

# Modeling of thermal processes in waveguide tracts induction soldering<sup>1</sup>

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**Abstract.** The problem solving of the induction heating models development, which describe the heating of the separate structural assembly components of the waveguide path and product generally, is presented in this paper. Proposed mathematical models are based on the thermodynamics equation and on the heat balance law. The system of the heating process mathematical models, such as surge tube and flange heating, and the mathematical model of the energy distribution are presented. During the modeling process with Matlab system by using mathematical models graphs of the tube, flange and coupling heating were obtained. These design charts are confirmed by the results of the experimental study. During the experimental studies pyrometers for temperature control and a video camera for visual control of the process parameters were used. On the basis of obtained models the induction soldering process features analysis is carried out and the need of its automation by the using of the information control systems for thermal management between the connection elements is revealed.

## 1. Introduction

Currently, restrictions on weight and size characteristics in the industry are tightened. This also applies to the waveguide channel antenna-feeder devices in radio engineering complexes. In this case the reliability of the elements must be high enough to ensure their operation during the period of active existence which is 12-15 years for the modern communication systems.

Waveguide can propagate different types of electromagnetic waves. The preferential propagation of waves of a particular type depends on the geometric dimensions of the waveguide, electromagnetic waves excited frequency and their excitation method [1].

Constituent elements of waveguides are connected to the assembly by the induction soldering, which has a number of advantages with respect to the other heating types, such as the open flame heating or heating in a furnace:

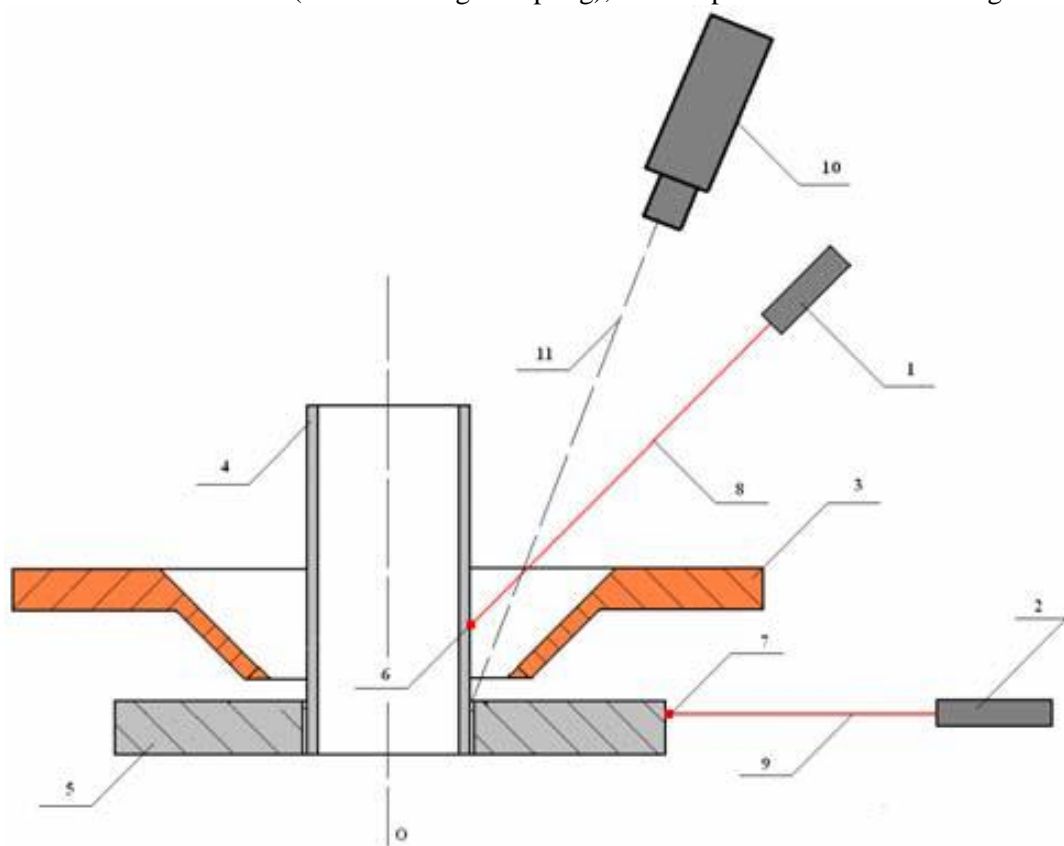
- 1) rapidity;
- 2) high performance;
- 3) stability;
- 4) unique accountability;
- 5) good working conditions;
- 6) efficient use of the space;
- 7) non-contact process.

However, using of this high-tech method is constrained by the number of limitations which are related to the high speed of the process that complicates manual control as well as the complex relationship between energy released by the inductor and the heat distribution on the constituent elements of the waveguide [2, 3]. Formation of the automated control system of induction soldering

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process requires development of the models for describing the heating of assembly waveguide channel individual structural elements (tube and flange/coupling), and the product as a whole in figure 1.



