Design of inductors for the installation of induction soldering of pipeline joints in the oil and gas industry

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Abstract. The article discusses the use of induction brazing for connecting oil and gas pipelines. The rationale for the choice of induction brazing in the oil and gas industry is considered. The work calculates the main parameters of the inductor. On the basis of calculations, using a mathematical apparatus, a schematic diagram of an inductor with a diameter of 90 mm is created for installing induction soldering. It is proposed to use and develop inductors of various diameters (60, 90 and 135 mm) to create an induction unit that allows connecting pipelines of oil and gas equipment in order to increase the reliability of equipment and the efficiency of oil and gas production and processing.

1. Introduction

Currently, a large number of different equipment is used in the oil and gas industry, which must be combined into a single integral complex that fulfills its technical purpose. These are both components of the pipeline system and parts of pumping and processing oil and gas equipment. These joints are formed on the basis of various thermal processes, the main of which are welding and brazing [1-3].

When using standard welding methods, the required joint quality is not always achieved. Therefore, it is necessary to use modern, high-tech and high-precision methods, one of which is soldering by induction heating [4-6].

In the oil and gas industry, induction brazing can be used to connect flanges to pipes, to form transitions, tees, in some cases for flange plugs, for brazing tube bundles of heat exchangers and various types of equipment [7-9].

When using induction heating, it becomes possible to melt high-temperature solders, with a melting temperature difference between the base material and the solder of 20-50 °C, which makes it possible to reduce the requirements for external conditions and increase the reliability of technological equipment. Induction brazing can find wide application in the oil and gas industry, improve the reliability of equipment and, ultimately, significantly increase the efficiency of oil and gas production and processing [10-12].

The purpose of this work is to improve the quality of the connection of flanges with branch pipes of unions of vessels and devices operating under pressure using the example of an automated gas metering unit (AGMU).
2. Materials and methods
To develop an inductor, it is necessary to calculate the basic parameters of the inductor. For the following mathematical apparatus was used. Mass of the heated volume of metal (1), kg:

\[ G = 0.45 \cdot m \]  

(1)

where \( m \) is the mass.

The minimum and maximum frequencies of the inductor \( f \) (frequency interval) are calculated by the equation (2), Hz:

\[ \frac{3 \cdot 10^6 \cdot p}{\mu \cdot D_2^2} \leq f \leq \frac{6 \cdot 10^6 \cdot p}{\mu \cdot D_2^2} \]  

(2)

where \( p = 2 \cdot 10^8 \text{ Ohm} \cdot \text{m} \) – electrical resistivity of a copper inductor;

\( D_2 \) – product diameter, m;

\( \mu = 1 \) - relative permeability of metal, p.u.

In this work, according to the calculated frequency range, we will choose power supplies from the following series of standard frequencies \( f \): 500, 1000, 2500, 4000, 8000 Hz.

The depth of wave penetration into the inductor material is calculated by expression (3), mm:

\[ \Delta = 503 \cdot \sqrt{\frac{\rho}{\mu \cdot f}} \]  

(3)

where \( f \) - frequency of the selected power supply.

Net power (4) used to heat the workpiece, kW:

\[ P_{\text{net}} = \frac{C \cdot G \cdot (t_{\text{end}} - t_{\text{init}})}{\tau_{\text{heat}}} \]  

(4)

where \( C \) - specific heat of the part material at the melting point of the solder, kJ/kg·\(^\circ\)C; \( G \) - load weight; \( t_{\text{end}}, t_{\text{init}} \) - respectively, the end and initial temperature of the metal, where \( t_{\text{end}} \) corresponds to the melting point of the solder, \( t_{\text{init}} \) corresponds to the ambient temperature (\( t_{\text{init}} = 200 \text{ \(^\circ\)C} \)); \( \tau_{\text{heat}} \) - heating time, s.

