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Investigation of impeller design and flow structures in mechanical stirring of molten aluminum

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A B S T R A C T

This study investigated the flow characteristics of aluminum melt agitated by differently shaped impellers. A typical impeller used in the aluminum industry has twisted blades. The present study examined the effect of twisting angle on the flow pattern through PIV experiments and numerical simulation using water model. The results revealed that the twisting angle affects the strength and direction of discharge flow. The strength of discharge flow became weaker with increasing the twisting angle while the flow direction was influenced by both the front blade surface of impeller and space interval between the adjacent blades. The structure of trailing vortices was found to be also varied depending on the impeller twisting angle.

1. Introduction

Secondary aluminum is getting much attention because it does not require the process of electrolytic refining, which consumes a huge amount of electric power. Moreover, the secondary aluminum can be produced from cheap aluminum scrap. These advantages make secondary aluminum attractive for the aluminum industry. However, in response to steadily growing demand for aluminum automotive sheets and body parts for light-weight vehicles, aluminum industry will face significant challenges in recycling automotive scrap in the near future. Scrap contains undesirable metals, chemical compounds, and other impurities, which have to be removed. Processing of aluminum scrap includes shredding of dismantled components, separation from non-aluminum materials and sorting of different aluminum alloys before melting. Like any other developing technology, these operations are not perfect and suffer from a number of limitations. As a result, such elements as iron, chromium, nickel, copper, magnesium as well as tramp elements, notably calcium and sodium, are inevitably mixed into the aluminum scrap during processing. Many of these elements exhibit a significant degree of mutual incompatibility in aluminum alloys used in various applications. That is why the aluminum smelting and following melt treatment is the last operation where the impurities can further be removed or at least substantially reduced. It is worthy of note that a widely-used practice of diluting aluminum scrap with pure primary aluminum to solve the above problems is not a cost-effective strategy in aluminum recycling. Besides, the production of primary aluminum is not an environmentally friendly technology because it uses a lot of energy. Therefore, improvement in efficiency of impurity removal during the molten scrap treatment is highly desirable from both economic and environmental aspects.

It is a common practice in the melt treatment to use a mechanical stirring in combination with other techniques, such as gas injection and flux addition. A variety of rotary impeller systems have been used for these purposes aiming at a better dispersion of the gas bubbles and molten flux in liquid aluminum. In the aluminum melt treatment, the shape of impeller is severely restricted in comparison with the other areas like chemical engineering, food processing, and biotechnology. The main features required for impellers in the aluminum industry are (1) heat-resistance and (2) sufficient mechanical strength to prevent any damage as well as (3) chemical stability to avoid any contaminations during the stirring operation. Also, the material of which impeller is made must be well machinable. The above requirements impose strict limitations on the choice of material and shape required for impellers used in the treatment of liquid aluminum. As a rule, impellers of large sizes are made of graphite. However, graphite has low mechanical strength and, therefore, blades and other parts of impeller should be made thick enough to be stiff. This imposes limitations on the impeller shape. The impeller geometry used in aluminum industry differs depending on the furnace shape. Impellers of the first group are used for degassing and inclusion removal in crucible-type furnaces, while impellers of the second group are used for the melt treatment in hearth-type melting and/or holding furnaces. As a rule, crucible-type furnace has a large aspect ratio (ratio of depth to diameter) and cylindrical shape. On the other hand, hearth-type furnace has mostly a small aspect

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ratio and rectangular shape. Saternus (2012) reviewed the impeller geometry used in purification of molten aluminum in the crucible-type furnaces. A large variety of impellers has been designed and used for molten aluminum treatment in both continues and batch processes. Most of the gas injection methods in the crucible-type furnaces use rotary impellers without large blades. Below is a brief outline of the recent results obtained in the crucible-type furnaces.

Warke et al. (2005a) conducted an Euler-Euler simulation to evaluate the phenomena occurring during mechanical stirring combined with gas injection using a rotary impeller. The simulation indicated that the volume fraction of purge gas is larger near the impeller shaft. Based on the simulated results, Warke et al. (2005b) created a mathematical model to predict the hydrogen and inclusion transport in the aluminum melt. In their studies, the efficiency of smelting is assessed on the basis of mass transfer coefficient and population balance. Johansen et al. (2004) simulated inclusion movement in an agitated tank. Their simulation adopted the diffusion equation with the gravitational force for the particle inclusion transport. However, the mathematical model was unable to predict the entrainment of inclusions adequately. Mirgaux et al. (2009) simulated an aluminum purification process focusing on inclusions floated by gas injection. The authors adopted a population balance equation for the transport of inclusions. Gómez et al. (2013a) simulated a bubble injection through a rotary impeller using an Euler-Euler model. They investigated the effect of gas injection rate on the bubble dispersion and flow pattern. Gómez et al. (2013b) also conducted an experimental investigation using the same system. The authors found that the swirling motion is dominant in the vessel, and the size of surface vortex generated at the free surface is strongly affected by the rotation speed of impeller. Besides, the same research group performed similar simulations and experiments. Hernández-Hernández et al. (2016) compared the bubble distribution in a water model agitated by impellers of three types. Abreu-López et al. (2017) conducted the related simulation using an Euler-Euler model. Their results showed that the newly-developed impeller has a number of advantageous features in stirring efficiency with gas injection. Mancilla et al. (2017) introduced a new non-dimensional parameter which evaluates the impeller pumping ability. Wan et al. (2018) investigated the efficiency of flux treatment using stirring vessel filled with aluminum melt. In their cylindrical furnace, the middle-depth location of impeller was the best for aluminum melt purification.

