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Algorithm for Movement Control in Multi-Inductor Heating System

1. Introduction

Various contemporary technological processes involve heating devices, which are quite often multi-input multi-output systems. Among various types of such devices the induction heated rotating steel cylinder has been chosen as a leading example, as it is one of electroheat systems used in many branches of industry e.g. in paper making, textile or gum industry. Heating of this type has many advantages, especially high speed and high efficiency. In order to obtain the required temperature distribution along the cylinder axis, several heating inductors have to be applied. It forms a set of heating zones, which enables to consider this plant as a multi-input multi output structure. The scheme of computerized temperature control system of the regarded plant, including six infrared thermocouples as temperature sensors – one for each heating zone, is shown in Figure 1.

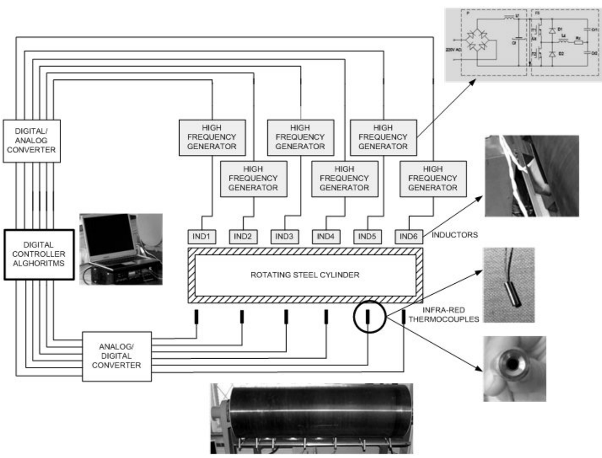

Fig. 1. The diagram of induction heated of the rotating steel cylinder

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The analyzed heating laboratory system consists of: 1.2 m long steel cylinder, six inductors (nominal power 1.5 kW) and six K-type infrared thermocouples for temperature measurement, giving six heating zones and six measurement channels for temperature control. The dynamic properties of such a system can be modelled and identified which makes it possible to apply different control methods [1, 2, 3].

Although such a set up can be very useful and efficient one, it may not be able to fulfil some high technological requirements, concerning for example uniformity of the cylinder surface temperature. Unfortunately, local overheating of the cylinder resulting from the discrete – type heat sources can not be easily overcome, even by the application of different types of multi-input multi-output control algorithms [1].

Therefore it seems reasonable to introduce in such cases the inductors that would be able to change their position along the cylinder axis. This solution, however, requires the appropriate algorithms to control of inductors movement and their power. In the paper such algorithm has been proposed and those influence on uniformity of temperature distribution in both steady and unsteady states have been shown.

Such studies require the use of numerical model of heating system which takes into account the possibility of heat generation anywhere on the surface of the charge. Such a model has been developed and various heating states of cylinder, including the case of mobile inductors, have been simulated and analysed.

2. Numerical modelling of the induction heated rotating steel cylinder

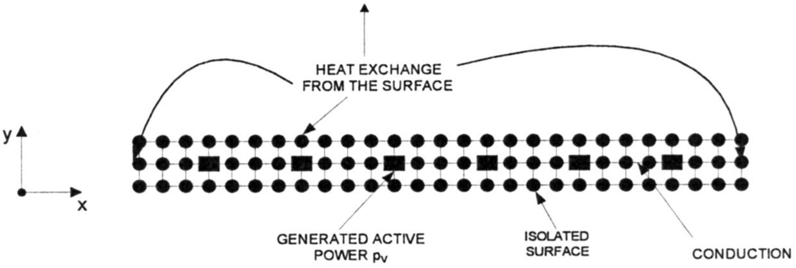
Properties of such a heating system can be modelled by a numerical model based on adequate thermal laws [2, 4]. Such a model can be a very convenient, time-saving tool for analysis of various working conditions of the device.

It is well known, that due to high frequency transverse electromagnetic wave coming from the inductor, the active power is generated under the surface of the cylinder (in the penetration depth area). For this reason the heating power corresponding to eddy currents made in electromagnetic field penetration depth area is located under the cylinder surface with heat exchange. Such a model is shown in Figure 2.

