increases transportation costs [1]. At this stage, the main heating method of oil tanks in oil tankers is steam coil heating, and this method has low heating efficiency and high energy consumption. In addition, considering the influence of the tank structure, the coil is generally set at the bottom of the mailbox. When the average temperature of the cargo oil meets the requirements, the steam coil heating has problems such as low heat utilization and high energy consumption; in addition, the steam heating coil is often limited by the oil tank structure and is arranged at the bottom of the oil tank. When the average temperature of the oil reaches the condition, there will be a phenomenon of local overheating. Practice has shown that this heating method takes too long to heat up, wastes resources and increases costs.

Compared with steam coil heating, microwave heating technology has the characteristics of good uniformity, fast speed and easy control. It is widely used in the fields of viscosity reduction of heavy oil [2]. In 1956, Bitchey the use of microwave technology in the exploration of crude oil, the world's first application for a patent [3]. Edward. T. Wall obtained the economical and efficient results of microwave
treatment of heavy oil through experiments [4]. In recent years, a large number of domestic researches have been conducted on the application of microwave technology to the viscosity reduction of crude oil. Ma Baoqi applies microwave technology to the viscosity reduction of waxy heavy oil, and the effect of crude oil treatment is related to the power of microwave [5]; Wang Ying Through a large number of experiments, different microwave power treatments were performed on heavy oil, and they concluded that there would be local overheating inside the heavy oil[6-8]; Song Tianzhu obtained the theoretical value of microwave absorption power under different conditions through physical experiments, but did not consider the scale has an impact on the results, so the experimental results have certain errors [9].

Based on the previous studies, this article uses microwave technology to appropriately modify the traditional heating method based on the heating of cargo oil steam coils, and uses microwave heating as the auxiliary steam coil as the main composite heating form, and explores the effect of microwave power towards heat transfer efficiency.

2. Construction of mathematical and numerical models

2.1. Construction of mathematical model
Cargo oil absorbs microwave energy to increase its internal energy and raise its temperature. The microwave field can be solved by Helmholtz equation, its expression is as follows:

\[ \nabla \times \mu^{-1} (\nabla \times E) = k_0^2 \left( \varepsilon_r - \frac{i\sigma}{\omega \varepsilon_0} \right) E \]  

(1)

Where: \( \mu \) is the permeability of the medium, \( E \) is the intensity of the electromagnetic field, \( \varepsilon_r \) is the relative permittivity of the medium, \( \varepsilon_0 \) is the vacuum permittivity of the medium, \( k_0 \) is the free space wave number, \( \omega \) is the angular frequency, and \( \sigma \) is the conductivity.

In the compound heating process, the mass equation, momentum conservation equation and energy conservation equation should also be satisfied.

Energy equation:

\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = \frac{1}{2} \omega \varepsilon_0 \varepsilon'' |E|^2 \]  

(2)

\[ q = -k\Delta T \]  

(3)

Quality equation:

\[ \frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho u) \]  

(4)

Navier-Stokes momentum conservation equation:

\[ \rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u - \rho g - F = \nabla \cdot [-\rho I + \mu_l (\nabla u + (\nabla u)^T)] \]  

(5)

In the formula, \( \rho \) is the fluid density, \( C_p \) is the constant pressure heat capacity, \( k \) is the thermal conductivity, \( \varepsilon'' \) is the relative dielectric loss, \( u \) is the velocity tensor, \( P \) is the fluid pressure, \( F \) is the fluid domain stress tensor, and \( I \) is the unit Tensor.

2.2. Construction of the numerical model

In order to simplify the research, the following basic assumptions are made for the numerical model:

(1) It is assumed that the heating environment is in a static water environment;
(2) Ignore the changes in the physical and chemical parameters of the oil caused by heating;
(3) Ignore the influence of phase change during heating;

This paper takes a certain VLCC as the research object. According to similar principles, the oil tank of 22m in length, 20m in width and 30m in height is simplified to a model cabin of 0.55m in length, 0.5m in width and 0.75m in height according to the ratio of 1:40. And the Carrying rate is 80%, as shown in Figure 1.
2.3. Parameter setting
In order to ensure consistency with the actual heating process, considering that the change of viscosity will trigger the scaling effect, according to the Graschev number Gr [10], a certain type of lubricant with similar viscosity changes is selected as the numerical test oil, as shown in Table 1. It is the physical parameter of a certain type of lubricating oil at 20℃.

| temperature /℃ | density /kg.m⁻³ | thermal conductivity /W.m⁻¹.k⁻¹ | dynamic viscosity /pa.s |
|----------------|-----------------|-------------------------------|------------------------|
| 20             | 887.45          | 0.147                         | 0.78                   |

In order to explore the influence of power distribution on heat transfer efficiency, the total power is set to 300W, the heating time is 15min, and the power ratio is 1:9, 1:19, and 1:29.