**Figure 1.** Map of the pyrometric sensors and video cameras

1 - pyrometer for monitoring the waveguide tube heating; 2 - pyrometer for monitoring the flange (coupling) heating; 3 - the inductor; 4 - waveguide tube; 5 - a flange (coupling); 6 - the control point of the waveguide tube heating; 7 - control point of the flange (coupling) heating; 8 - pyrometer beam 1; 9 - pyrometer beam 2; 10 - video camera; 11 – axis of the video capture

Developed mathematical models are based on the thermodynamics equation as well as on the thermal balance law; real system's parts, which have little influence on the heating process generally, are not considered, that allows to simplify the calculations, as well as to maintain the adequacy of the obtained models [4].

## 2. Mathematical modeling

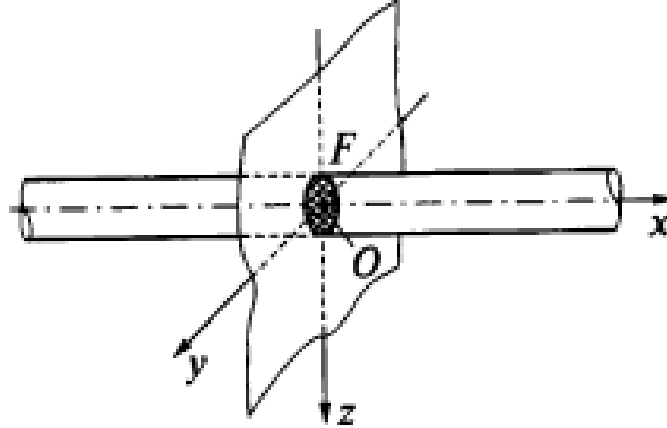
### 2.1. Mathematical model of waveguide tube heating

Solution of the heating rod (linear heat flux) differential equation will be the mathematical model of the tube heating.

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} - b(T - T_c) \quad (1)$$

$$b = \frac{\alpha p}{V h c F} \quad (2)$$

Infinite heat conducting rod with a section of  $F$  has an initial temperature  $T_{int}$ . At the initial time  $t = 0$  in the volume element, which is a flat layer with the base, coinciding with the plane  $yOz$  in figure 2 and the infinitesimal height  $dx$ , has amount of heat equal to  $Q$  with uniform surface intensity  $Q/F$ .



**Figure 2.** Scheme of the flat heat source in the rod

In this case the non-stationary temperature field of the flat heat source instantaneous action can be described by the expression:

$$T(x, t) = T_{int} + \frac{Q}{F \cdot Vhc \cdot \sqrt{4\pi at}} \exp\left(-\frac{x^2}{4at} - bt\right) \quad (3)$$

where  $T_{int}$  – temperature in initial time [ $^{\circ}\text{C}$ ];

$Q$  – energy [J];

$F$  – the tube cross section [ $\text{m}^2$ ];

$Vhc$  – volumetric heat capacity [ $\text{J}/\text{m}^3$ ];

$a$  – coefficient of thermal conductivity;

$x$  – the distance from the heat source [m];

$t$  – time [sec];

$b$  – heat convection coefficient to the outside environment from the surface of the rod (formula 2);

$x$  – distance from the arbitrary rod cross section to the flat heat source located in the plane  $yOz$ .

Temperature field is symmetrical with respect to the plane  $yOz$  and one-dimensional, i.e. at any moment temperature in the arbitrary point of the infinite rod can be determined only by its  $x$ -coordinate [5].

Based on the consideration that the waveguide tube is somewhat the same rod, namely:

- sufficiently long body of a homogeneous material;
- it has a relatively uniform cross section over the entire length;
- it has a similar mechanism of heat transfer and thermal conductivity.

It can be concluded that the mathematical model of a flat heat source in a rod is also valid for the flat heat source in a rectangular tube [6]. Therefore, in our system this model is adopted for the calculations with only one simplification, namely the material heat transfer of the temperature to the environment will not be considered on the assumption that it is negligible and thus can be neglected without risking losing the model adequacy. This allows simplifying the calculations associated with calculating unsteady factor « $bt$ », which will have a variable value with respect to time. Thus the model takes the following form:

$$T(x, t) = T_{int} + \frac{Q}{Fcp\sqrt{4\pi at}} \exp\left(-\frac{x^2}{4at}\right) \quad (4)$$

## 2.2. Flange heating mathematical model

It was established due to the experiments that the flange (coupling) heating is close to the linear on condition that the maximum heating zone is chosen optimally, which can be achieved by the using of inductors with specific form with an oblique window and constrained heating rate.

