Velocity Characteristics of Air-mist Jet during Secondary Cooling of Continuous Casting Using PIV and LDV

Ya-zhu ZHANG,^{1,2)} Zhi WEN,¹⁾ Zeng-wu ZHAO,^{2)*} Jun HUANG,²⁾ Wen-fei WU²⁾ and Bao-wei LI²⁾

1) School of Energy and Environment Engineering, University of Science and Technology Beijing, Beijing, 100083 P. R. China.

2) Key Laboratory of Integrated Exploitation of Bayan Obo Multi-Metal Resources, Inner Mongolia University of Science and Technology, Baotou, 014010 P. R. China.

(Received on November 2, 2018; accepted on January 10, 2019; J-STAGE Advance published date: April 1, 2019)

Air-mist jet is increasing in number of facilities for a variety of applications in surface cooling. It can provide a good balance of high heat removal capability. The present study focused on the velocity characteristics of the air-mist jet produced by a fan-shaped nozzle under different operating conditions during secondary cooling of continuous casting. To this end, the authors conducted experimental research, employing optical techniques, *i.e.*, particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) to measure a fanlike flow field in an air-mist jet. However, the researchers observed different results between the PIV and LDV measurements, mainly at the outlet of the nozzle region. This article identifies velocity characteristics of air-mist jet during secondary cooling of continuous casting, which is divided into two parts for velocity distribution structure of air-mist jet, and self-similar and well described by a Gaussian distribution for the whole flow field. The study provides a suggestion to optimise the flow field of a fanlike air-mist nozzle for different working conditions. Furthermore, the behavior of gas-liquid two-phase flow can be understood by examining the difference in velocity characteristics between the PIV and LDV measurements of the air-mist jet.

KEY WORDS: air-mist jet; PIV; LDV; secondary cooling of continuous casting; velocity characteristics.

1. Introduction

A number of applications require efficient cooling techniques. High efficiency and high heat flux are especially important for modern industrial and technological applications, such as in the cooling of electronic components, nuclear power generation, high-power lasers, and metallurgical processes.

Air-mist jet cooling is a promising technology with a variety of applications. Since the air-mist jet can efficiently and uniformly remove high heat flux, air-mist jet cooling is widely used in the secondary cooling of continuous steel casting practice.¹⁾

To guarantee productivity and slab quality, an appropriate secondary cooling is necessary, which enables a fast and uniform heat extraction in the steel casting. Industrial practice has confirmed that bulging, cracks, and segregation could occur in the steel slab if the secondary cooling process is not optimised.

The nozzle characteristic significantly affects the amount of heat that can be removed during casting. To optimize heat transfer conditions at the hot interface, researchers must experimentally investigate nozzle performance with its cold characteristics. Many reports have been published regarding

nozzle characteristics of air-mist jets,^{2–7)} such as the influence of nozzle design,²⁾ procedure on nozzle flow,^{3,4)} cooling intensity,⁵⁾ the fluid dynamics of air mist,⁶⁾ size and velocity characteristics of droplets⁷⁾ and so forth. The flow characteristics of the air-mist jets were experimentally identified with respect to the droplet size and velocity distribution, spray cone angle, and breakup length. In addition, Jose E. Navedo,⁸⁾ measured the droplet velocity during the air-mist jet cooling and found that the critical heat flux was considerably changed by the droplet velocity. Hernandez *et al.*⁶⁾ and Minchaca *et al.*⁷⁾ studied drop velocity well. However, detailed velocity characteristics of air-mist jet are missing in the aforementioned studies. In particular, optimising the velocity distribution of different working conditions in the same nozzle has not been understood. Due to the fact that it might significantly influence the steel cooling in terms of the cooling intensity and uniformity of the heat removal, a more effective method to optimize exact velocity characteristics is necessary.