On the other hand, impellers used in the hearth-type melting and/or holding furnaces have a different shape, particularly large blades to ensure a strong discharge flow. In the furnaces of this type, powdered flux materials or chlorine gas is injected through rotary impellers to remove the above-mentioned impurities. Under these conditions, mainly two impeller functions are required: uniform stirring and bubble (droplet) dispersion. However, because tons of aluminum melt have to be treated, the mechanical stirring should be efficient enough to be applicable in short time operations. To satisfy these requirements, propeller-like impellers have generally been used in the aluminum industry.

Studies using impeller with blades for stirring in the hearth-type melting/holding furnaces and their related issues are briefly outlined below. Bilodeau and Kocaefe, 2001 investigated the removal of alkali elements from molten aluminum in a holding furnace. The authors used a thick propeller-type impeller for both the experiments and simulation aiming at removal of alkali impurities from the aluminum melt. However, the agreement between the experimental and numerical results is very poor. Kiss and Bilodeau (2001) investigated the dispersion of bubbles produced by gas injected from the bottom of impeller using water model. The authors used a thick six-blade propeller-type impeller. They found that the leading edges of the impeller blades produce small bubbles. Kerdouss et al. (2005) applied a thick five twisting blades impeller, which was capable of generating primary and secondary vortices in a water model. These vortices are caused by trailing vortex elongated from the rear surface of blade. The trailing vortex traps bubbles and makes the bubbles lines, which is vital for stirring efficiency and bubble dispersion. Besides, the authors found that there is a difference in the flow directions between a single-phase flow and a gas-liquid multiphase flow. With gas injection, the flow direction is converted to more perpendicular one relative to the impeller shaft. Riverin et al. (2006) developed a new crucible metal purification system using an impeller with teeth-like blades. Bujalski et al. (2004) investigated a stirring water model with different impeller types. The impeller shapes were the same as that of a typical impeller used in chemical plants in order to develop downward flows. These authors investigated the effect of impeller shape on the mixing time. Chiti et al., (2004) proposed an analytical model to predict the mixing time in a melting furnace using propeller-type impellers, which produce downward flows. Yamamoto et al. (2018) investigated the mass transfer in the typical melting furnace using water model experiments and numerical simulation to investigate the flow structures.

Investigations on stirring by the similar blade shape impellers used in aluminum melting/holding furnaces can be found in other research fields. In chemical, food and biological processes, pitched-blade and propeller-blade impellers have been applied, however, the width of these blades is thinner compared with that used in the aluminum treatment. Roy et al. (2010) investigated turbulent flow structures generated by an impeller with four 45-degree pitched blades. They found that the macro-instability and trailing-edge vortices are made simultaneously. Aubin et al., (2004) investigated the calculation accuracy of turbulent flow produced by an impeller with 45-degree pitched blades using a number of turbulent models and numerical schemes. Murthy and Joshi (2008) validated turbulent modeling for a flow agitated by impellers of various designs such as disk turbine, pitched blades with different angles, and hydrofoil. Simulation results using the impellers which develop the vertical flow, are also summarized in Joshi et al. (2011).

As discussed above, the turbulent flow structures generated by impellers of different shapes have been investigated in the food, chemical, and biological engineering. On the other hand, the characteristics of flow produced by thick impellers used in the aluminum industry have not been investigated yet. The present study, therefore, focuses on the mechanical stirring efficiency and structures of turbulent flows produced by impellers used in aluminum melting/holding furnaces. First of all, the flow structures of a single-phase flow are investigated. To investigate these phenomena, the authors conducted Particle Image Velocimetry (PIV) measurements and Computational Fluid Dynamics (CFD) simulation of a water bath stirred in a cylindrical vessel by impellers of the same design as those used in the aluminum industry.

2. Experimental methods and procedures

Fig. 1 shows the experimental setup used in the present study. Various impellers were used to investigate the structure of flow in a water bath. The impellers were mounted on a vertical shaft and rotated by a motor in a cylindrical acrylic tank of 192 mm in the inner diameter. Water was filled to a height of 320 mm. The rotation speed of impeller was set to 300 rpm. The impeller shapes used are shown in Fig. 2. The diameter and height of each blade were 60 mm and 12 mm, respectively. Under this condition, the stirring Reynolds number, Re equals to 18,000. Re is defined as $Re = ND^2/\nu$, where N is the impeller rotation speed [rps], D is the tip-to-tip impeller diameter [m] and ν is the kinematic viscosity [m^2/s]). The blade thickness was 11 mm, which is thicker compared with typical impellers used in the chemical, food and biological processing., A 3D printer (Finder FLASH FORGE, Apple Tree Co., Ltd.) was employed to fabricate an impeller of a specific shape using a polylactic acid resin. Approximately two hours were taken to fabricate one impeller. Then, the fabricated impeller was jointed to the motor shaft. To prevent the light scattering at the impeller and shaft, the impeller surface was painted black.

A Particle Image Velocimetry (PIV) system was applied to record the