The heat loss power (5) is calculated on the basis of Fourier's law as the power transferred by thermal conductivity from the inner surface to the outer surface (in contact with the inductor) through a single-layer cylindrical lining, kW:

\[ \Delta P_{\text{hl}} = \frac{(t_1 - t_2) \cdot \mu}{z_T} \]  

(5)

where \( t_1, t_2 \) - respectively, the internal and external temperatures of thermal insulation (lining); for calculations take \( t_1 = t_{\text{end}} \) (end temperature of the heated billet), \( t_2 = t_{\text{water}} \) (temperature of cooling water at the outlet of the inductor); \( z_T \) - thermal resistance of the lining (6):

\[ z_T = \frac{\ln \left( \frac{D_1}{D_2} \right)}{2 \cdot \pi \cdot \lambda} \]  

(6)

where \( \lambda = 0.7 + 0.64 \cdot 10^{-3} \cdot t_{\text{avg}} \) - the thermal conductivity coefficient of chamotte, in simplified calculations I accept \( t_{\text{avg}} = t_{\text{end}} \).

\[ D_3 = D_2 + 0.01 \]  

(7)

\[ D_4 = D_2 - 0.01 \]  

(8)
where \( D_1, D_3 \) - respectively, the outer and inner diameters of the thermal insulation; Inner diameter of the inductor, m:

\[
D_4 = D_2 + 2 \cdot h
\]  
(9)

where \( h \) - air gap between the inductor and the heated part. It is usually chosen within 2-5 mm if \( D_2 \leq 50 \) mm, and 5-10 mm, if \( D_2 > 50 \) mm.

Power consumption in load (10), kW:

\[
P_L = 1.05 \cdot (P_{\text{net}} + \Delta P_{\text{hl}})
\]  
(10)

where 1.05 - coefficient that considers losses in metal guides along which the part moves; \( P_{\text{net}} \) - net power, power used to heat the part; \( P_{\text{hl}} \) - heat loss power [20].

Let's calculate the inductor based on the data for the first type and the first version for the nominal pressure \( P_y = 0.6 \) MPa (6 kgf/cm\(^2\)) according to ATK 24.218.06-90 “fittings for vessels and welded steel apparatus”. For the calculation, we will use the widespread material for fittings and pipes 12KH18N10T and, accordingly, the PSr45 solder suitable for it, the melting point of which ranges from 665 to 730 °C.

Let's start the calculation with the minimum value \( D_y = 90 \) mm. We calculate the mass of the heated volume of metal by the equation (1):

\[
G = 0.45 \cdot 1.5 = 0.675
\]

The calculated frequency is calculated by the equation (2):

\[
3 \cdot 10^6 \cdot 2 \cdot 10^{-6} \leq f \leq \frac{6 \cdot 10^6 \cdot 2 \cdot 10^{-6}}{1 \cdot 0.09^2}
\]

\[
740 \leq f \leq 1480
\]

We choose the frequency \( f = 1400 \) Hz. This frequency will be enough for us to carry out the process of induction soldering of a given volume of metal. The depth of wave penetration into the inductor material is calculated by the equation (3), mm:

\[
\Delta = 503 \cdot \frac{2 \cdot 10^{-6}}{1 \cdot 1.400} = 1.6
\]

Useful power is calculated by the equation (4), kW:

\[
P_{\text{net}} = \frac{575 \cdot 0.675 \cdot (730 - 20)}{120} = 2.296
\]

The power of heat losses is calculated by the equation (5), kW:

\[
\Delta P_{\text{hl}} = \frac{(730 - 50) \cdot 1}{0.067} = 10.14
\]

where \( z_T \) - thermal resistance of the lining, calculated by the equation (6):

\[
z_T = \frac{\ln (0.08)}{2 \cdot 3.14 \cdot 1.167} = 0.067
\]

where \( D_3 = 0.09+0.01=0.1; D_1=0.09-0.01=0.08; \lambda = 0.7 + 0.64 \cdot 10^{-3} \cdot 730 = 1.167 \)

The inner diameter of the inductor is calculated by the equation (9), m:

\[
D_x = 0.09 + 2 \cdot 0.007 = 0.104
\]
The power that must be transmitted electromagnetically from the inductor to the workpiece (part) is calculated by the equation (10), kW:

\[ P_2 = 1.05 \cdot (2.296 + 10.14) = 13.05 \]

Let's summarize all the initial and received data, configured in the calculations in table 1.

**Table 1. Initial and calculated data.**

| Name                                      | The quantity |
|-------------------------------------------|--------------|
| 1. Solderable metal                        | 12KH18N10T   |
| 2. Final heating temperature, °C          | 730          |
| 3. Diameter of a part, D2, mm              | 0.09         |
| 4. Inner diameter of the inductor, D4, mm  | 0.104        |
| 5. Heating time, s                         | 120          |
| 6. Mass of heated metal volume, kg         | 0.675        |
| 7. Calculated frequency, Hz                | 740 ≤ f ≤ 1480 |
| 8. Selected frequency, Hz                 | 1400         |
| 9. Depth of wave penetration into the inductor material, mm | 1.6          |
| 10. Useful power, kW                       | 2.296        |
| 11. Power of heat losses, kW               | 10.14        |
| 12. Power consumption in loading, kW       | 13.05        |

Let's calculate the electrical parameters of the inductor at \( D_y = 60 \) mm. Since the diameter of the heated part has increased, it is necessary to perform repeated calculations, in the same way according to equations (1)-(10). Let's summarize all the initial and received data, configuring in the calculations in table 2.

