Marine Fuel Oil Recovery System with Induction Heating

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This paper describes fundamental characteristics of high frequency induction heating applied for Marine Fuel Oil (MFO) recovery system. The system is analyzed for an induction-heating load, related to operating frequency and input power. Frequency domain characteristics of load equivalent circuit parameters in induction heating are investigated to clarify an effective circuit design of the high frequency power supply. Furthermore, the effectiveness of a high permeability ferrite gum mat on the induction heating unit to improve the heating efficiency of the induction heating system is experimented and elucidated. The practical connection method of working coils is examined. On the basis of these fundamental characteristics, MFO filled in the large-scale oil tank is simulated as the sunken ship is successfully heated up by the high frequency induction method.

1. Introduction

From the standpoint of conservation of the marine environment, it is absolutely necessary to recover the Marine Fuel Oil (MFO) loaded on board the ship as cargo or fuel, when the ship has happened to encounter shipwreck and so on. However, in the deep sea or in the wintertime of Japan Sea where the temperature is low, it is extremely difficult to recover the MFO as it becomes to be of high viscosity as much as it is nearly solid. Also, because of the feature of shipping industry that the transferability of cost-up to freight rates is extremely difficult, the use of lower and more heavy quality of the MFO has been made progress in recent years and as a result it is becoming very difficult to carry out the recovery of the MFO in the event of ship’s wreckage at the coastal area.

As a measure to seek a solution of the above problem, it has been conducted to investigate the heating recovery system of the heavy oil which has been applied the technology of high frequency induction heating. This system is a completely new applied technology which utilizes the technology of high frequency induction heating for the environmental conservation, and therefore, there is no existing basic data necessary for system design upon the construction of the actual system with the application of the induction heating for recovery of the MFO. Taking into consideration the above situation, the authors of this paper have attempted to obtain in many sided ways the fundamental characteristics of the induction heating system of shell board, and aimed at forming the base for the practical use of the system in future through its evaluation and investigation.
2. System outline

Figure 1 shows an overview of high viscosity MFO recovery system at low temperature with high-frequency induction heating (IH). In the proposed system, sunken ship and MFO salvage ship are connected with suction pipe of which end is inserted in tank of sunken ship, and the system consists of IH direct heater which heats MFO directly, mat type IH heater, which heats shell board of sunken ship and indirectly heats inside MFO through heat conduction, and IH re-heater that prevents heavy oil in recovery pipe from cooling and congelation.

In this paper, assuming the case in IH direct heater is not applicable, shell board heating unit, which is applicable under such condition, is investigated. The system is developed to enable effective heating of heavy oil inside the tank in low temperature water by direct heating of shell board with high-frequency induction heating device. Moreover, the system, different from former vapor heating system, needs no such large-scale facilities as new boilers, and can be simplified as a whole, and has advantage that electric source can sufficiently be supplied from auxiliary generator of MFO salvage ship.

3. The problems to be examined in relation to the induction heating load of shell board

In this Chapter the authors summarize the concrete problems to be examined in relation to the IH load of shell board. Taking into consideration the special characters of the IH load of shell board, it is expected that the heating will be conducted mainly under seawater.

The following points are enumerated accordingly;
① It is difficult to obtain the parameters of equivalent circuit of the IH load necessary for designing of the system, since the load is changed at every time when the heating is made.
② The heating is conducted in underwater where the heat is easily deprived.
③ It is necessary to secure the heating area as wide as possible.

The problems enumerated hereinafore will have to be cleared.

As a method to attempt a solution of the above problem ①, an equation is introduced for prediction calculation of the load equivalent circuit parameters and the power source is designed with the permission of a certain aberrant values, making use of the prediction value calculated thereby, since it is extremely difficult to measure the real load equivalent circuit parameters of shell board of the actual sunken ship.

Regarding the above problem ②, the magnetic couplings between the working coils and shell board of the sunken ship are more strengthened so that the more heat can be obtained inside the shell board. Also, the temperature of seawater surrounding the surface being heated is utilized as a new heat source, since the temperature of seawater surrounding the said heated surface rises.

As for the above problem ③, it may be considered that plural number of working coils are provided.

The results of the investigation carried out in relation to the above problems ①～③ are briefly explained hereinafter.

4. The prediction equations of the load parameters of induction heating of shell board.

As mentioned in the item ① of the above Chapter 3, the value of the equivalent circuit parameters necessary for carrying out the design of working coils and the effective induction heating are not given beforehand with relation to the induction heating load of shell board.

