Investigation of High-Frequency Induction-Heating System for Recovery of Heavy Fuel Oil from Sunken Ship

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This paper investigates an induction-heating (IH) system applied for heavy fuel oil (HFO) recovery system in the tank of sunken ship. For design of the system, the characteristics of load equivalent circuit parameters in case of varying the steel board square meters and gaps between steel board and working coil unit are studied. On the basis of these characteristics, the experiment of heating up heavy fuel oil in the tank under the low temperature has been tested. Through the experiment, the availability of the proposed system was verified. Finally, the design procedure of large-scale working coil unit for induction heating and operation frequency is proposed.

1. Introduction

Japan surrounded by sea from every direction, in which cargo transportation mainly depends on shipping, has been suffered from shipwrecks and consequential secondary disasters in territorial waters. At present countermeasures like improvement of ability of ships’ crew and so on are under investigation at international and domestic levels such as IMO, etc., but shipwrecks do still not cease to occur. For the time being, heavy fuel oil (HFO) flowed out on the surface of sea is firstly protected from spreading with oil fences, and then recovered with oil absorbing mats, or HFO reached to seashore is cleaned with primitive method of human wave tactics. Although these methods need tremendous manpower, recovery is possible. However, if the ship is sunken into deep sea with fuel oil and cargo HFO in it, or if the ship is not sunken but grounded at low temperature region like winter Japan Sea, it is not possible to recover HFO unless viscosity of such HFO be decreased to a degree enabling oil to flow, as HFO becomes very much viscous like solid in tanks at low temperature. At present there are two methods, one is to inject water vapor from boiler into tanks for heating, and another is to dilute heavy oil with light oil like kerosene. However, in case of the ship sunken into deep sea, these methods are not capable of effectively lowering viscosity of oil in tanks, and HFO is left as it is. Therefore, in this thesis, in order to be able to recover HFO in tanks of ship even if sunken in deep sea, a technology to heat and to lower viscosity of HFO in tanks through conductive heat, by heating tank side steel plates of sunken ship, with high-frequency induction-heating is studied.

In this paper, verification is carried out experimentally using small model tank (Fig.1) in order to investigate effectiveness and possibility of heating HFO in tank with induction heating under low temperature. Firstly fundamental experiment to get design data of working coil for heating model tank were carried out, and secondly experiment of heating model tank with induction heating under low temperature was carried out using working coil designed on the basis of first experiment. At this experiment, firstly, the model tank with HFO inside was cooled by ice water at the temperature of 10 [deg. Cels.] or lower and then the model tank was heated and verified effectiveness of the system. Further, effectiveness of thermal insulator was evaluated comparing cases when thermal insulator was used and not used.

Translated from Journal of the JIME Vol.38, No.9 C 2003 (Original Japanese)
2. High viscosity HFO recovery system at low temperature with induction heating

Figure 2 shows an overview of high viscosity HFO recovery system at low temperature with high-frequency induction heating (IH). In the proposed system, sunken ship and HFO 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 HFO directly, mat type IH heater, which heats shell board of sunken ship and indirectly heats inside HFO 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 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 HFO salvage ship.

3. Theory of high-frequency induction heating

In high-frequency induction heating, as shown in Fig.3, high-frequency alternate current (AC) that is produced by high-frequency inverter is supplied to working coil, and high-frequency alternate magnetic field is produced around the working coil. Eddy current is induced in a conductor (in this case shell board, hereinafter steel plate) placed in that magnetic field. Joule-loss is generated due to eddy current and inside resistance of steel plate, and steel plate is heated without working coil heat generation. This phenomenon is strictly and theoretically analyzed through the Maxwell’s equations of electromagnetism.

They are expressed as equations (1)~(4) (equations (1)~(11) in attached supplement), and from them, differential equation expressing magnetic field inside steel plate statically placed in magnetic field that changes sinusoidal wave in time scale, becomes equation (5). Equation (5) is equal to Helmholtz’s differential equation in periodical heat conduction, and in practice this is numerically solved considering shape of body. In this paper, for the purpose of simplicity, boundary surface of steel plate is taken as x-y plane, direction of depth as z axis, and it is assumed that sinusoidal alternate magnetic field $H_0 e^{i\omega t}$ is imposed to z axis direction, and that boundary value of steel plate boundary plane is $H_0 (z_0)$ and steel plate is homogeneous and isotropic (i.e. conductivity $\sigma$ and permeability $\mu$ are constant), and then the equation is solved to be equation (6). Differentiating (in practice calculating vector rotation) solution of this equation, proportional equation (7) is introduced with eddy current in steel plate. From this equation, it is known that the higher is the frequency, the stronger the eddy current is, and as a result the more loss in Joule’s loss i.e. the easier heating is.