**Table 2. Initial and calculated data.**

| Name                                      | The quantity |
|-------------------------------------------|--------------|
| 1. Solderable metal                        | 12KH18N10T   |
| 2. Final heating temperature, °C          | 730          |
| 3. Diameter of a part, D2, mm              | 0.06         |
| 4. Inner diameter of the inductor, D4, mm  | 0.068        |
| 5. Heating time, s                         | 120          |
| 6. Mass of heated metal volume, kg         | 0.18         |
| 7. Calculated frequency, Hz                | 1200 ≤ f ≤ 1600 |
| 8. Selected frequency, Hz                 | 1500         |
| 9. Depth of wave penetration into the inductor material, mm | 1.1          |
| 10. Useful power, kW                       | 0.612        |
| 11. Power of heat losses, kW               | 8.6          |
| 12. Power consumption in loading, kW       | 9.6          |

In order to find out to what nominal bore diameter of fittings and pipes it is possible to carry out induction soldering of flanges, it is necessary to find the nominal diameter at which calculations will show the impossibility of implementing this soldering method. To do this, it is necessary to repeat the calculations.

Let's calculate the electrical parameters of the inductor at \( D_y = 135 \) mm. Since the diameter of the heated part has increased, it is necessary to perform repeated calculations using equations (1)-(10). Let's summarize all the initial and received data, configuring in the calculations in table 3.
Table 3. Initial and calculated data.

| Name                                           | The quantity       |
|------------------------------------------------|--------------------|
| 1. Solderable metal                            | 12KH18N10T         |
| 2. Final heating temperature, °C               | 730                |
| 3. Diameter of a part, D2, mm                  | 0.135              |
| 4. Inner diameter of the inductor, D4, mm       | 0.151              |
| 5. Heating time, s                             | 120                |
| 6. Mass of heated metal volume, kg              | 0.945              |
| 7. Calculated frequency, Hz                    | 2300 ≤ f ≤ 3300    |
| 8. Selected frequency, Hz                      | 2500               |
| 9. Depth of wave penetration into the inductor material, mm | 1.9                 |
| 10. Useful power, kW                           | 3.396              |
| 11. Power of heat losses, kW                    | 34                 |
| 12. Power consumption in loading, kW            | 37.396             |

We will take the following characteristics for the installation of induction brazing of flanges of fittings and pipes: installed power 40 kW, power supply 380V with a frequency of 50 Hz, frequency of the power supply converter 2500 Hz.

3. Result and discussion

In the course of the work, a schematic diagram of the proposed inductor (figure 1) with a diameter of 90 mm was designed, which is used for the subsequent design of an induction unit for connecting pipelines of oil and gas equipment.

![Figure 1](image)

Figure 1. 1. Material hardness – 57HV; 2. Unspecified limit deviations of dimensions h14, ±IT14/2; 3. * Dimensions for reference; 4. The set of accuracy indicators is set by the manufacturer according to Russian State Standard 30893.1-2002.

Thus, the electrical parameters of the inductor were calculated for different diameters (60, 90 and 135 mm). Calculations have shown that inductors of this diameter meet the technical requirements.

These structures are collapsible, which allows them to be used on different objects. The inductors developed by the authors (with a diameter of 60, 90 and 135 mm) are disassembled in three places, which allows not only assembling the setpoint at any object, but also compactly transporting the inductors themselves. The proposed solution simplifies the assembly of an induction unit for connecting pipelines in the oil and gas industry.
4. Conclusion
In the course of this work, an analysis was carried out of the current methods of connecting pipelines for oil and gas equipment. Also, the main parameters of the inductor were calculated using the mathematical apparatus. Current calculations have shown the applicability of this approach. As a result, the design of a general view of a set of inductors for induction brazing of flanges of fittings and pipes for the nominal diameter was carried out $D_y = 90$ mm were carried out; $D_y = 60$ mm; $D_y = 135$ mm.

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