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THEORETICAL STUDY ON THE DEPENDENCE OF THE ELECTROMAGNETIC FIELD PENETRATION DEPTH IN SEAWATER, WITH THE SALTS CONCENTRATION

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Abstract: *Whereas the induced of an electrical machine is the element in which electromagnetic field energy is converted into useful mechanical energy, it becomes extremely important to analyze its properties. The issue of the liquid induced is not treated in all its aspects in the literature, therefore in this paper were highlighted aspects that the authors consider to be important for naval propulsion engines, having seawater as induced. Mechanical and electrical behavior of liquids depends very much on their nature, but also on many other factors, such as temperature, pressure, concentration of dissolved substances, etc. In the case of electrical machine with the solid induced (metal), electrical and mechanical properties of the induced remains almost unchanged as long as it is not replaced with another. For electrical machines with liquid induced, electrical and mechanical properties of the induced are dependent on many factors that may change during machine operation. The electrical conductivity, the most important parameter that determines the functioning of the electrical machine, depends strongly on the temperature and other factors. Whether for melted metals, conductivity depends only on temperature, in the case of an electrical machine which uses an electrolyte solution as induced, the whole phenomenology becomes more complex due to the strong dependence of the conductivity with temperature, and the concentration of dissolved substances.*
Keywords*: penetration depth, induced, electrically conductive liquid*

Introduction

The various studies on linear induction machine with induced liquid, highlighted the importance of penetration depth of the electromagnetic field which is electroconducting liquid. Also, in the theory of induction electrical machines it is shown there are the size called quality factor Q, which occurs in the strength and yield relations. [2, 3, 4].
For this reason, we considered necessary to conduct a study on the penetration depth, taking into account the seawater as electroconducting environment. "Penetration depth" is not only a physical quantity related to intrinsic properties of material, but are important in characterizing the environment in terms of its ability to achieve useful effects through interaction with an electromagnetic field [5,6,7].
In the following, the authors will analyze the electromagnetic field penetration in seawater in a general way, without regard to the origin of this field.

The penetration depth of the electromagnetic field in liquid. We will consider an electromagnetic wave with harmonic variation in time that propagate along the axis Oz, in seawater, that is considered to have infinite dimensions. The electric field of the wave is expressed by the relation:

$$\vec{E}(z,t) = \vec{E_0}(z)\exp(j\omega t) \quad (1)$$

Knowing that perpendicular field penetrates the electroconducting liquid with infinite deep, wave equation satisfied by the component $\vec{E}_0(z)$ is:

$$\Delta \vec{E_0} + \omega^2 \varepsilon\mu_0 \vec{E_0} - j\vec{E_0}\sigma\mu_0 = 0 \quad (2)$$

In terms of equation above, they just represent wave timeless equation for dielectric medium:

$$\Delta \vec{E_0} + \omega^2 \varepsilon\mu_0 \vec{E_0} = 0 \quad (3)$$

Provided that the real permittivity ε be replaced by complex $\underline{\varepsilon} = \varepsilon + j\frac{\sigma}{\omega}$

Equation (3) above will have the form:

$$\Delta \vec{E_0} + \omega^2 \underline{\varepsilon}\mu_0 \vec{E_0} = 0 \quad (4)$$

Therefore in the case of electrically conductive liquid as in any dissipative environment, real wave number is replaced by the complex measure:

$$\underline{k}^2 = \omega^2 \underline{\varepsilon}\mu_0 = \omega^2 \varepsilon\mu_0 - j\omega\sigma\mu_0 \quad (5)$$

If notes $\mathrm{Re}(\underline{k}) = k$ and

$\mathrm{Im}(\underline{k}) = s$ then

$\underline{k} = k - js$

Replacing in the previous formula (5), we have:

$$\begin{aligned} k^2 - s^2 &= \omega^2 \varepsilon\mu_0 \\ 2ks &= \sigma\omega\mu_0 \end{aligned} \quad (6)$$

From the equations system above, results:

$$k^2 = \frac{\omega^2 \varepsilon \mu_0}{2}\left(\sqrt{1+(\frac{\sigma}{\varepsilon\omega})^2}+1\right)$$
$$s^2 = \frac{\omega^2 \varepsilon \mu_0}{2}\left(\sqrt{1+(\frac{\sigma}{\varepsilon\omega})^2}-1\right) \quad (7)$$

