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Research Paper

Surface temperature control of a rotating cylinder heated by moving inductors

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HIGHLIGHTS

- A system for precise temperature control of a cylindrical surface is proposed.
- The rotating steel cylinder is heated by induction using a set of moving inductors.
- An infrared camera serves as a information source on thermal state of the cylinder.
- The tracking algorithm for inductors movement is better than the systematic one.
- Both simulation and experiments prove the effectiveness of the proposed methods.

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ABSTRACT

This paper concerns the precise temperature control of a cylindrical object heated by induction using a set of moving inductors. Induction heating by moving inductors in tandem with the rotating movement of the cylinder enables the temperature field to be formed and corrected in any region on the cylinder surface. The temperature control can be effectively supported by appropriately processed images acquired from the infrared camera. Since the movement of inductors over the surface of a cylinder plays a crucial role in temperature control, this paper presents two different algorithms for inductor positioning: a systematic algorithm and a tracking algorithm. In the systematic approach the inductors move periodically along the whole length of the cylinder generatrix while in a tracking one their movement is governed by a detailed analysis of an infrared image of the cylinder. Specific features of both solutions have been analyzed in this paper. Both simulations based on a numerical thermal model of the cylinder and experiments performed during the heating-up phase and during the normal work of a semi-industrial heating system prove the effectiveness of the proposed methods.

1. Introduction

Cylindrical objects are used in many industrial thermal processes for drying or forming materials, including in the textile, rubber and chemical industries. Papermaking machines, in which cylinders are a key element, provide a typical example of industrial thermal processes. Various heating methods can be applied [1,2], with one of the most promising being electrical heating by induction [3,4]. Such applications require effective temperature measurement, monitoring and control [5–9]. Many different methods of temperature control have been developed [1,5,6,10]. These commonly employ temperature scanners, thermovision cameras [11–13] and CCD cameras [14]. One important area of research and development is the induction heating of rotating cylinders in papermaking machines, along with precise control of the temperature on the cylinder surfaces [15–17]. This approach not only offers ecological benefits, but also enables the temperature profile of a cylinder's surface to be controlled in a flexible and selective way. Technical solutions have been developed in recent years using both static and moving inductors (also applied in other systems [18]), with thermovision cameras to provide information on the thermal state of the controlled object.

Temperature control of a cylinder surface using a set of movable inductors located along the cylinder generatrix requires two control loops working together (Fig. 1): one to control the positions of the inductors along the cylinder generatrix and one for the generating heat power distributed around the cylinder circumference. In such systems, the shape of the temperature field of the cylinder

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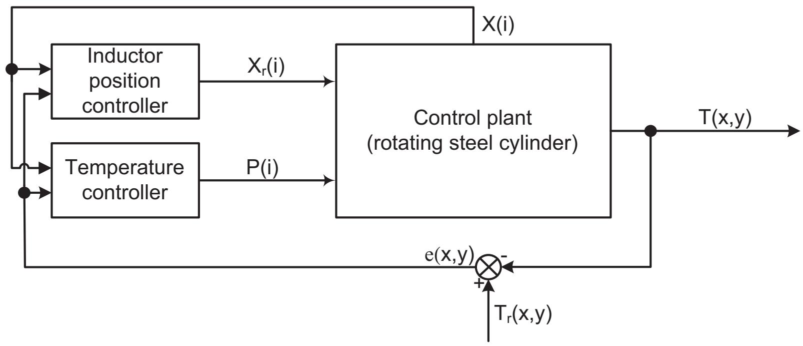

Fig. 1. Block diagram of a two-loop temperature control system for a cylinder surface (X_r – setpoint value of inductor position, X – measured position of inductor, P – heating power, T – measured temperature of cylinder surface, T_r setpoint value of cylinder surface temperature, e – temperature control error, I – inductor index, x, y – coordinates of cylinder surface).

surface results from the movement of heat sources and the rotation of the cylinder, as well as from the heating power generated in its mantle. Since the movement of inductors over the surface of a cylinder can play a crucial role in temperature control, this paper presents two different algorithms for inductor positioning: a systematic algorithm and a tracking algorithm.