Further, if magnetic flux generated by eddy current thus calculated and that generated by electric current in working coil are added as vectors, a chain flux comes out, and load inductance $L_0$ of working coil can be calculated with equation (8). However, except for the case of eddy current induction of small electric power such as eddy current testing etc., eddy current in magnetic substance like steel plate is known 2~3 times as large as that expressed in equation (7) (eddy current anomaly). The reason of this anomaly is that when a magnetic substance is magnetized with external magnetic field lining up arrangement of atomic spin, there exists a part where atomic spin is already lined up and a part where atomic spin is being
lined up (transition region between two parts is called as magnetic domain wall or Bloch wall), and much more eddy current flows than calculated with equation (7) to prevent magnetic domain wall from shifting. Therefore, it is not possible to calculate accurately heat quantity generated in steel plate using equation (7) only, and moreover magnetic flux generated by eddy current to outside of steel plate is underestimated. Accordingly, magnetic flux chained with that of working coil can be different from actual one, and there is a high possibility of causing difference between calculated value with this theory and actually observed one when induction heating load is expressed with equivalent circuit for the purpose of circuit design. In order to get such actual value, concrete data of atomic spin arrangement around magnetic domain wall are necessary, but observation of magnetic wall is possible on surface of material only, and such observation is changed if steel plate is changed. Further, strength of eddy current depends on arrangements of atomic spins on both sides of magnetic wall, static magnetic energies of materials, as well as defects of lattice, locations of carbon atoms of melted metals, etc., and it is very difficult to strictly and theoretically analyze and calculate eddy current, taking all parameters, even nowadays in that computer and numerical calculation technologies are much developed.

From the above considerations, it is thought that calculation of equivalent circuit parameter of induction heating load should be based on actual heating experiment. From this viewpoint, experiments for getting characteristics of load equivalent circuit parameter, changing conditions of heating, in relation to various conditions for applying induction heating technology to shell board heating of sunken ship, are described in next Chapter.

4. Experiment of model steel plate heating

In IH, high-frequency inverter is necessary as a power supply. In order to operate effective heating, the inverter should be operated at or near resonant point with resonant circuit connecting working coil and condenser. Therefore, load inductance $L_o$ and operating frequency are necessary beforehand to decide capacity of condenser. In development of shell board heating system, it is necessary to get beforehand characteristic variation of load equivalent circuit parameter according to change of heating condition under actual operation of system. As to change of heating condition, following factors need especially be investigated. A) change of load impedance depending on ratio of shell board square versus heated area of working coil unit, and B) effect of air gap between working coil unit and shell board. In this experiment, change of load equivalent circuit parameter was investigated in relation to change of heating condition.

As described in Chapter 3, accurate measurement of load equivalent circuit should be made when the system is actually activated with electric power. Circuit for experiment is shown in Fig.4. Volt-slider adjusting electric power supplied to inverter through transformer for harmonic-wave protection to 3-phase AC, 3-phase digital power meter were connected between transformer and inverter, and after them hard switching inverter was connected. To output side of inverter, resonant capacitor, working coil and single-phase power meter were connected and constituting the circuit. Electrical equivalent circuit of IH load is a $L_o$ (load inductance) and $R_o$ (load resistance) series connecting circuit. Through the experiment of this chapter, input power ($P_{in}\ [kW]$) was kept 2 [kW] constantly which was measured by 3-phase power meter, adjusting input voltage with volt slider. Frequency output ($f_o \ [kHz]$), output current ($I_o \ [A]$; RMS value), which flows through the working coil, and voltage ($V_o \ [V]$; RMS value), which across the working coil, were measured with single phase power meter, and values of $L_o$ and $R_o$ (equation (9): $R_o$ and equation (10): $L_o$) induced from sine wave AC theory were calculated from these data. Capacity of resonant capacitor was calculated in advance with equation (11) from which was calculated the equation of series resonant frequency, using temporary load equivalent circuit parameter introduced from LCR meter under the condition that working coil and steel plate were put in sea water.
4.1 Experiment of steel plate square is changed