As reported in the literature (1) referred to at the end of this paper, the authors carried out the heating experiment with making change of the area of steel board placed under water and the value of air gap, and showed that any effect to the load equivalent circuit parameters had not been observed by the difference of area of steel board and the value of air gap, but such effect had been observed more conspicuously as the action frequency increases.

Now, considering the installation conditions of working coils under the operation of the load of induction heating of shell board, they should be positioned closely to the side steel board of tank as far as possible, since they are surrounded by sea water and the heat is easily deprived by the convection into sea water and so the surface of the heated steel board never becomes overheated.
Therefore, it seems to be fully possible to put the system to practical use by introduction of the prediction equation(2) of the load equivalent circuit parameters with use of the experiment data (Fig.2 and Fig.3) obtained by the area heating test of steel board without air gap that is mentioned in the literature(1) referred to hereinabove.

The results are concluded as follows;

The load inductance is shown in equation (1), and the load resistance is shown in equation (2). Also, Gs included in the equation (1) and equation (2) is the geometrical parameter to be decided depending on n [Tum] as the turn number of working coil, d [m] as the diameter of conductor and Lz [m] as the length of coil side, and it is shown in equation (3).

$$L_0 = 2.81G_Sf_0^{-0.24} \quad \ldots \text{(1)}$$  
$$R_0 = 1.14 \times 10^{-5}G_Sf_0^{-0.74} \quad \ldots \text{(2)}$$  
$$G_S = \frac{(n-1)L_z}{4d} \quad \ldots \text{(3)}$$

The above equations make it possible to predict the electric characteristics of the load.

**5. Increase the heating efficiency at the under water heating condition**

As described in the Chapter 3-②, it is considered that the induction heating system of shell board will be conducted mainly under water because of its characteristics.

The literature⁽¹⁾ referred to at the end of this paper reports that the improvement of the efficiency was successfully attempted by the method that the heat of the heated surface and the like were kept by the insulation materials which made the heating efficiency increase by more than two times. In this paper the authors investigated other method to improve the heating efficiency with making use of the IH load by strengthening the magnetic couplings between working coils and the heated steel plate.

There are also other literatures⁽⁴⁾⁽⁵⁾ which report the phenomenon in which the temperature rose when the highly permeable materials existed on the back side of working coil. The heating recovery system of the MFO is characteristically in need of the working coils which are flexible, and so, ferrite gum mat is used as the materials that are of high permeability and flexible property. The permeable ratio of this material is

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Transcribed from Journal of the JIME Vol.41, No.6 ©2006(Original Japanese)
approximately 10-20 which is 1/100~1/1000 of solid ferrite, and therefore, it is necessary to complete the investigation of the effects of such materials whose permeability is rather small. As the solvable method of the above, the authors attempted to verify the effect by the difference of the temperatures of the heated surface of steel plates between in a case of the ferrite gum mat was used for the working coils and in another case in which it was not used.

Fig.4 shows the characteristics of temperature rise on the surface of steel plate when the heating test was carried out with use of the frequency 30 [kHz] and the input electric power 600 [W]. Moreover, two kinds of materials having different permeability are used (\(\mu = 9.5\) : FD ferrite rubber, \(\mu = 25\) : SS ferrite gum ; trade name in either case) for ferrite gum sheet so that the effect on the heating efficiency could be verified by the difference of the permeability.

As clarified in Fig.4, it can be observed that the highest temperature increases in proportion to the increase of permeability.

Therefore, even the ferrite gum sheet whose permeability is very small in comparison with the solid ferrite core can make the heating efficiency improve, and the effectiveness of the ferrite gum mat was successfully verified.

From figure 4, the higher permeability was used, the higher temperature was obviously obtained.

Therefore, increasing the heating efficiency is achieved even in the case of utilizing the ferrite gum mats that has very small permeability value comparing with solid ferrite. And the effectiveness about the utilizing the ferrite gum mat is validated.

6. The expansion of heating area.

As described in the Clause 3-③, in regard to the induction heating system, it is considered to be an indispensably necessary subject to investigate for the effective operation of the system to secure the large heating area as much as possible.

As regards how to expand the heating area, the following two methods are considered.

① The method in which a plural number of coils to be installed.

② The method in which the heated water surrounding the heated surface to be used as the new heating source.

