Development and application of induction and resistive electrical heating systems for industrial pipelines

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This paper examines problems of calculation of heating units for ferromagnetic steel in weak electromagnetic fields. Such installations are low-temperature induction heating installations. In these plants, the electromagnetic field energy is converted into heat due to the induced currents and hysteresis. Comparison of use options of induction, electrical contact and combined methods of pipe heating has been provided. Special problems – heating system options have been considered: use of bimetallic outer conductors; use of increased frequency; effect of a lengthwise cut (clearance) of a steel pipe. Possibilities of the survey results utilization have been investigated, as well as engineering and techno-economic problems.

Introduction

Low-temperature induciton, electrical contact and combined methods for heating of parts made of ferromagnetic steel become rather widely used in various processing procedures, e.g. for thermal trating of products, parts preheating before welding, mould heating, heating of vessels etc. In the process of such heating units development, one comes up against a problem of calculation of the electromagnetic field parameters in ferromagnetic conductive medium in solving of which it is requried to take into account nonlenear dependence of relative magnetic permittivity of the material μ on the magnetic field strength H [1].

There are processing procedures in which heating of steel parts is mainly used for heat loss compensation: heating of pipelines, tanks, hoppers etc., for that low specific surface heat densities (up to 5 kW/m^2) and, accordingly, low magnetic fields (H<4000 A/m) are requried. At that the electromagnetic field paramters will be significantly influenced by hysteresis loss that must be taken into account in the calculation of the heatin units performance.

In such cases, at calculation of induction, resistive and combined induction-resistive heating of steel parts using industrial-frequency voltage, particularly for steel pipes heating (schematics of the heating units are given in Figure 1), one encounters a problem of taking into account power loss caused by alternating magnetization (hysteresis).

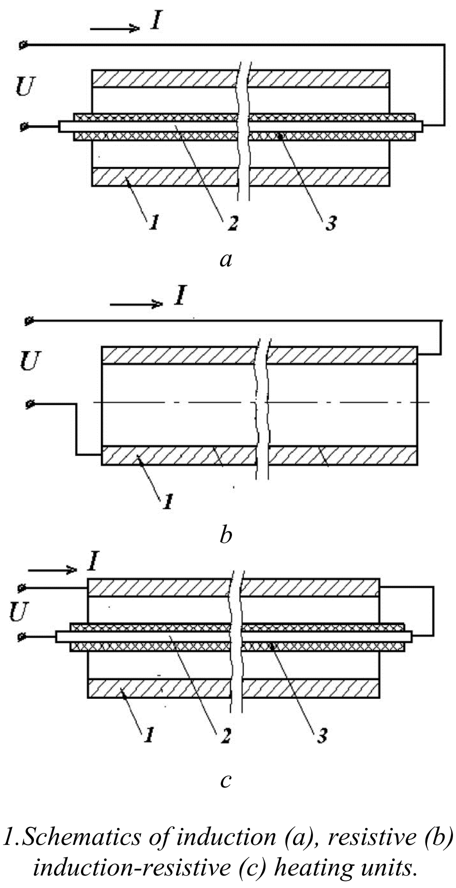

Fig. 1.Schematics of induction (a), resistive (b) and induction-resistive (c) heating units.

Important problems in designing of heating units for industrial pipelines are lowering of supply voltage to minimize a number of power supply points along a pipeline and lowering of the voltage on the pipe surface to ensure electric safety of the heating system. These requirements necessitate engineering study of various options of electrical heating systems for pipelines.

Calculation of electromagnetic field in ferromagnetic steel

There are general-purpose program packages, e.g. *ELCUT*, that enable modelling of electromagnetic field in ferromagnetic steel using finite elements method.

Since the alternating magnetization of steel is not provided in the *ELCUT* package, it can be used only for preliminary evaluations.

By this reason, a method for calculation of induction, resistive and induction-resistive heating taking into account the reverse magnetization was developed, which is based on using of electric equivalent circuits [2] – [5].

Calculation of electric parameters of the heating element necessitates taking into account a number of factors which include: electromagnetic interaction of currents flowing in the cable conductor and steel tube, nonlinear dependence of magnetic permeability μ on magnetic field strength *H* and hysteresis losses in ferromagnetic steel of the tube.

The authors have developed a mathematical model for calculation of the electromagnetic field parameters in ferromagnetic media that is based on an equivalent electric circuit and takes into account heating of the ferromagnetic caused by Joule heat and alternating magnetization (hysteresis). As an example of the model development, division of the tube wall to 4 layers (to *n* layers in general case) through its total thickness δ is shown in Figure 2. At that it is accepted that the current in each layer flows through its middle and only the 1st current harmonic is taken into account, at that the wall is considered to be plane since the penetration depth of the electromagnetic field into the tube material is less than the pipe radius.