Figure 5 shows the waterproof working coil used in this experiment and partially expanded drawing (b). As experiment was carried out in seawater, 2.5 [mm] diameters high-frequency Litz-Wire was instead in silicon tube of 6 [mm] outside diameter and 4 [mm] inside diameter for the waterproof (Fig.5 (b)). This waterproof Litz-Wire was wound to square of 310 [mm] side, and formed working coil as shown in Fig.5 (a). Steel plate had square shape with a side of each 400, 800 and 1200 [mm] and thickness of 3.2 [mm] and was SS41steel. The pool as shown in Fig.6 had square shape with a side of 1400 [mm] and could contain 200 liters of seawater. Lo-fo graph is shown in Fig.7 and Ro-fo graph is shown in Fig.8 with area of steel plate as a parameter when air gap was zero.
From these two graphs, it is seen that the higher the frequency is the smaller the $L_o$ and the larger the $R_o$. The reason of this is considered to be that eddy current induced in steel plate increases if frequency goes up as shown in equation (7), and therefore working coil current decreases as alternate magnetic field under same output power and $R_o$ calculated from equation (9) increases, and $L_o$ decreases as it is directly related to magnetic energy. Accordingly, in actual design of system, even if $L_o$ of working coil actually fitted to hull of sunken ship is not known, capacity of resonant capacitor can be designed in accordance with equation (11) from $L_o$ and $f_0$ using load equivalent circuit parameter decided in advance on land.

![Seawater Pool](image1)

**Fig.6 Seawater Pool**

**Fig.7 Lo-fo Graph as the Parameter of the Square of Steel Plate**
4.2 Experiment of air gap is changed

Figure 9 shows $L_0$-fo graph, and Fig.10 shows $R_0$-fo graph with air gap as a parameter for experiment using 800mm square steel plate. If air gap is the same, similarly as in case of Section 4.2, the higher the frequency is, the smaller the load inductance is, and the larger the load resistance is. Further if frequency is the same, the larger the air gap is, the larger the $L_0$ is, and vice versa the larger the air gap is the smaller $R_0$ is. And it is found that these characteristics are more strongly influenced from air gap at high frequency zone.

From the above experiments to get the characteristics of load equivalent circuit parameter when air gap is changed, output frequency should be low in order to reduce influence of air gap on load equivalent circuit parameter and further to reduce influence on stable operation of inverter. From the results of this experiment, it was seen that strong influence of air gap appears at output frequency zone of 20 [kHz] or more, and therefore it is considered desirable to operate shell board heating system at less than 20 [kHz]. However, if output frequency is less than 10 [kHz], noise and capacity of resonant capacitor increase and there is a report that effect of electro-magnetic induction is reduced, and therefore this frequency zone should be avoided. Accordingly, desirable output frequency zone is in between 10~20 [kHz]. In low temperature condition model experiment described in next chapter, 15 [kHz] were selected so that capacity of resonant capacitor is not too big and frequency is as low as possible.
5. **Experiment of low temperature condition**

In this chapter, to verify effectiveness of HFO recovery system with proposed shell board IH heater, heating experiment under low temperature condition using small model tank was carried out and results are described. Fig.11 shows dimension of tank, and Fig.12 shows arrangement of thermostats located in the direction of tank depth to measure temperature rise of HFO. As shown in Fig.12, HFO was filled up to 270 [mm] from upper edge of 700 [mm] deep tank (430 [mm] from bottom of tank), and volume of HFO was 87.1 liters. This HFO tank was put inside one size bigger cooling tank (Fig.1) that is cooled to 0 [deg. Cels.] with ice water. During experiment, ice was added and melted water was drawn through bottom plug, to prevent water temperature from rising. Input electric power was set to 2 [kW] and heating time was set to 5 hours to have the same condition as induction heating experiment of chapter4.
Working coil was extended to 330mm square in order to have nearly the same size as model steel plate induction heating and as large heating area as possible. Due to this extension change of leading length was 60 [cm] compared with 15.4 [m] of model steel plate heating experiment (to 16.0 [ml]), and it was assumed that load equivalent circuit parameter that was obtained at experiment of chapter4 could be used, also it was presumed that $L_0$ was approximately $L_0=70 \ [\mu H]$ and $R_0$ approximately $R_0=4 \ [\Omega]$.  