Basing on former experiences with similar systems the following main assumptions in numerical modelling have been made:

- Eddy currents, induced in the cylinder mantle, are replaced by sets of nodes with active power placed near the penetration depth.
- Values of active power put in nodes were determined by prior inductor-cylinder system electromagnetic calculations and verified by calorimetric method.
- Two dimensional model is considered, because the heat conduction along the cylinder axis and through its thickness are the most important factors from system dynamic point of view.

$$c_w \gamma_w \frac{\Delta x}{2} \Delta y \frac{T_{m,n}^{k+1} - T_{m,n}^{k}}{\Delta \tau} = \lambda \Delta y \frac{T_{m-1,n}^{k} - T_{m,n}^{k}}{\Delta x} + \lambda \frac{\Delta x}{2} \frac{T_{m,n+1}^{k} - T_{m,n}^{k}}{\Delta y} + \alpha \, \Delta y \left(T_{\infty} - T_{m,n}^{k} \right)$$



$$\frac{T_{m,n}^{k+1} - T_{m,n}^{k}}{\Delta \tau} = \frac{p_v}{c_w \gamma_w} + \frac{\lambda}{c_w \gamma_w} \left[\frac{T_{m+1,n}^{k} + T_{m-1,n}^{k} - 2T_{m,n}^{k}}{(\Delta x)^2} + \frac{T_{m,n+1}^{k} + T_{m,n-1}^{k} - 2T_{m,n}^{k}}{(\Delta y)^2} \right]$$

Fig. 2. The outline of numerical model of rotating steel cylinder with thermal boundary conditions. Indications of symbols used in differential formulas: α – convection coefficient [W/(m^2·K)], c_w – specific heat of the cylinder mantle [J/(kg·K)], γ_w – density of cylinder mantle [kg/m^3], $T_{m,n}^{k}$ – temperature in node (m, n) in k^{th}-iteration time step, Δx, Δy – distance between calculation nodes, Δt – interval of heating time

3. Evaluation of temperature uniformity along cylinder axis

3.1. Optimum active power distribution along the cylinder axis

It is easy to predict, there is a natural relationship between the number of heating inductors positioned along the cylinder axis, uniformity of temperature profile and temperature level in thermal steady state.

To determine the optimal distribution of heating power, it could be assumed many small heat sources along the cylinder axis. In numerical model those heat sources are located in each of 78 computational nodes.

It may be noted that due to the heat exchange there is a greater demand for supplied power near the lateral surface of the cylinder. So, the optimum heating power distribution provided the most temperature uniformity is growing up in the ends of the cylinder (Fig. 3).

As a measure of non-uniformity of temperature distribution it can assumed difference between the maximum and minimum temperature value at any point on the surface of the cylinder in time when thermal steady-state is reached. This measure can be called peak-to-peak temperature amplitude:

$$R = \max\left(T_{i,k}\right) - \min\left(T_{i,k}\right) \tag{1}$$

where:

- i – number of element of cylinder's model,
- k – sampling time.

