International Journal of Heat and Mass Transfer 125 (2018) 104–115

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Study on influence of lateral liquid feeding into crystallizer on solidification process of copper billets

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ARTICLE INFO

Article history:
Received 27 November 2017
Received in revised form 13 April 2018
Accepted 15 April 2018

Keywords:
Copper processing
Crystallizer
Flow field
Structure field
Cast
Copper tube

ABSTRACT

The first process in the production, namely, horizontal continuous casting process, directly influences the performances of finished copper tubes. Numerical calculation and comparative analysis were conducted for the flow field and microstructural field of the flow and solidification of casting liquid in two kinds of crystallizers for horizontal continuous casting. It was found that the internal factors influencing the internal heat exchange effect of crystallizer and the microstructural uniformity of casting billets are swirl effect, and turbulence intensity. The structural parameters of liquid inlet of a crystallizer with lateral opening, i.e., the forward tilt angle and lateral tilt angle of liquid inlet, were analyzed from the source, and the reasonable parameter values of liquid inlet for improving the quality of casting billets were finally obtained with the mean value of maximum spin speed, the turbulence intensity, and the microstructural grain size of casting billet as evaluation criteria. The accuracy of the numerical calculation was visually verified through metallographic experimental analysis. This study provides measurable reference theoretical basis for production of inner grooved copper tube with efficient heat exchange.

1. Introduction

Inner grooved copper tubes are efficient heat exchangers universally used in such industries as refrigeration. For example, Yang et al. [3] found that the heat transfer effect of nano refrigerants in an internal thread tube was superior to a smooth tube. With the constant progress of copper processing technology in the future, inner grooved copper tubes are developed gradually towards the thin wall and thin-tall tooth directions, to increase the heat exchange efficiency, thus to achieve the purposes of energy saving, environmental protection, and efficient utilization of energy. This also increases the manufacturing difficulty in the copper processing industry. Li et al. [12] used FE software to analyze the deformation of grooves, distribution of equivalent stress and strain, and pointed out that when the shrinkage rate increased to 50.0%, apparent collapse occured. Zhang et al. [5] analyzed the folding defects formed both on one side of the fin and on the bottom of inner grooves of the copper tubes, and proposed efficient measures to prevent the folding defects. Yu et al. [13] calculated and analyzed the evolution of defects in the production of capillary copper tubes using FE software, and found that the inner surface of capillary copper tubes could be destructed along with accumulation of sludge, which would be the cause of throughput capacity fluctuations. Li et al. [9] found that the temperature of the tubes increased from about 20 °C to 700 °C in three-roll planetary rolling, which not only reduced the rolling force, but also improved the performance of the rolled copper tubes. Han et al. [6,14] gave methods for improving the fan speed, the heights of the gas-guiding cylinder, and the load frame for annealing in a copper-tube pit furnace, and discussed influences of different parameters on temperature uniformity.

To raise the finished product rate in manufacturing thin-wall inner grooved copper tubes, improving the casting quality of copper tube billets first is of important significance. Refining the grains of casting billet is an effective direction, including such methods as using electromagnetic equipment, adding inoculant, electric pulse treatment, and vibration. Li et al. [10] found that with the imposition of rotating electromagnetic field, finer and more homogeneous solidification structures could be obtained. Liu et al. [4] found that the mechanical properties and the microstructures of Al–7.5Si–4Cu cast alloys were improved immensely by combining addition of grain refiners and modifiers compared with the individual addition and cast conditions. Zhang et al. [11] indicated that the conform process induced obvious grain refinement. To investigate the effect of electromagnetic field on horizontal continuous casting process, Wu et al. [8] developed a comprehensive three-dimensional model, and found that under the electromagnetic field the microstructure of

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.068
0017-9310/

Nomenclature

ρ_s	the density of copper liquid, kg/m^3	G_k	the growth rate of turbulent kinetic energy
P	the pressure of copper liquid, Pa	ε	the dissipation rate of turbulent kinetic energy, m$^2 \cdot$ s^{-3}
μ_{eff}	the effective viscosity coefficient, kg $\cdot$ m^{-1} $\cdot$ s^{-1}	n	the density of grains
μ_1	the molecular viscosity coefficient, kg $\cdot$ m^{-1} $\cdot$ s^{-1}	ΔT	the degree of supercooling
μ_t	the turbulent viscosity coefficient, kg $\cdot$ m^{-1} $\cdot$ s^{-1}	n_{max}	the maximum nucleation density
μ	the dynamic viscosity of copper liquid, kg $\cdot$ m^{-1} $\cdot$ s^{-1}	$\sigma_{\Delta T}$	the standard deviation
k	the turbulent fluctuation kinetic energy, m$^2 \cdot$ s^{-2}	ΔT_{max}	the maximum degree of supercooling for nucleation

Table 1
Model data table.