5.1 Experiment when insulation is not used

Characteristics of temperature rise without thermal insulator are shown in Fig.13. In this experiment, only working coil was installed in tank and ice water was in direct contact with tank. It was found from Fig.13 that HFO inside tank could be heated even under low temperature without insulation by electric power as low as 2 [kW]. If more electric power is put, more temperature rise of HFO is expected. Accordingly, it can be said that HFO recovery system with shell board induction heating proposed in this paper is effective even under low temperature condition.

5.2 Experiment when insulation is used

Characteristics of temperature rise with thermal insulator are shown in Fig.14. thermal insulator used in this experiment was of 13 [mm] thick foamed rubber insulation K-FLEX IC clad sheet that was pasted to whole surfaces all of tank sidewalls. From Fig.14, maximum temperature measured with thermometer at 40 [mm] high from liquid surface attained to 70 [deg. Cels.] which was 30 [deg. Cels.] higher than that without insulation of 40 [deg. Cels.] at the same position. Further, temperature rise was found at bottom of tank and that is due to effect of insulation. Therefore thermal insulator should be used as far as applicable. Temperature of heated surface ceased to rise at boiling point of water (100 [deg. Cels.]) and remained almost constant during heating. The reason of this phenomenon is considered to be that cold water between tank sidewall and working coil was boiled and replaced with cold water by convection, and that temperature rise stopped. In actual system it is inevitable that water penetrate between shell board and working coil but on the contrary penetrated water may act as material to prevent damage of working coil unit due to excessive heating.
5.3 Comparison of thermal efficiency

Comparison of thermal efficiency and result of calculation are shown in Table 1. Thermal efficiency that was calculated to be about 6.2 [%] without thermal insulator and was calculated to be 14.4 [%] with thermal insulator, and increase of thermal effectiveness was 2.3 times. Thus, effectiveness of insulation was verified.

<table>
<thead>
<tr>
<th></th>
<th>without Thermal Insulator</th>
<th>with Thermal Insulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of HFO</td>
<td>85.7kg</td>
<td>85.7kg</td>
</tr>
<tr>
<td>Specific heat of HFO</td>
<td>1.83 kJ/kg/K</td>
<td>1.83 kJ/kg/K</td>
</tr>
<tr>
<td>HFO temperature before heating</td>
<td>5 degrees Celsius</td>
<td>5 degrees Celsius</td>
</tr>
<tr>
<td>HFO temperature after heating</td>
<td>20 degrees Celsius</td>
<td>40 degrees Celsius</td>
</tr>
<tr>
<td>Heating time</td>
<td>5 hours</td>
<td>5 hours</td>
</tr>
<tr>
<td>Supplied electric power</td>
<td>10.5kWh (=38MJ)</td>
<td>10.5kWh (=38MJ)</td>
</tr>
<tr>
<td>Supplied heat for HFO</td>
<td>2.4MJ</td>
<td>5.5MJ</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>6.2%</td>
<td>14.4%</td>
</tr>
</tbody>
</table>

5.4 Characteristics of load equivalent circuit parameter during heating time

Time base characteristics of Lo and Ro during tank heating experiment are shown in Fig.15. It is seen that these shows almost the same value against heating time, although initial values are a little different. Average value of Lo through the heating time was Lo=63.5 [µH] and that of Ro was 3.3 [Ω]. These values are very similar to those initially estimated (Lo=70 [µH], Ro=4 [Ω]), and therefore it can be said that design of circuit is possible using load equivalent circuit parameter obtained from model steel plate heating experiment. The fact that load equivalent circuit parameter remains constant over the time during heating, means that trip and error of inverter may scarcely occur due to abrupt change of load and the system has high stability during operation, and that resonant circuit needs no parallel resonant circuit for countermeasure against abrupt change of load, and the system need only series resonant circuit.