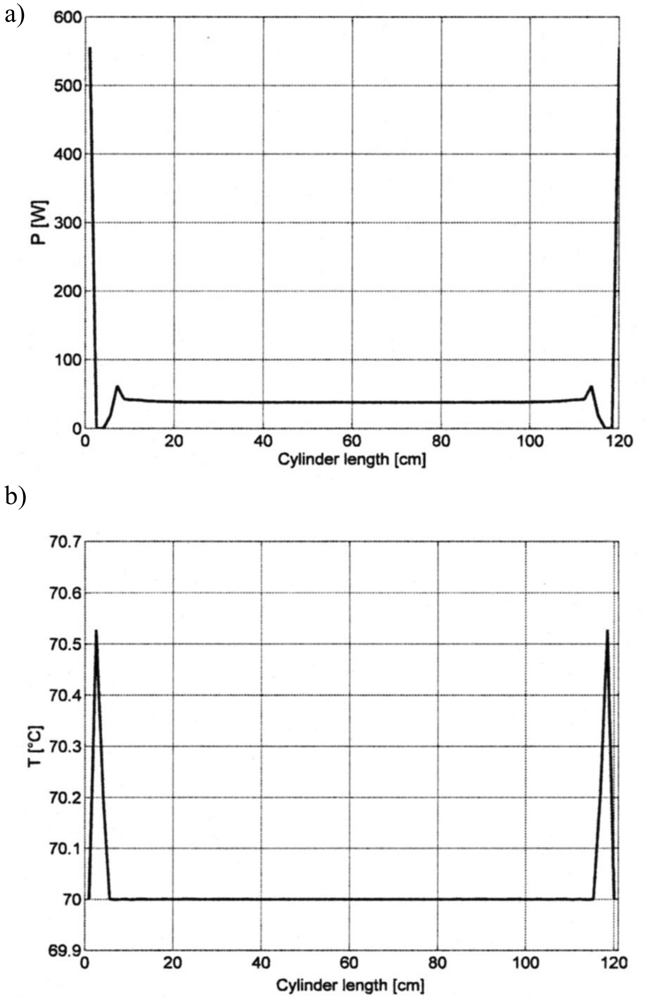


Fig. 3. Optimum heat power distribution (a) and corresponding temperature distribution (b) along cylinder axis

For proposed optimum heating power distribution *R* coefficient is about 0,52 ^{o}C on 70 ^{o}C temperature level.

This value could be the asymptote value of the *R* coefficient for the rest manner of cylinder heating. Basic on the summarized value of optimal power it is possible to determine a minimum inductor's power which is needed to obtain uniform temperature distribution at desired temperature level, which is shown in Figure 4.

Based on shown in Figure 4 characteristics $P = f(T)$ it is possible to predict energy needed to obtain desired temperature level on the rotating cylinder surface.

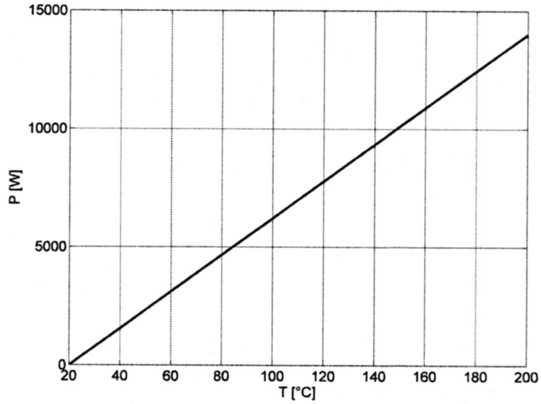


Fig. 4. Dependence of uniform temperature level of summarized heating power

3.2. Moving inductors with non-restricted heating power

As mentioned above, natural way of reduction of the R coefficient is to use a large number of small heating sources, but the realization of this idea is not possible at least due to real size of inductors. However, the effect of "dilution" can be obtained by heating through the appropriate motion of inductors along the cylinder axis.

The basic type of inductor's motion is shown in Figure 5. It can be called „lift" algorithm.

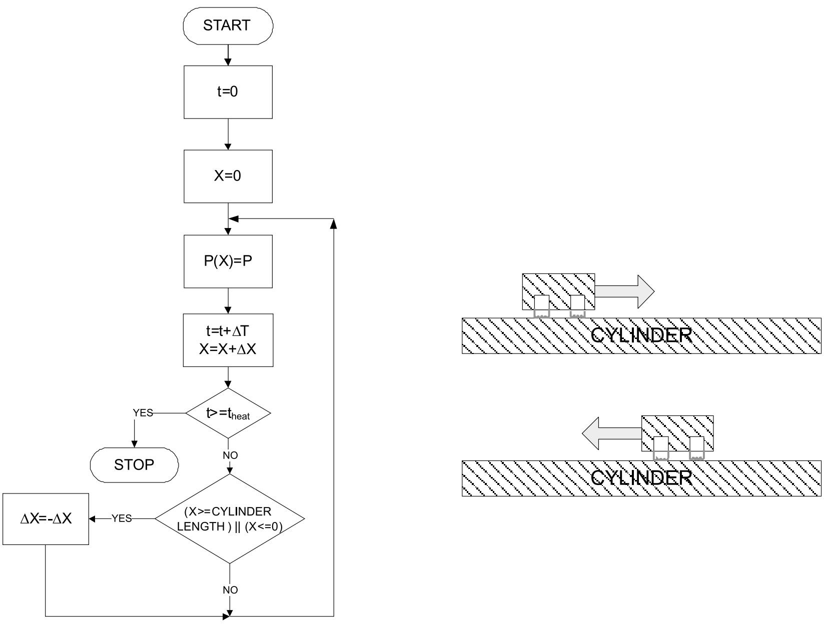


Fig. 5. Networks of inductor's moving by "lift" algorithms supplied by power P
ΔX – value of moving step of inductor, t – heating time