The solution of the equation for one-dimensional propagation along the Oz axis is:

$$\vec{E}(z,t) = \vec{E}_{max}\exp(j\omega t - j\underline{k}z) = \vec{E}_{max}\exp(-sz)\exp(j\omega t - jkz) \quad (8)$$

From above relation results the exponential decrease in wave amplitude, inside the conductive space, so the penetration depth can be defined as the distance for which amplitude decrease with ***e*** times:

$$\delta = \frac{1}{s} = \sqrt{\frac{2}{\omega^2\varepsilon\mu_0\left(\sqrt{1+(\frac{\sigma}{\varepsilon\omega})^2}-1\right)}} \quad (9)$$

It will be examined how the term $\frac{\sigma}{\varepsilon\omega}$ influences the penetration depth for seawater. We admit a less favorable case for operation of naval magnetohydrodynamic propulsion type for seawater, namely: - At salinity c = 5 g/kg, physical conductivity has a value of $0{,}48\Omega^{-1}m^{-1}$. For the same conditions electric permittivity value is approximately $\varepsilon = 30\varepsilon_0$ [5]. For frequency is selected f = 15kHz, value. In this case, the term $\frac{\sigma}{\varepsilon\omega}$ is:

$$\frac{\sigma}{\varepsilon\omega} = \frac{0{,}48\Omega^{-1}m^{-1}}{30\cdot 8{,}856\cdot 10^{-12}Fm^{-1}\cdot 2\pi\cdot 15000s^{-1}} = 19{,}18\cdot 10^3$$

As in the case of metal conductors, this value is much higher than the unit, which can be neglected, so, can be used classical relationship for the penetration depth:

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu_0}} \quad (10)$$

In the table below, are shown calculated values of penetration depths based on the above relationship for a saturated solution of sodium chloride, at different values of temperature and frequency.

:

Table 1

t^0C	$\sigma(\Omega^{-1}m^{-1})$	$\delta[m]$					
		50Hz	**500Hz**	**1000Hz**	**5000Hz**	**10000Hz**	**15000Hz**
15	**20,15**	**15,75**	**4,88**	**3,52**	**1,57**	**1,10**	**0,904**
16	**20,36**	**15,66**	**4,85**	**3,50**	**1,56**	**1,09**	**0,900**
17	**21,12**	**15,38**	**4,76**	**3,38**	**1,54**	**1,07**	**0,888**
18	**21,62**	**15,20**	**4,71**	**3,34**	**1,52**	**1,06**	**0.877**
19	**22,10**	**15,03**	**4,65**	**3,30**	**1,50**	**1,05**	**0,867**
20	**22,60**	**14,87**	**4,60**	**3,26**	**1,49**	**1,04**	**0,858**
21	**23,10**	**14,71**	**4,56**	**3,14**	**1,47**	**1,03**	**0,849**

Tables 2, 3, 4, 5 and 6 indicate values for penetration depth in sea water at different temperatures and salt concentrations. Penetration depths are in meters. The graphs representing the dependence of the penetration depth by the concentration of salts at different values of temperature and frequency are plotted in figures 1, 2, 3, 4 and 5

Table 2

f = 50Hz	$\delta[m]$			
c [g/l]	**0** ^0C	**10** ^0C	**20** ^0C	**30** ^0C
5	**102,04**	**89,07**	**79,54**	**71,78**
10	**83,04**	**67,20**	**61,30**	**55,02**
15	**60,84**	**52,99**	**47,13**	**42,79**
20	**56,80**	**45,01**	**41,03**	**36,03**
25	**48,10**	**42,02**	**37,42**	**33,97**
30	**42,30**	**36,80**	**33,40**	**29,82**
35	**41,30**	**36,17**	**32,20**	**29,23**