In this Chapter the above two methods are investigated.
6.1 The investigation of installation of plural number of working coils.

In the first place the authors investigate the method of connection of electric cables in case of the plural number of working coils is installed. In the case of the working coils being closely positioned, the magnetic coupling is generated between each of the working coils, and as a result it will be highly possible that the heating characteristics may change as per the method of connection of electric cables in such manner that the magnetic fluxes generated by coil currents are weakened or reversely strengthened. Therefore, it is considered to be significant to acquire the characteristic change in the case that plural number of working coils is installed and to conduct the investigation about the connection method in which the heating efficiency is excellent. In this Chapter the authors produced 4 pieces of square working coil having each side of 50 [cm] and investigated the effective connection method of working coils by measuring the surface temperature of the actually heated steel plate.

As shown in Fig.5, two kinds of the experiments were carried out, namely, one experiment was conducted under the condition that all the electric currents of working coils flow in the same direction and another one was conducted under the condition that each of electric currents flows completely in the opposite direction each other. The former case, that the electric currents of 4 pieces of working coil flow all in the same directions as shown in Fig.5(a), is named “the all-same-connection”, and the latter case, that each electric current of 4 working coils flows reciprocally in the opposite direction, is named “the all-opposite-connection”.

Since, looking at the direction of electric current at the boundary part of working coils, the electric currents flow in opposite direction at the boundary part in case of the all-same-connection, it is supposed that the magnetic fluxes generated by the working coils adjacent to each of them are weakened each other due to the occurrence of the negative interference. Contrariwise, it is supposed that the magnetic fluxes generated by the working coils adjacent to each of them are strengthened each other with the occurrence of the positive interference, since the electric currents changed their flows all in same directions at the boundary part in case of the all-opposite-connection.

Therefore, comparing the above two cases, it seems that the all-opposite-connection has more effective heating characteristics than the all-same-connection because this connection has the positive interference of magnetic fluxes that they are strengthened each other due to the electric currents generated by the adjacent working coils.

For the experiment, 4 pieces of working coil of 50 [cm] square were prepared and the heating area was made 1 [m] square. Fig.6 shows the temperature sensing points for the experiment.

Nine points were positioned in the direction of the boundary line of No.1 coil and No.2 coil, and 12 points were positioned in the direction of diagonal line of No.1 coil respectively with the space of 70 [mm]. Fig.7 shows the temperature distribution in the direction of diagonal line of No.1 coil.

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Nine points were positioned in the direction of the boundary line of No.1 coil and No.2 coil, and 12 points were positioned in the direction of diagonal line of No.1 coil respectively with the space of 70 [mm]. Fig.7 shows the temperature distribution in the direction of diagonal line of No.1 coil.

Fig.7 clearly shows that the all-opposite-direction apparently brought the higher temperature under the condition that the equal electric power was input. Also, Fig.8 shows there was no significant difference in the temperature distribution. Therefore, as predicted at the beginning, it can be said to be more effective and desirable to apply the all-opposite-connection which generates the higher temperature, if the working coils are divisionally installed.

6.2 The water proof of the circumference of the heated area.

In the matter of the IH load of shell board, the heated steel plate makes the seawater surrounding it heated and then the substantial portion of quantity of heat is lost by the convection of seawater, and therefore, it is anticipated that the efficiency will be improved if the convection could be prevented by some method. Here, the authors complete the report about the effects which were verified by the model heating test of steel plate with covering the working coils by the larger sheet.

In this experiment the working coils of each 30 [cm] square were installed on the model steel plate of 70 [cm] square which was covered by gum sheet, and the heating was conducted under the condition that all of the model steel plate, working coils and gum sheet were completely placed under water. The input of the electric power was 3.5 [kW], the frequency was 15 [kHz], the heating time was 2 hours and the sensing points were arranged lattice-wise in total 36ch with a space of 10 [cm] on the heated surface so that the measurement of temperature distribution could be made possible.

The results of the experiment are shown hereinafter. The comparison was made between the cover of 40 [cm] square which was the almost same size as the working coil, and the cover of 70 [cm] square which fully covered the whole of steel plate.
Fig. 9 shows the temperature distribution of the heated area after the termination of heating (2 hours later) in case of the cover sheet of 40 [cm] square. Also, Fig. 10 shows the temperature distribution of the heated area upon the termination of heating in case of the cover sheet of 70 [cm] square.