Parameter	Lateral opening	Bottom opening
Size of casting billet (mm)	$\phi 92 \times \phi 35$	$\phi 92 \times \phi 35$
Size of crystallizer (mm)	$\phi 120 \times 400$	$\phi 120 \times 400$
Wall thickness of crystallizer (mm)	14	14
Size of liquid inlet (mm)	$4 \times \phi 8$	$6 \times \phi 8$
Size of copper sleeve (mm)	$\phi 140 \times 180 \times 10$	$\phi 140 \times 180 \times 10$

the clad composite hollow billet became fine and the diffusion of the elements at the interface was promoted. Peixoto et al. [7] assessed the main features of the flow field inside a beam blank continuous casting mold through mathematical and physical modeling techniques. In another study, Viswanath et al. [1] analyzed the free surface flow characteristics during mold filling in a low pressure casting process through water model experiments and numerical simulations. Ji et al. [2] pointed out that the jet exiting from the nozzle port swings, which was not steady, and turbulent velocity variation frequencies decreased with distance from the nozzle port region.

The horizontal continuous casting of copper tubes are affected by the gravity and cooling water, easily lead to the upper and lower parts of uneven grain size. The size of the grain directly determines the tensile strength and elongation of copper. In this paper, based on the features of horizontal continuous casting of copper tubes and the crystallizer with bottom opening used by a factory, a crystallizer with lateral opening was designed and applied, and a forward tilt angle and lateral tilt angle transformation scheme was proposed for the liquid inlet structure of the crystallizer, so as to effectively improve the microstructure of casting billets. Therefore, the flow, solidification and crystallization processes of casting billet during copper tube casting were analyzed and studied in detail. Numerical

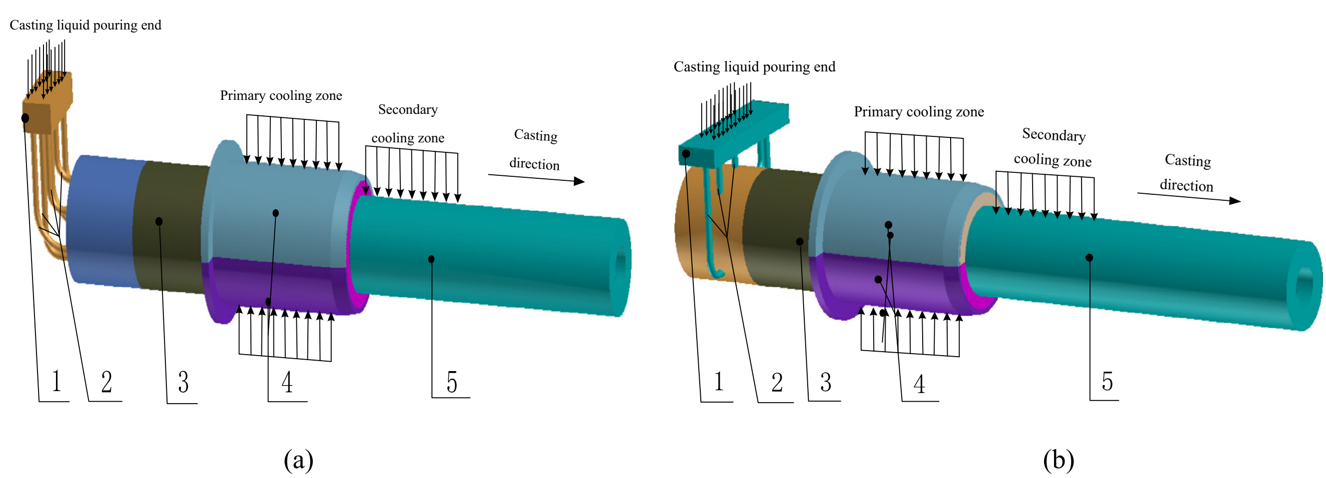

Fig. 1. Assembly drawings of crystallizer. (a) Bottom opening; (b) lateral opening. (1. Virtually equivalent liquid feeding chamber. 2. Liquid inlet of crystallizer. 3. Graphite crystallizer. 4. Cooling copper sleeve. 5. Casting billet for continuous casting.)

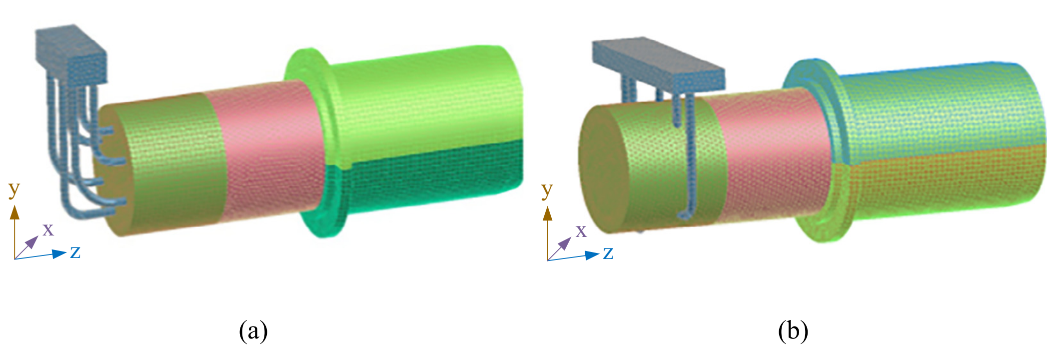

Fig. 2. Meshing of crystallizer. (a) Bottom opening (The element number: 45876); (b) lateral opening (The element number: 48966).