Figure 1

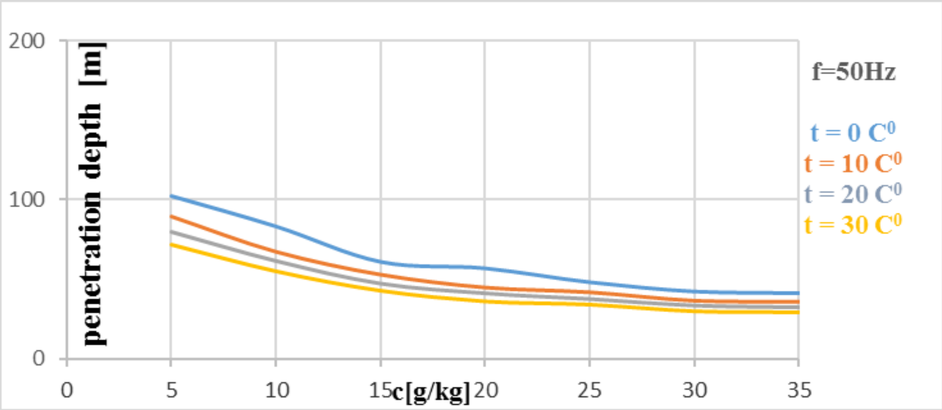


Table 3

f = 1000Hz	$\delta[m]$			
c [g/l]	**0** ^0C	**10** ^0C	**20** ^0C	**30** ^0C
5	**22,9**	**20,06**	**17,79**	**16,06**
10	**17,20**	**15,01**	**13,20**	**11,8**
15	**13,60**	**11,85**	**10,54**	**9,57**
20	**12,90**	**11,40**	**10,31**	**9,02**
25	**10,75**	**9,58**	**8,36**	**7,59**
30	**9,62**	**8,60**	**7,98**	**7,11**
35	**9,23**	**8,09**	**7,20**	**6,53**

Figure 2

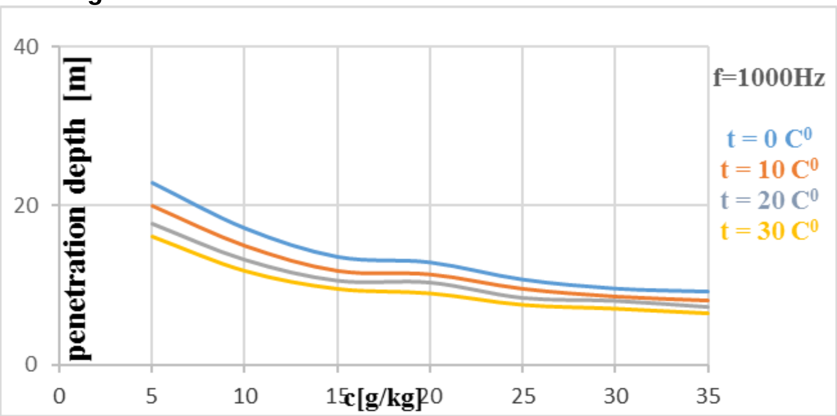


Table 4

f = 5000Hz	$\delta[m]$			
c [g/l]	**0** ^0C	**10** ^0C	**20** ^0C	**30** ^0C
5	**10,20**	**8,90**	**7,95**	**7,18**
10	**8,30**	**6,72**	**6,13**	**5,50**
15	**6,08**	**5,30**	**4,71**	**4,28**
20	**5,68**	**4,50**	**4,10**	**3,97**
25	**4,81**	**4,20**	**3,74**	**3,63**

30	4,23	3,68	3,34	2,98
35	4,13	3,61	3,22	2,92

Figure 3

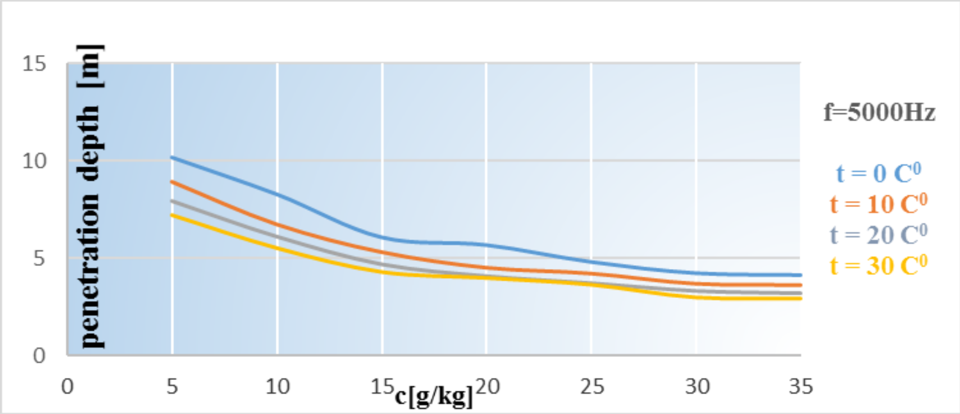


Table 5

f = 10000Hz	$\delta[m]$			
c [g/l]	0 ^0C	10 ^0C	20 ^0C	30 ^0C
5	7,66	6,26	5,62	5,07
10	5,40	4,60	4,15	3,82
15	4,30	3,75	3,33	3,03
20	3,92	3,28	2,88	2,63
25	3,40	2,93	2,64	2,40
30	3,17	2,72	2,51	2,20
35	2,92	2,56	2,27	2,06