Using the shown above method of moving inductors a series of simulations of induction heating process of a rotating cylinder have been carried out. The effect of moving inductors was introduced by sequential activation of heat sources in the superficial elements of the model. Simulation covered the full cycle of warming up from the state of the cold cylinder, and subjected to detailed analysis of the temperature distribution in thermal steady state. It was assumed that the heating power providing from inductor to cylinder surface can take necessary values for appropriate (with minimum of *R* coefficient) heating. The study was conducted for various numbers of inductors and for some typical values of speed of inductors movement. Results of the calculations are shown in Figure 6.

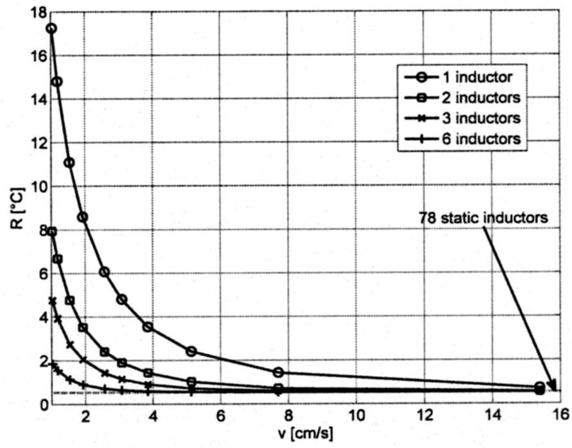


Fig. 6. Dependence of the *R* coefficient of the number of inductors and their linear velocity of inductors. The heating power of each inductor is not restricted

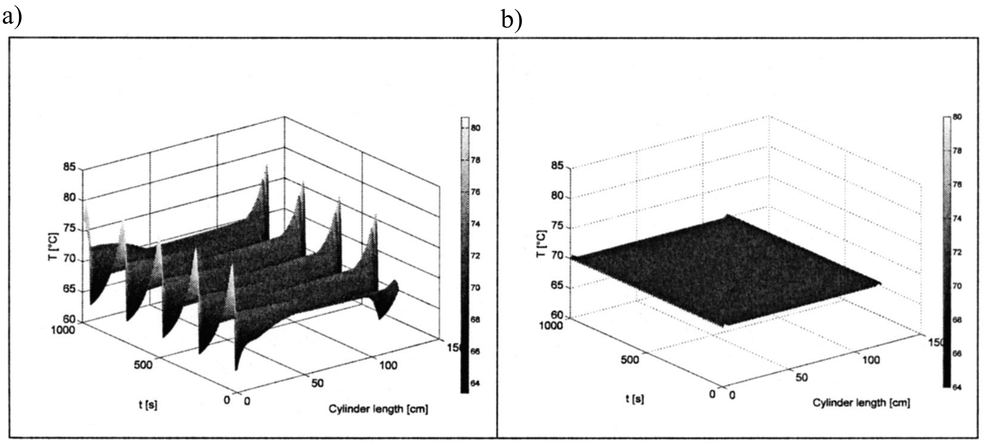


Fig. 7. Changes in time of cylinder surface temperature for inductors velocity equal: a) 1 cm/s; b) 15 cm/s

These simulations show that the best results were obtained using speed of inductor motion above 7 cm/s. Further increasing speed of inductors does not give a significantly greater improvement of temperature uniformity along the cylinder axis. Noteworthy is heating the cylinder with six moving inductors, where *R* coefficient not exceeds 2 °C even for velocity between 1 cm/s and 5 cm/s.

In addition, in velocity of inductors above 5 cm/s increasing the number of inductors (from 3 to 6) do not give a significant improvement in the quality of heat.

It should be noted, that inductors is usually supplied by the nominal power value.

Exemplary changes in time of cylinder surface temperature for one moving inductor are illustrated on Figure 7.