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6. Guidance of design applied to actual system

Up to previous chapter, design of working coil, decision of capacity of resonant capacitor and setting of output frequency were described through model steel plate experiment that aimed at heating small HFO tank, and also lastly heating experiment of small model tank was described. Load equivalent circuit parameter in case of small model tank experiment, where circuit was constituted using load equivalent circuit parameter obtained from model steel plate experiment, was almost the same as that in case of model steel plate experiment, and stable operation of inverter in even long period was maintained. However, these parameters obtained here were effective only to working coil for heating small tank, and cannot be used for large scale working coil for actual system. Hereunder guidance of design for large scale working coil is simply summarized.

1) Shape of working coil shall be decided. That is, before making working coil, shape, objective dimension, winding shape, diameter, length and number of winding of leading wire shall be decided in advance. For example, waterproof working coil referred in Chapter 4 had square shape, flat winding and output 2 [kW], and length and number of winding of leading wire can be approximately decided, solving simultaneous equations with length and number of winding as variables, considering shape of winding and 2.5 [mm] diameter Ritz-wire in silicon tube of 6 [mm] (diameter of silicon tube) outside diameter for waterproofing.

2) After deciding fundamental shape of working coil, load equivalent circuit parameter and its characteristic shall be estimated. That is because load inductance value and frequency characteristic shall be known in order to decide capacity of resonant capacitor and to design circuit. As described in Chapter 4, load equivalent circuit parameter does not depend on area of steel plate, but depends on mostly air gap, and therefore, such frequency zone as to have small change of load equivalent circuit parameter shall be selected, from heating experiment of model steel plate with air gap as variable.

If capacity of resonant capacitor is decided from frequency selected according to the above guidance and load inductance, operation of system is possible near resonant point where heating efficiency is good.

7. Conclusion

In this paper, guidance of design of working coil for tank heating was proposed, and in addition to effectiveness of proposed system, safety and stability of system were verified, through fundamental experiment and verifying experiment for HFO recovery system in tanks of sunken ship under low temperature condition. Hereafter, we wish to carry out experiments to heat actual large size HFO tank, to verify effectiveness of design guidance proposed in this paper and also to verify same safety and stability as those of small model tank, even in case of using large-scale electric power.

Finally we wish to express sincere thanks to Dr. M. Kojima assistant professor of Machinery and Equipment Laboratory, Tokyo University of Marine Science and Technology who supplied ice for experiment, and to Mr. T. Takeuchi Development and Sales Department of Fukoku Co. Ltd. who supplied thermal insulator.

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<Supplement>
[Equation]
Maxwell’s electro-magnetic equation in quasi-steady state

\[ \nabla \times E(x, y, z, t) = \frac{\partial B(x, y, z, t)}{\partial t} \] ...(1)

\[ \nabla \times H(x, y, z, t) = i(x, y, z, t) \] ...(2)

\[ i(x, y, z, t) = \sigma E(x, y, z, t) \] ...(3)

\[ B(x, y, z, t) = \mu H(x, y, z, t) \] ...(4)

Where,
E: electric field
B: magnetic flux Density
H: magnetic field
i: current Density
\( \sigma \): conductivity
\( \mu \): permeability

Differential equation expressing magnetic field in conductor

\[ \nabla^2 H(x, y, z, t) = \sigma \mu \frac{\partial H(x, y, z, t)}{\partial t} \]

Assuming sinusoidal magnetic field

\[ \nabla^2 H(x, y, z, t) - j \omega \sigma \mu H(x, y, z, t) = 0 \] ...(5)

One-dimensional solution of equation (5)

\[ H_z(z) = H_0(z_0) e^{-j \frac{\omega \sigma \mu}{2} (z-z_0) + j \omega \sigma \mu \left[ \frac{e^{-j \frac{\omega \sigma \mu}{2} (z-z_0)}}{\sqrt{2 \pi \omega \sigma \mu}} \right]} \] ...(6)

Proportional equation of eddy current density

\[ i \propto \sqrt{\frac{\omega \sigma \mu}{2}} H_z(z) \] ...(7)

Relationship between magnetic flux and inductance

\( \phi(t) = LI(t) \) ...(8)

Derivation of load equivalent circuit parameters from measured value

\[ P_0 = \frac{P_o}{I_0^2} \] ...(9)

\[ L_0 = \sqrt{\frac{V_0^2}{I_0^2 - R_0}} \times 10^6 \] ...(10)

Derivation of resonant condenser capacity

\[ C_s = \frac{1}{(2 \pi f_0)^2 L_0} \] ...(11)

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