Figure 4

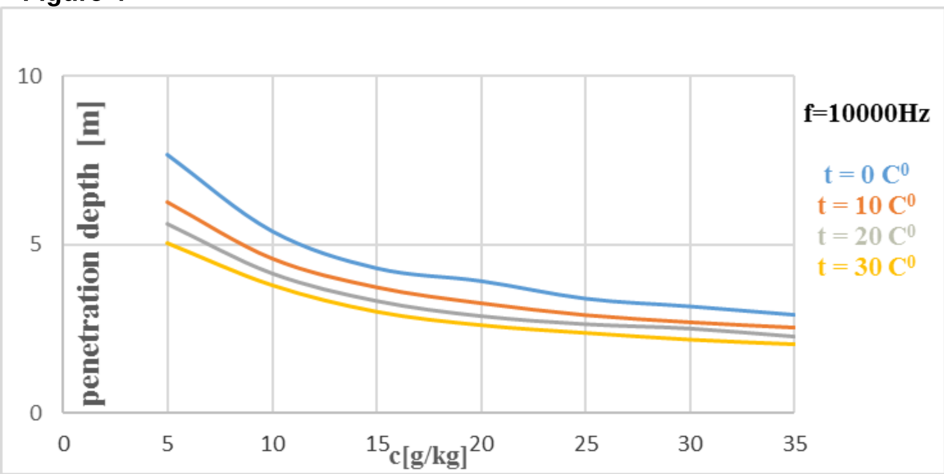
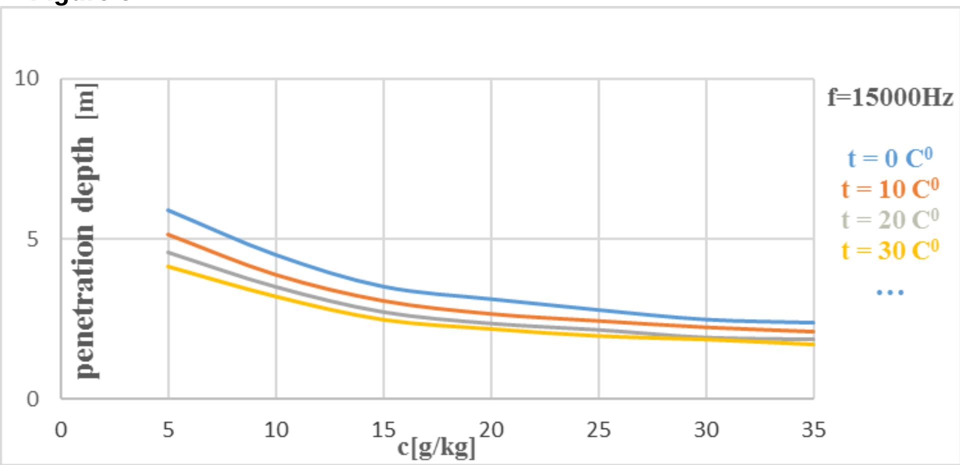


Table 6

f = 15000Hz	$\delta[m]$			
c [g/l]	0 ^0C	10 ^0C	20 ^0C	30 ^0C
5	5,89	5,14	4,59	4,14

10	**4,50**	**3,88**	**3,51**	**3,20**
15	**3,51**	**3,06**	**2,72**	**2,47**
20	**3,12**	**2,65**	**2,36**	**2,18**
25	**2,78**	**2,43**	**2,16**	**1,96**
30	**2,48**	**2,23**	**1,92**	**1,85**
35	**2,38**	**2,09**	**1,86**	**1,69**

Figure 5



The penetration depth dependence with temperature and salinity of the seawater. Analyzing graphics above, it is found approach of curves that are representing the penetration depth dependence with concentration at different temperatures. In other words, the penetration depth dependence with temperature decreases with increasing concentration.