3.3. Moving inductors with restricted heating power

Shown above study describes a case in which value of heating power provided to the cylinder's mantle has no upper limit. In fact, each generator supplied the inductors has set the nominal power, which restricts possibilities of providing a uniform temperature distribution along the cylinder axis. Figure 8 shows the situation, in which each inductor gives nominal power limited to approximately 1.5 kW.

a) b)

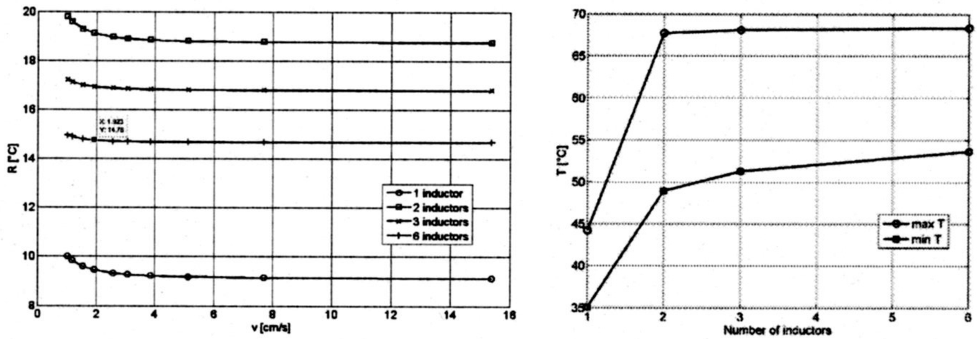


Fig. 8. Dependence of the *R* coefficient of the number of inductors and their linear velocities (a) and minimum and maximum value of temperature level obtained by usage varying number of inductors (b). The heating power of each inductor is limited to approximately 1.5 kW

Presented above results of simulation allow concluding that:

– The value of *R* coefficient is depending on number of inductors.
– Speed of inductor has little influence on the value of variation of temperature on the surface of the cylinder.
– The lowest value of *R* coefficient on the surface of the cylinder was observed for 1 inductor. The highest values are observed for 2 inductors.

Strictly speaking the lowest value of *R* coefficient can be observed in Figure 7a for 1 moving inductor. It could be regarded as a surprise until it is compared to data illustrated in Figure 7b. It can be noticed that for 1 inductor temperature of cylinder surface reaches lower value then for more inductors, because of too low summarized value of power heating (see Fig. 4)

3.4. Moving inductors with changing length of heating zones

Method of decreasing non-uniformity of temperature distribution obtained by usage of inductors supplied by restricted power is to divide the length of cylinder into several heating zones in which inductors are moving by "lift" algorithm. In addition, to each of heating zones different total energy is supplied.

Two cases have been taken into consideration: induction heating of the cylinder by 3 and 6 inductors.

Assume that for temperature level 70 ^{o}C, total energy per 1 second is about 3900 J. In case of 3 heating inductors one inductor should give a 1300 J. Taking into consideration the optimal power distribution (shown in Fig. 3a) the discretized length of the cylinder can be divided for zone 1 and zone 3 (from 1st to 22th and from 57th to 78th element), zone 2 (from 23rd to 56th element). By analogy for 6 inductors the cylinder must be divided for zones 1 and 6 (from 1st to 5th and from 72 to 78th element), zones 2 and 5 (from 6th to 22nd and from 55th to 77th element) and zones 3 and 4 (from 23rd to 39th and from 40 to 54th element). For 6 heating inductors one inductor should give about 650 J energy. Figure 9 shows described above two cases of cylinder dividing.

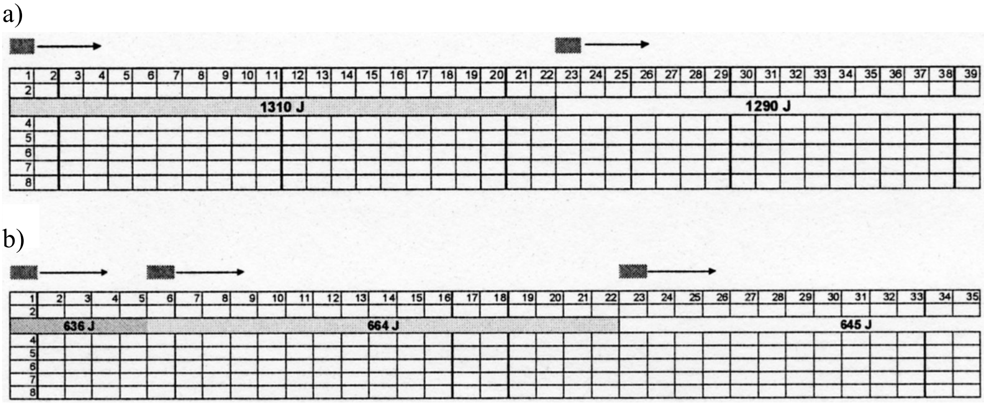


Fig. 9. Outline of half numerical model of the cylinder with marked zones of moving of each inductor (a) for heating by 3 inductors, (b) for heating by 6 inductors

