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# Study on temperature distribution non-uniformity of inner grooved copper tubes during pit furnace annealing

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ABSTRACT

Inner grooved copper tubes have been widely applied as a kind of enhanced heat transfer tube. Annealing in a copper-tube pit furnace has a relatively high cost to performance ratio, and its operation at elevated temperature and the temperature uniformity of workpieces inside the furnace are difficult to control. Considering the structural characteristics of a pit furnace and using the wall function method, we establish a three-dimensional turbulent flow fluid–structure interaction heat transfer model and compute and analyze the flow field and temperature field inside the furnace. Methods for improving the fan speed, the heights of the gas-guiding cylinder, and the load frame are given. The temperature of critical points inside the furnace during annealing of the copper tubes has been measured and then compared with simulated values, directly validating the accuracy of the computation results. This study not only offers specific methods for improving the annealing quality of inner grooved copper tubes but will serve as a reference basis for quantifying pit furnace improvement.

## 1. Introduction

Subject to environmental protection requirements including air protection, the air conditioning and refrigeration industry in the future will need heat exchangers that enable lower energy consumption of equipment, have smaller volume, and are more environmentally friendly [1–3]. As one kind of widely used high-performance heat transfer tubes, copper tubes call for higher requirements for processing quality [4–6]. In copper processing enterprises, the casting-rolling method is universally used to make copper tubes [7], and, in this case, work hardening occurs in the tubes after the inner grooves take shape [8,9], so the tubes have to be annealed to improve their overall mechanical properties [10]. Recrystallization annealing is the final, crucial process of manufacturing copper tubes in the casting-rolling method. The annealing temperature directly impacts the stability of the mechanical properties of inner grooved copper tubes. With too high an annealing temperature, the copper tubes are prone to local overheating, thereby decreasing their elongation; with too low an annealing temperature, residual stress is not effectively eliminated, increasing the hardness, which can easily lead to cracking during tube bending [11–13].

Planetary rolling, internal grooving, and annealing are three critical process steps of producing high quality copper tubes. In terms of annealing, the pit-type annealing furnace has high benefit-cost ratio, and is thus widely applied. But in practical production, annealing of copper tubes hardly guarantees temperature consistency. In engineering application, improvement in copper tube annealing process mostly depends on high-cost industrial test. In order to lower experimental cost while improving annealing quality, flow field and temperature field driven by a high-speed blower have to further understood, this brings a challenge to practitioners. Focusing on copper tube annealing process step, this paper computes and analyzes intrafurnace flow field and temperature field in an attempt to further improve copper tube quality.

## 2. Mathematical model

In this paper we adopt a time-averaging method commonly applied in turbulent flow research nowadays (i.e., turbulent flow is deemed as an overlay of time-averaged flow and transient pulsating flow), and the fluid–structure interaction heat transfer model in FLUENT was used to compute the flow field inside the pit-type annealing furnace and the heat transfer process of various solid parts. The Reynold number of the fluid flow is about 10,000, and the flow state is turbulent flow. For numerical simulation of

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## Nomenclature

| | |
|---|---|
| $k_p$ | turbulence kinetic energy of node *P* |
| $\Delta y_p$ | distance from the node to the wall surface |
| $T_P$ | temperature at node *P* within the governing volume adjacent to the wall surface |
| $T_w$ | temperature at the wall surface |
| $q_w$ | heat flux at the wall surface |
| $C_\mu$ | average speed of the logarithmic rate |
| $u_p$ | node *P* with the wall surface parallel to the flow velocity |
| $k$ | heat transfer coefficient |

| | |
|---|---|
| $c_P$ | specific heat capacity |
| $q'$ | internal heat source of the solid |
| $a$ | gas-guiding cylinder height |
| $b$ | load frame height |

*Greek*

| | |
|---|---|
| $\rho$ | density of the solid |
| $\mu$ | dynamic viscosity of the fluid |

the flow field in a pit furnace in this paper, the standard $k$–$\varepsilon$ model was adopted, but, in light of insufficient turbulent flow development in the zone near the furnace wall, the wall function method was further introduced. The related physical quantity of the near-wall zone correlates to an unknown quantity of the core portion of the turbulent flow zone. Hence information on near-wall fluid flow can be directly obtained without solving for the fluid flow process in the near-wall zone. The equations of the wall function method are

$$\begin{cases} u^+ = \frac{1}{k} In(Ey^+) \\ y^+ = \Delta y_p (C_\mu^{1/4} k_p^{1/2}) \\ \tau_w = \rho C_\mu^{1/4} k_p^{1/2} u_p / u^+ \\ T^+ = \frac{(T_W - T_P)\rho c_p C_\mu^{1/4} k_p^{1/2}}{q_w} \end{cases} \tag{1}$$

where $y^+$, $u^+$, and $T^+$ are three dimensionless quantities, representing distance, velocity, and temperature, respectively, and $E = 9.8$.