This paper is organized as follows. Section 2 describes a temperature control algorithm governing the generation of heat power, based on spatial information concerning temperature field distribution. In Section 3, the two algorithms for controlling the movement of inductors are discussed and some of their features are described. Simulation studies, including the formulation of a numerical model of the heated object and analyses of different control conditions, are summarized in Section 4. Experimental results are given in Section 5.

2. Temperature control of the cylinder surface

During induction heating of a cylindrical surface, the temperature distribution at the surface T(x,y;t) depends directly on the heating power generated at each point on the cylinder mantel. Thus, in the most general case, it can be imagined that the temperature distribution can be controlled towards the reference T_r(x,y;t) distribution by a two-dimensional power field P(x,y;t) (Fig. 2, case 1). The easiest way to control such a temperature distribution is to use the two-dimensional, surficial version of an on-off control algorithm, described by Eq. (1):

$$e(x,y;t) = T_r(x,y;t) - T(x,y;t)$$
$$P(x,y;t) = \begin{cases} 0, & when\ e(x,y;t) \leqslant 0 \\ P_{max}, & when\ e(x,y;t) > 0 \end{cases} \quad (1)$$

where e – control error, P – heating power, T_r – temperature setpoint, T – measured value of temperature, P_{max} – maximal value of heating power, x, y – coordinates of the cylinder surface.

The generation of such a heating power field is possible only theoretically, using an infinite set of static, point-wise inductors placed at all points on the rotating cylinder. However, the control law (1) can be realized in an approximate way using a heating system that contains a reduced number of finite-size inductors (Fig. 2, case 2). In such systems, each inductor affects a specified part of the cylinder, and the temperature field can thus be considered as the average value for that region. It follows that the same process of averaging should be applied to determine the reference temperature value. Assuming that there are $m \times n$ inductors of length l and width w over the entire cylinder surface (m along the cylinder generatrix and n along its circumference), the XY coordinate system can be replaced with an IJ coordinate system, where i and j are inductor indexes along the generatrix and the circumference of the cylinder, respectively. In the case of total adjacency of inductors in both directions, Eq. (1) can be rewritten in the form (2):

$$T_r(i,j;t) = \overline{T_r}(x,y;t) : x \in \langle (i-1)\cdot l; i\cdot l\rangle \wedge y \in \langle (j-1)\cdot w; i\cdot w\rangle$$
$$T(i,j;t) = \overline{T}(x,y;t) : x \in \langle (i-1)\cdot l; i\cdot l\rangle \wedge y \in \langle (j-1)\cdot w; i\cdot w\rangle$$
$$e(i,j;t) = T_r(i,j;t) - T(i,j;t)$$
$$P(i,j;t) = \begin{cases} 0, & for\ e(i,j;t) \leqslant 0 \\ P_{max}, & for\ e(i,j;t) > 0 \end{cases} \quad (2)$$

Due to the rotational motion of the cylinder, the availability of cylinder surface along its circumference can be ensured by arranging the inductors only along the generatrix of the cylinder (Fig. 2, case 3), synchronizing time instants of power generation with

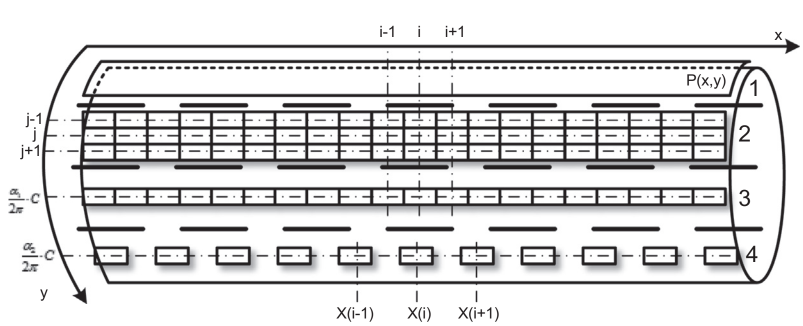

Fig. 2. Various ways of generating heating power (arrangement of inductors). 1 – surface power distribution layer, 2 – set of static inductors covering the whole surface, 3 – linear set of adjacent static inductors along the cylinder generatrix, 4 – set of linearly-arranged moving inductors.