Research shows that the temperature gradient in the flange (coupling) is very high due to the small product proportions and the high thermal conductivity of the product material. Based on these data model of the instantaneous heat source action on the flange (coupler) can be considered as the effect of the heat flow on the concentrated mass, which in turn makes model very simple for calculations. Accordingly, the heat transfer surface is quite small that allows ignoring this aspect of the real system, without accuracy loss.

$$T = \frac{Q}{c * p * m} \quad (5)$$

where  $Q$  - energy [J];

$c$  – specific heat per unit mass [J/kg];

$p$  – density [kg/m<sup>3</sup>];

$m$  – weight [kg].

It is assumed that the temperature is spread over the body evenly.

## 2.3. Mathematical model of the energy distribution

Mathematical model of the energy distribution is presented below:

$$q_{gen} = q_{tu} + q_{fl} \quad (6)$$

$$q_{fl} = q_{tu} * K_h \quad (7)$$

$$K_h = \alpha * h \quad (8)$$

where  $q_{gen}$  - power supplied by the generator;

$q_{tu}$  - power obtained by the tube;

$q_{fl}$  - power obtained by the flange (coupler);

$K_h$  - dependency coefficient of the energy transferred from distance;

$h$  - the distance from the inductor to the flange (coupler);

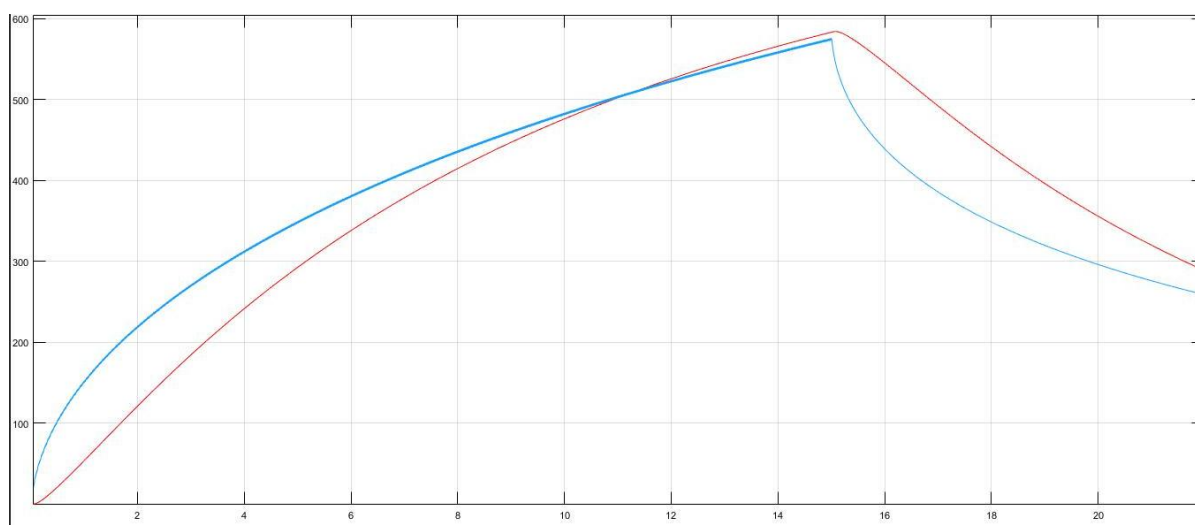
$\alpha$  - coefficient, which reflects the dependence of the distance between the product and the inductor and the power transferred to him.

## 3. Results of the experimental study

During the modeling process with Matlab system by using mathematical models, described in the Section 2, graphs of the tube and flange/coupling heating were obtained, they are shown in figure 3. When modeling on the heating stage capacity was set as a constant, and the power setting was carried off when the temperature reached the 580°C.

Figure 3 shows a comparison of the dynamics of heating tube and flange/coupling, from which it follows that at the heating stage when the same power is applied, the lag flange/coupling temperature on the tube temperature is occurred, but at the cooling stage due to the smaller volume of the flange the tube cooling rate exceeds that of the flange/coupling [6].

Comparison of the graphs shows that tube is more susceptible to the cooling process due to the small cross section at the large area. The flange or coupling has more smooth temperature curve because of the substantial material mass concentration within the small volume.



**Figure 3.** Simulation of the tube and the flange/coupling heating process with applying the constant power  
Red - flange/coupling, blue - tube

Presented charts in the figures 3 are confirmed by the results of experimental studies, which prove the adequacy of the proposed mathematical models to the real object. During the experimental studies pyrometers for temperature control and a video camera for visual control of the process parameters were used.

### Conclusion

Discussed mathematical models of the waveguide elements heating show that in the induction soldering process discrepancy of the waveguide tube and flange temperatures happens, which can lead to defects in the solder joints [7]. Therefore, measures to control the heating process, which allows conducting the heating process with the same temperature conditions for connection elements, are needed.

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