In computation of the heat transfer process inside a pit-type annealing furnace, the equations used for fluids differ from those used for solids, and among governing equations the following energy conservation equation was used for a nitrogen gas heat transfer process:

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho U h) = \nabla \cdot (k \nabla T) + S_T \tag{2}$$

where $S_T$ is a generalized source item [14].

The following heat conduction equation was used for solid parts inside the furnace:

$$\frac{\partial(\rho T)}{\partial t} = \nabla \cdot \left( \frac{k}{c_p} \nabla T \right) + q' \tag{3}$$

In numerical simulation computing of fluid–structure interaction (FSI) temperature field inside the pit-type annealing furnace, certain condition shall be satisfied in order to guarantee continuous temperature and heat flow on the interface where fluid zone and solid zone adjoin:

$$\begin{aligned} T_W|_{\mathrm{I}} &= T_W|_{\mathrm{II}} \\ q_W|_{\mathrm{I}} &= q_W|_{\mathrm{II}} \end{aligned} \tag{4}$$

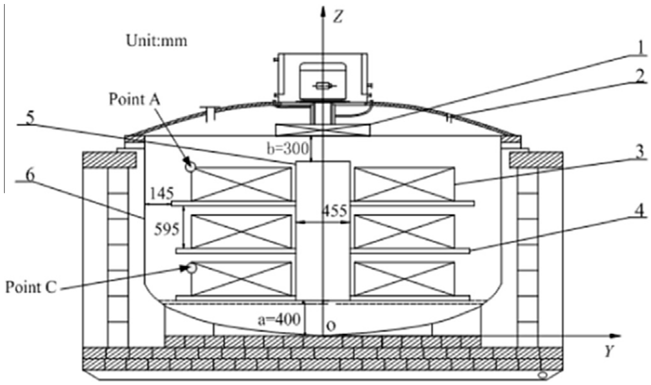

**Fig. 1.** Schematic of the pit-type annealing furnace. (1. Blower. 2. Furnace cover. 3. Copper tube coils. 4. Load frame. 5. Gas-guiding cylinder. 6. Retort.).

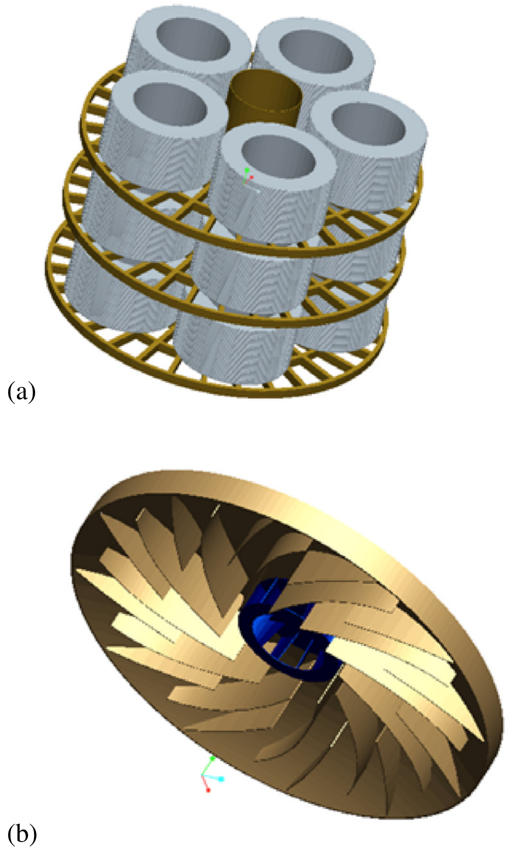

**Fig. 2.** Geometric model. (a) Copper tube coils and load frame. (b) Furnace cover and blower.

**Table 1**
The initial condition.

| | |
|---|---|
| Overall furnace dimensions | $\phi 5100 \times 3400$ (mm) |
| Dimensions of the copper tube to be heated | $\phi 7 \times 0.29$ (mm) |
| Size of coils | $\phi 900 \times 300$ (mm) |
| Height of coils | 510 (mm) |
| Preset heating temperature | 410 (°C) |
| Height of the forced convection blower | 219 (mm) |
| Inside diameter | 480 (mm) |
| Outside diameter | 698 (mm) |
| Rotational speed | 900 (rpm) |
| Initial temperature | 30 (°C) |
| Heating time | 180 (min) |