| Case  | Power ratio | Microwave input power /W | Heating coil power /W | heating time | Carrying rate |
|-------|-------------|--------------------------|-----------------------|--------------|---------------|
| Case 1| 1:9         | 30                       | 270                   |              |               |
| Case 2| 1:19        | 15                       | 285                   | 15min        | 80%           |
| Case 3| 1:29        | 10                       | 290                   |              |               |

3. Results and analysis

3.1. Analysis of the influence of power ratio on heat transfer process
As shown in Figure 2, the temperature field and velocity field cloud diagram of the cross section of the model cabin at X=0.24 when the heating time is 300s. Comparing the cloud map of the temperature field, the heat transfer method is mainly through natural convection, and the heating rate in the oil tank is higher. It can be seen from the velocity field cloud diagram of Scheme 3 that the maximum flow velocity in the central area of the oil tank reaches 0.0114m/s; while the maximum velocity of the central area in the Scheme 1 tank reaches 0.0106m/s. Comparing the velocity field cloud diagram, it can be seen that when the heated oil flows to the upper layer, it couples with the oil heated by the microwave on the upper layer, flows to the oil tank bulkhead, and flows downward along the bulkhead, creating a vortex.
between the bulkhead and the central area. Spin. Scheme 1 has a higher microwave power and higher local temperature, which hinders convective heat transfer; while scheme 3 has lower microwave power, less microwave energy obtained in the upper layer, and lower local oil temperature, resulting in a density difference with the oil around the coil. The oil flows upward to the upper layer, and then flows down the bulkhead, creating a smaller vortex.

**Figure 2.** Cloud diagram of temperature field and velocity field at $t=300s$
Figure 3. Cloud diagram of temperature field and velocity field at t=900s

As shown in Figure 3, the temperature field and velocity field cloud diagram of the cross-section of the model cabin at X=0.24 when the heating time is 900s. It can be seen from the temperature field cloud diagram that the temperature in the upper zone is relatively uniform as a whole. The temperature above the coil is the highest, and the temperature at the bottom of the tank is the lowest. Because of natural convection, the low-temperature oil at the top of the tank flows down along the tank wall, which results in the temperature gradient of the upper zone decreases, and the temperature gradually becomes uniform; the bottom of the oil tank and the wall of the oil tank conduct heat, the heat loss increases, and the temperature is lower. At this time, the convective heat transfer between the central area and the tank wall gradually becomes gentle, the vortex gradually decreases, and the temperature in the local area is relatively uniform. Comparing the temperature field cloud diagrams of the three schemes, it can be seen from scheme 1 that local heating unevenness occurs in the upper area, which is not conducive to heat transfer. However, in Scheme 3, the microwave power is small, the microwave field is weak, and the upper layer heats up slowly, which promotes temperature uniformity.

3.2. Energy efficient utilization

The effective energy utilization rate [11] is used as an evaluation index to reflect the heat transfer efficiency of oil products. The formula is as follows:

$$\eta = \frac{Q_e}{Q_t}$$  \hspace{1cm} (6)

In the formula: $\eta$ is the effective energy utilization rate, $Q_e$ is the absorbed heat energy, and $Q_t$ is the total heat energy.

By sorting out the results, a graph of the effective energy utilization rate versus time is obtained as shown in Figure 4.

It can be seen from Figure 4 that the effective energy utilization rate of oil products increases first and then decreases slowly with the increase of time, indicating that the heat transfer efficiency first increases and then decreases. In the early stage of heating, it is mainly the natural convection stage. Due to the large heat flow density of the coil, a large density difference is generated in the oil tank. The natural convection is relatively severe, the internal energy of the oil increases rapidly, and the system does less external work in the early stage. Less loss, so the heat transfer efficiency is rapidly improved; when it is heated to about 300s, the heat flow flows to the upper area and exchanges heat with the outside world, the heat loss increases, and the heat transfer efficiency slows down; in the later heating stage, the oil products in the upper area follow the oil tank wall flows downwards, the heat exchange range with the outside is increased, the heat loss further increases, and the heat transfer efficiency slowly decreases [12].
It can be seen from the figure that the heat transfer efficiency of Scheme 3 is significantly higher than the other two schemes in the middle and late stages of heating. When the microwave power is larger, it will cause the local temperature in the upper zone to be too high, and the internal energy increased per unit time will decrease. In addition, the local temperature will be too high to promote heat exchange with the outside world, increase heat loss, and be unfavorable for heat transfer inside the oil.

![Figure 4. The effective energy utilization rate versus time is obtained](image)

### 4. Conclusion

In this paper, by setting the different power distributions of steam and microwave under static water conditions, analyzing the temperature field and velocity field cloud diagram of the heating process, which obtained the power ratio in the compound heating process has an influence on the heat transfer efficiency. When the microwave power is larger, the effective utilization rate of energy is lower, and it is more unfavorable for heat transfer; when the microwave power is smaller, it is beneficial to heat transfer and improves heat transfer efficiency.

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