The equivalent electric circuit for calculation of parameters of induction-resistive heating unit is presented in Figure 3. The following key symbols are used in the diagram: U – supply voltage; I_i - currents of the layers; R_i and R_{gi} – active resistances of the layers, taking into account losses caused by induced currents and hysteresis losses; L_i – self-inductances of the layers; i – the layer number.

Adequacy of the developed mathematical model has been verified experimentally and also by comparison with the calculation results obtained using the known program packages *FEMM* and *ELCUT*.

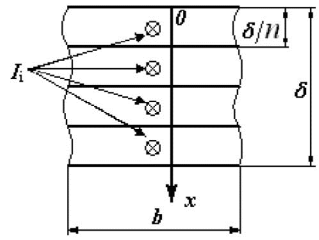

Fig. 2. A fragment of the wall tube with division into layers with current values I_i.

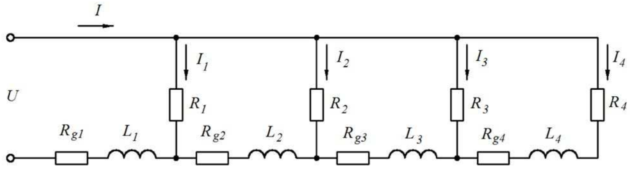

Fig. 3. Equivalent electrical circuits for induction-resistive heating unit.

The results of the electromagnetic field in ferromagnetic steel calculation

Using the developed methods, electromagnetic field parameters in ferromagnetic steel taking into account the hysteresis effect have been calculated. It has been found also that variations of the electromagnetic field parameters in the tube's wall are different for induction, resistive and induction-resistive heating units that is reflected on distribution of the magnetic field, currents and power output by the layers. The calculated distributions of the magnetic field strength in the tube's wall for induction, resistive and induction-resistive heating units are presented in Figure 4 for the input data described above.

As calculation and praxis show, at equal heat output the supply voltage and the voltage on the outer surface of the pipe in case of induction-resistive heating system (IRHS) are lower than those for units *a* and *b* in Figure 1. For this reason, in most cases using of induction-resistive heating systems is viable. The length of the IRHS, that is generally no more than 15 km, is defined by the ratio of the supply voltage *U* (normally no more than 5 kV) to linear voltage drop equal to 0,3÷0,5 V/m. The supply voltage is limited firs of all by partial discharge inception inside the insulating elements occurring at high supply voltage values.

Induction-resistive heating systems with bimetallic outer conductor

One of the methods of increasing the system length is lowering of the linear voltage drop that can be achieved by internal shunting of the heater's outer conductor (tube).

The voltage on the outer surface of the tube also decreases at shunting.

As a result of an experiment, dependencies of the linear voltage drop *U* on the total system power *P* that is presented in Figure 5 for a system with the shunting copper layer having 16 mm^2 cross-section and the system without this layer. Calculated-to-experimental comparison within a wide range of power output in the tube shows the difference not exceeding 10%.

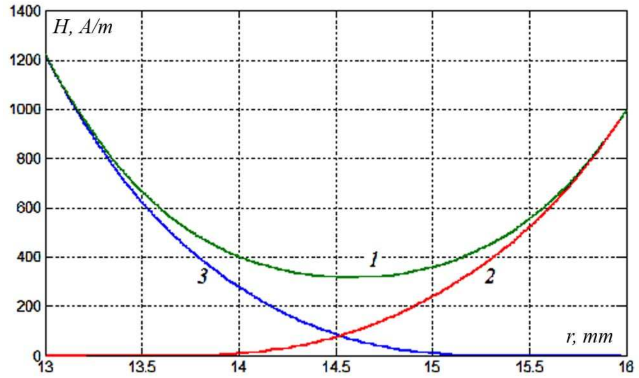

Fig. 4. Distribution profile of magnetic field in the tube's wall for induction (1), resistive (2) and induction-resistive (3) heating units.

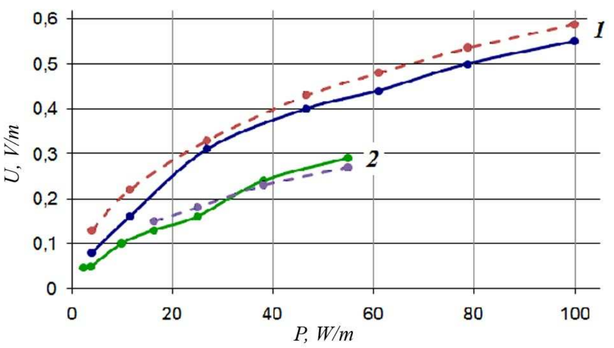

Fig. 5. Linear voltage drop vs total system power (the solid line represents the experimental data, the dashed line – the calculated values):
1 – without shunting; 2 – with S_c=16 mm^2

The obtained calculated and experimental results indicate that using of the copper shunt leads to significant decrease of the linear voltage drop required for the same heat output generation in the system. At that for the IRHS with the copper layer cross-section S_c=16 mm^2 the inductor's current is increased by 50 – 70 % compared with the IRHS without the copper layer.