Obtained results of are shown in Figure 10.

Comparing heating the cylinder by 3 and 6 inductors with restricted power it is easy to see that non-uniformity of temperature is significant lower for heating by six inductors. Moreover, for velocity above 2 cm/s this kind of supplied heating energy is practical independent of inductor's velocity. This gives hope to using this kind of supplying the cylinder to closed loop temperature control systems.

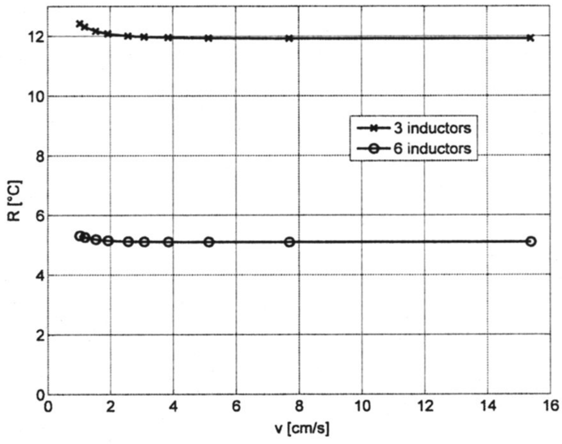


Fig. 10. Temperature *R* coefficient vs inductor's velocity

4. Conclusions

In the paper three variants of induction heating of the rotating cylinder by moving inductors have been examined. Those study shows dependence between uniformity of temperature distribution on the cylinder surface and number of heating inductors as well as variant of its velocity. Examined methods are compared in Figure 11.

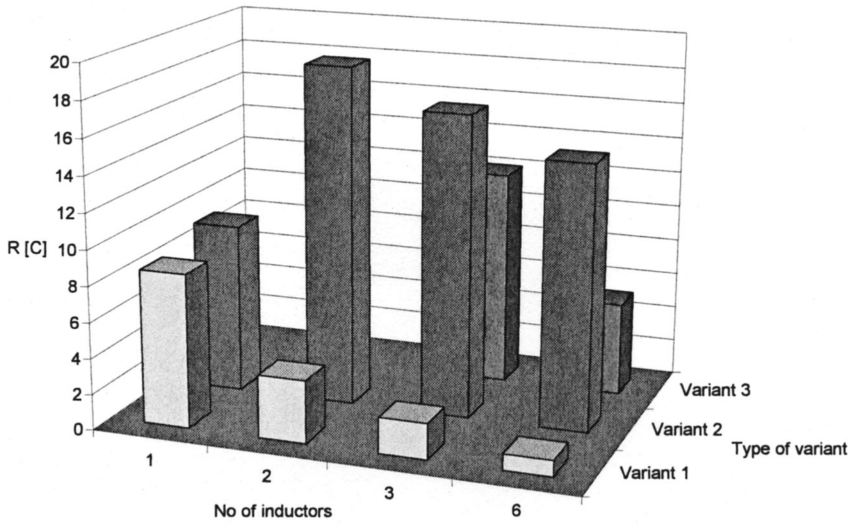


Fig. 11. Comparison of examined method of cylinder heating.
Variant 1 – heating by non-restricted power, variant 2 – heating by restricted power, variant 3 – heating by restricted power with variable length of heating zones

It is easy to notice that method of heating cylinder by moving inductors supplied by non-restricted power provides the best results from minimizing point-to-point temperature amplitude. However, practical reasons don't allow supplied to inductors arbitrarily large heating power. This implies using heating by restricted power with variable length of heating zones. Practical verification of presented simulations to be followed by upgrading the laboratory induction heating system of a rotating steel cylinder.

Acknowledgments

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