We believe that phenomenon is a consequence of the viscosity dependence with temperature and Walden's law. If is noted:

$$\alpha = 1{,}78 \cdot 10^{-9}; \quad \beta = 0{,}037; \quad \gamma = 0{,}00022$$

Poiseuille's formula for viscosity is written as follows:

$$\eta = \frac{\alpha}{1 + \beta\theta + \gamma\theta^2} \quad (11)$$

If we note by A the Walden's constant, this equation can be written as:

$$\Lambda_C \cdot \eta = A \quad (12)$$

Using the relation (11) we can write the following relation between conductivity and viscosity physical:

$$A = \frac{\sigma\alpha}{c\ (1 + \beta\theta + \gamma\theta^2)} \quad [13]$$

So the expression of penetration depth will be:

$$\delta = \sqrt{\frac{2\alpha}{\omega\mu_0 Ac\ (1 + \beta\theta + \gamma\theta^2)}} \quad (14)$$

Depth variation with temperature will have the following expression:

$$\frac{\partial\delta}{\partial\theta} = -\frac{1}{2}\sqrt{\frac{\alpha}{\omega\mu_0 Ac}} \cdot \frac{\beta + 2\gamma\theta}{\sqrt[3]{1 + \beta\theta + \gamma\theta^2}} \quad (15)$$

In fact, it is noted a decrease of penetration depth variation with temperature, inversely proportional to the square root of the concentration or salinity of seawater.

Using the formula Arhenius - Guzman [10] for the dependence of viscosity with temperature, we obtain:

$$\eta = \chi \cdot e^{\frac{\varphi}{KT}} \quad (16)$$

where:

T – absolute temperature;

K – Boltzmann's constant

From the law of Walden we infer the following relation conductivity:

$$\sigma = \frac{C \cdot A \cdot e^{\frac{\varphi}{KT}}}{\chi} \quad (17)$$

And the penetration depth will be:

$$\delta = \sqrt{\frac{2\chi}{\omega\mu_0 Ac}} \cdot e^{\frac{\varphi}{2KT}} \quad (18)$$

Absolute temperature variation with depth is:

$$\frac{\partial\delta}{\partial T} = -\frac{\varphi}{2KT^2} \cdot \sqrt{\frac{2\chi}{\omega\mu_0 Ac}} \cdot e^{\frac{\varphi}{2KT}} \quad (19)$$

Also, in this case, It is noted the same type $\frac{\partial\delta}{\partial T}$ of concentration dependence. The veracity of this statement is verified by observing that for a constant temperature the relation [14] will take the form:

$$\delta = \frac{B}{\sqrt{C}} \quad (20)$$

where B is a constant. In this case, the ratio between two successive values of penetration depth in the table below are expressed by the relation:

$$\frac{\delta_i}{\delta_{i+1}} = \sqrt{\frac{C_{i+1}}{C_i}} \quad (21)$$

We calculated the value ratio $\frac{\delta_i}{\delta_{i+1}}$ at different temperatures

Table 7

$\sqrt{\frac{C_{i+1}}{C_i}}$	$\frac{\delta_i}{\delta_{i+1}}$			
	0 ^0C	**10** ^0C	**20** ^0C	**30** ^0C
$\sqrt{\frac{10}{5}}$ **= 1,41**	**1,31**	**1,32**	**1,31**	**1,29**
$\sqrt{\frac{15}{10}}$ **= 1,22**	**1,28**	**1,26**	**1,29**	**1,29**
$\sqrt{\frac{20}{15}}$ **= 1,15**	**1,125**	**1,15**	**1,15**	**1,13**
$\sqrt{\frac{25}{20}}$ **= 1,118**	**1,122**	**1,09**	**1,15**	**1,13**
$\sqrt{\frac{30}{25}}$ **= 1,09**	**1,121**	**1,09**	**1,125**	**1,03**
$\sqrt{\frac{35}{30}}$ **= 1,08**	**1,042**	**1,07**	**1,03**	**1,09**

The above analysis shows that the penetration depth of field electromagnetic at different frequencies, temperature and concentration is at least ten times higher than seawater induced of linear induction machine, possible to be used in the propulsion of ships.

CONCLUSION

The concentration of solutes, through the mechanisms of ion-ion interaction strongly, influences both the conductivity and permittivity environment. The tractive force and efficiency of unconventional magnetohydrodynamic shipping propulsion will depend very much on the geographical region in which the vessel is provided with this propulsion. The conductivity of the electrolyte solution depends on the frequency and the intensity of the electric field. It is obvious that these two quantities have not a decisive influence on the conductivity in the frequency and intensity of the electric field that is currently working in the area of fluid induced engines.

Penetration depth increases as salinity increasing and decreases with temperature increasing. As results from previous studies, a greater depth of penetration lowers the propulsion parameters. A vessel equipped with a hydroelectromagnetic induction propeller will have a lower efficiency in Arctic regions, where temperature and salinity are lower and parameters functions of the drive will be reduced significantly.

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