Basing on the above study, it is established that using of IRHS with copper layer having 16 mm^2 cross-section allows to lower the voltage drop per unit length by 30 – 40% compared to the system without copper layer within the system output range from 20 to 60 W/m.

At that the linear voltage drop decreases with the increase of the inner shunt cross-section provided the total power output of the system is the same.

It should also be noted that the presence of the inner copper layer of the tube causes increase of the IRHS power factor and decrease of conditional electrical efficiency (the ratio of the power output in the shunt and in the pipe to the total power output in the system) [6].

Induction-resistive heating system powered by medium-frequency current

IRHS is usually powered from an industrial frequency voltage source. To improve the flexibility of the heating tube that facilitates the installation work, ferromagnetic tube having wall thickness less than 1 mm can be used provided the heating system is powered by medium-frequency current.

The calculation of the IRHS operating at a medium frequency is performed using the same method as was used for the IRHS calculation at the industrial frequency and implemented in *IRSN* computer program. The *IRSN* program enables to calculate electrical and power parameters of the heating system taking into account alternating magnetization of ferromagnetic tube.

The calculated dependencies of the supply voltage U_1 on the total active system power *P* per unit length are presented in Figure 6 for frequencies 50, 2380 and 8800 Hz (curves *1*, *2* and *3* accordingly).

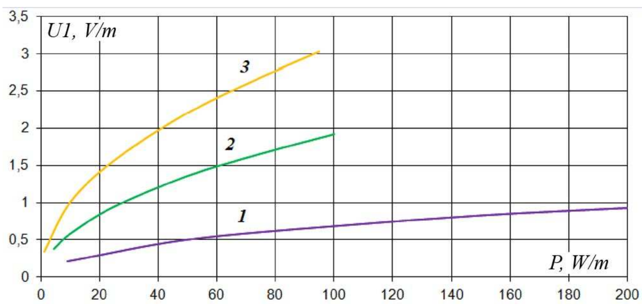

Fig. 6. Supply voltage vs total system power:
1 – 50 Hz; 2 – 2380 Hz; 3 – 8800 Hz.

Experimental studies of IRHS have been performed for the system powered by industrial frequency source and by medium-frequency source (at 2380 and 8800 Hz) with the tube 38x3 mm (made of steel 20) and the copper cable with the conductor cross-section 10 mm^2 as an inductor. It is established that when the operating frequency is increased, it is required to increase the supply voltage to keep the total system power at the same level because the system resistance grows with frequency.

Influence of longitudinal gap and overlapping edges on the parameters of induction-resistive heating system

The following requirements are imposed upon induction and resistive heaters: a limitation on supply voltage (usually U < 5.0 kV), minimum voltage drop per unit length (U_l, V/m), minimum voltage on outer surface of the tube (u_n, V/m), manufacturability, low metal consumption, etc.

For achievement of the best results in terms of the above parameters, the authors have proposed and studied various design options of induction and induction-resistive heaters which cross-sections are shown in Figure 7 *a, b, c, d* [7], [8].

The study has been performed using theoretic (mathematical modelling) and experimental methods. At that both software developed by the authors and professional program packages have been used.

For investigation of induction heaters, normal type IRHS and the IRHS with bimetal tube, a software have been used that realized the developed method of electromagnetic field calculation at low magnetic field strength levels (*H* < 4.0 A/m) taking into account nonlinear μ(*H*) dependence.

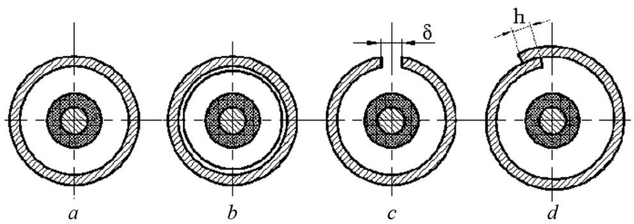

Fig. 7. Options of the heating tube fulfillment: normal (a), bimetal (b), open (c), open, with the overlapped edges (d).

Comparison of the calculated characteristics for induction heating units and IRHS design options (Figure 1 *a, b*) using the single-layer tube (Figure 7 *a*) shows that IRHS option is more favorable since in this case, in addition to one end powering, less u_n values are achieved (with linear power output *P* values being the same). But the induction heating option has distinct advantage related with heating system installation procedure because the heater's tube can be made of separate electrically unconnected fragments.