Comparing two Figures, it is recognized that the area at which the temperature has risen (the white part in the Figure) apparently expanded larger in the case in which the area was covered by larger sheet, and therefore, it is considered that the result has proven that the method was effective.

7. The heating experiment of large sized tank.

From the experiment result described in the Chapter 5, the improvement of the heating effect has been observed with covering the working coils by ferrite gum mat. On the basis of this result the experiment has been conducted as to if the method could be applied to the heating of the MFO with actually making the mechanism larger. Ferrite gum mat used in the experiment was FD. In this experiment the authors produced the tank of 1.5 [m] square (Fig.11) in which 3.3 [kℓ] of C heavy oil was filled, and they also produced 4 sets of working coil of 50 [cm] square (Fig.12), and carried out the experiment by placing them side by side and making the heating area 1 [m] square. The material of tank was the steel SS41 that was a ordinary construction steel member, the thickness of which was 12 [mm] at the heat-up side and was 6 [mm] at other side. The input electric power was 13 [kW] and the heating time was 10 [h].

Also, Fig.13 shows the graph of temperature rise at the point where the heavy oil was most heated at other part than the backside surface of the heated part during the side surface being heated.

Fig.14 shows the values of the thermal efficiency of tank calculated along the time series. Moreover, the thermal efficiency was the whole efficiency that included the cooling efficiency of cooling by seawater. Although it should be noted that the correct thermal efficiency to be what is calculated only about the tank actually used, it seems that the above data may be useful as one of the data upon the prediction of the system characteristics.

The thermal efficiency is simply calculated by the
ratio of the given heat of the MFO to the input electric power.

The given heat of the MFO is calculated with the following fundamental equation of calorie given to the object;

\[ Q = mC\Delta T \quad \ldots(4) \]

In the above equation, \( Q \) : Calorie [J], \( m \) : Mass [kg] and \( \Delta T \) : The difference of temperature [K].

The weight of the MFO is considered to actually change depending on the temperature. However, since the references of these data could not be obtained, the weight of the MFO occupying at each divided space was calculated by the method that the density was multiplied by the volume. Further, the efficiency calculated here is the roughly estimated value in a strict sense, as the calculation is made on the assumption that the temperature is constant in the divided block.

The isopiestic specific heat of MFO may be presumed by the following equation\(^{(*)}\);

\[ C_1 = \frac{1.6848 + 0.00339t}{d} \quad \ldots(5) \]

In this equation, \( C_1 \) : Isopiestic specific heat of liquid heavy oil\((Cp)\) [J/gK], \( t \) : Temperature in Centigrade [℃], and \( d \) : Density [g/cm³] at 16.6 [℃].

Since at the time of the experiment the MFO was placed under the condition that it was opened against the atmosphere through air escape hole for release of the gas, it was recognized that the condition was under the same constant pressure (atmospheric pressure) as the above equation premised, and therefore, the calculation was made on the condition that the specific heat might be calculated by use of the above equation.

Due to the characteristics of temperature rise described in Fig.13, the temperature of the MFO sharply rose within 30 minutes after the heating had started. Judging from the above, it will be possible to locally raise temperature within short time. Also, due to the heat efficiency characteristics against the heating time as shown in Fig.14, the value of thermal efficiency is about 10 [%] at the stage of 30 minutes after the heating has started.

Therefore, it seems that the recovery of the MFO with comparatively less electric power will become possible by sucking the MFO successively from the part which temperature has locally risen, making use of these characteristics as described hereinbefore.
8. Conclusion.

In this paper the authors described the frequency characteristics of the load equivalent circuit parameters of the induction heating system of shell board, and investigated the practical method for improving the heating efficiency of working coils to be applied to this system, and further, they investigated the connection method of working coils in order to expand the heating area. Also, they verified the possibility that the heat could be efficiently used as much as possible, if the convection of hot water of circumference of the heated area would be controlled when the tank heating is actually conducted. Finally, the authors actually conducted the heating experiments of large sized tank of heavy oil and verified thereby the effectiveness of the improvement method of the heating efficiency and the construction method of working coils under water which have been so far investigated.

References
5) Nakagawa, the journal of JEHC, No144, 2005-11, pp17~22 (in Japanese)
6) Awai, Yokozawa and hanajima, Fuel Oil for Land and Marine middle or Large Scale Diesel Engine, 1994-3, pp87~88 (in Japanese)