To simplify heating systems' manufacture and installation, using of open tubes with longitudinal gap (Figure 7 *b*) in heaters is assumed to be valuable, but even preliminary studies have shown that using of open tubes with the overlapped edges (Figure 7 *d*) is more favorable.

Experiments with the heater physical models as well as the data obtained from manufactured industrial pipeline heating systems confirmed the theoretical calculation results.

Operational experience

As has been said above, the IRHS found their application in the field of pipeline heat tracing. As of today it is virtually the only economically sound methods for heating of pipelines with a length of 3 km and more. The IRHS ensure warming-up, process temperature maintenance as well as freeze protection of pipelines (Figure 8).

The main objects on which these systems are installed are: water lines (at development and operation of any fields), flow lines (transferring products: crude oil and oil products), sulfur piping (transferring liquid sulfur), pipelines for viscous substances transferring (interplant intershop piping of chemical and petrochemical industry enterprises), gas pipelines (IRHS of anti-condensation purpose) [8, 9].

Basing on the study of the effect of inner conductive layer of ferromagnetic tube of IRHS, longitudinal gap and gap edges overlapping, data have been obtained applicable for solving of various specific design problems of induction and induction-resistive heating units which are partially implemented in pipeline heating systems manufactured and brought into operation by the Special Systems and Technologies Company.

Fig. 8. A heated pipeline with IRHS installed on it.

Conclusions references

1. Calculation of induction, resistive and induction-resistive heating using electric equivalent circuit makes it possible to take into account the hysteresis

loss. At that the difference in the method of the electrical calculation of the units lies in the equivalent circuit specificity.

2. In the units under study, in case of the heating with low magnetic field strength (up to 4000 A/m) the effect of magnetic hysteresis on the calculation results must be taken into account; in particular, the contribution of the hysteresis to the total active power output in a ferromagnetic load at H_0 of up to 2500 A/m amounts to ≥ 24%, and that at H_0 of up to 3800 A/m amounts to ≥ 15%.

3. An inner copper layer significantly lowers the linear voltage drop at the same total heating power output that enables to increase the heating system length. For the considered option (Figure 5), using of double-layer IRHS makes it possible to lower the voltage drop per system unit length by 30 – 40% and to increase the IRHS length accordingly.

4. The developed calculation methods can be used in designing of the considered types of heating units for ferromagnetic steel objects.

REFERENCES

[1] Kuvaldin, A.B. Induction heating of ferromagnetic steel. M. Energoatomizdat, 1988, 200 p.

[2] Kuvaldin, A.B., M.L. Strupinskiy, N.N. Khrenkov, V.A. Shatov. Mathematical models for investigation of electromagnetic field in ferromagnetic conductive media. Electricity, 2005, No. 11, pp. 56 – 61.

[3] Kuvaldin, A.B., M.L. Strupinskiy, N.N. Khrenkov, M.A. Fedin. Calculation of electrical parameters and energy performance of core-type inductor for ferromagnetic load heating. Electricity, 2009, No. 10, pp. 54-61.

[4] Kuvaldin, A., M. Strupinskiy, N. Khrenkov, M. Fedin. Simulation of electromagnetic field in ferromagnetic steel taking into account hysteresis effect. International Symposium on Heating by Electromagnetic Sources HES-10, Padua, May 18-21, 2010, pp. 83-89.

[5] Kuvaldin, A.B., M.L. Strupinskiy, N.N. Khrenkov, M.A. Fedin. Simulation of electromagnetic field in ferromagnetic steel at induction, electric contact and combined heating. Informational Scientific & Engineering Journal “Induction Heating”, No. 13, 2010, pp. 17-21.

[6] Kuvaldin, A.B., M.L. Strupinskiy, N.N. Khrenkov, M.A. Fedin. Induction-resistive heating system with bimetallic outer conductor. Electricity, 2011, No. 2, pp. 58-63.

[7] Strupinskiy, M., N. Khrenkov, A. Kuvaldin, M. Fedin. The influence of a gap on electric parameters of induction-resistive heater. Tagungsband, Ilmenau, 2011.

[8] Kuvaldin, A.B., M.L. Strupinskiy, N.N. Khrenkov, M.A. Fedin. Comparison of induction and resistive electrical heating systems for industrial pipelines. Contemporary problems of energy saving electrotechnics APEET – 2014, Proceedings, Ekaterinburg, 2014, pp. 125-130.

[9] Kuvaldin, A.B., M.L. Strupinskiy, N.N. Khrenkov, M.A. Fedin. Calculation and implementation of induction-resistive heating system for pipelines. Contemporary problems of energy saving electrotechnics APEET – 2011, Proceedings, Ekaterinburg, 2011, pp. 55-60.

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