LDV and PIV are two well-known methods for non-intrusive flow diagnostics. But the LDV technique can only be suitable for measuring a single point. In contrast, PIV can be used to obtain the spatial distribution of particle velocities of the whole flow field. There are a number of studies on measuring velocity distribution of the spray process by using either PIV^{1,9,11,12)} or LDV.¹⁰⁾ These studies visualized the process using velocity field reconstruction. Since

* Corresponding author: E-mail: zhengwu@imust.cn

DOI: <https://doi.org/10.2355/isijinternational.ISIJINT-2018-735>

the researchers were convinced that this was a powerful method, the limitations of either PIV or LDV in measuring velocity distribution of the flow were seldom considered. Currently, a few researchers^{13–15} have attempted to combine these two techniques (*i.e.* PIV and LDV) in their studies, in which large differences between the results of PIV and LDV measurement were observed at high shear regions. The difference was considered to be caused by the spatial and temporal resolution and the limited frame number of PIV.

Air-mist is an atomization in which pressurized gas enhances the liquid breakup. At the exit orifice, gas expands rapidly and scatters the liquid into smaller fractions, and then the air-mist develops in time and space. The velocity and size of drops in this breakup process are changing, especially near the nozzle orifice. This paper aims to precisely identify (through planar seeding-free analysis) the velocity characteristics of the air-mist jet in secondary cooling of continuous casting. The optimizing velocity distribution of different working conditions in the same nozzle is suggested for the air-mist jet secondary cooling. At the same time the adaptability of the PIV and LDV techniques is assessed for measuring the velocity field of the gas-liquid two-phase flow.

2. Experimental Method

2.1. Experimental Setup and Test Conditions

Figure 1 shows a schematic layout of the experimental setup. This system comprised four major parts: (1) water supply system, (2) gas jet generation system, (3) PIV measurement system, and (4) LDV measurement system. The water supply system mainly included a water tank, a water pump (a frequency converter was used to control the impeller frequency of the pump and stabilize the output water flow), a mass flow meter, and an air pressure gauge. The water flow rate was measured by a JHLWGYB-10-25F intelligent turbine flow meter with range of 0.2–1.2 m³/h and precision of $\pm 0.5\%$, while the operation pressure was measured using a pressure gauge. The gas jet generation system included an air compressor, a pressure stabilizing

tank, a mass flow meter, and an air pressure gauge. The air flow rate was measured by the JHLWQ-25 intelligent turbine flow meter with range of 0.175–17.5 Nm³/h. It should be noted that fine structured meshes were located above the tank to avoid impact velocity (*i.e.*, rebound droplets). The details of the PIV and LDV measurement system can be seen in section 2.2.

On the left hand of the Fig. 1, it described the detailed external dimensions of the air-mist spray nozzle. This kind of air assisted flat nozzle is commonly employed to produce the air mist for secondary cooling of continuous casting. It has an air inlet entering the nozzle in line with the exiting spray tip. The water inlet enters 90° to the air inlet and impinges on a concave target bolt surface which is against the water stream shattering. An air stream rushes past the target bolt to further break up the water stream. The water and air then mix in the mixing expansion chamber and exit at the tip orifice. The main nozzle technical parameters are shown in Table 1.

2.2. Visualization Techniques

To investigate the velocity characteristics of the air-mist jet, the researchers used both PIV and LDV measurements. In this work, the measurements were focused on the central plane (along the nozzle central axis) of the air-mist

Table 1. Nozzle parameters.

Parameter	Value
Maximum enter water pressure (MPa)	0.6
Maximum Air flow rates (L·min ⁻¹)	7.45
Maximum inlet pressure (MPa)	0.3
Expansion angle (°)	90
Inner diameter at nozzle orifice (mm)	11.4
Outer diameter at nozzle orifice (mm)	18.7
Inner width at nozzle orifice (mm)	2.0
Outer width at nozzle orifice (mm)	3.4

Fig. 1. Schematic layout of the experimental setup for air-mist jet investigation. (Online version in color.)

interaction flow field. A double-pulsed Nd:YAG laser with a 120 mJ/pulse, 532 nm wavelength, and 15 Hz repetition rate illuminated the flow field. The laser light sheet, with a thickness of approximately 1.5 mm, was formed by two spherical lenses and a cylindrical lens coupled to the laser. A dual-frame CCD camera (Power View 2 M) with 1660×1220 pixels was used to capture the images. Based on the results obtained via a sensitivity analysis, 100 pairs of images were recorded with a time-averaged velocity field. A PIV algorithm with a decreasing interrogation window size from 64×64 to 32×32 and a 50% overlap was used for the cross-correlation calculation. The time interval ($15 \mu\text{s}$) between laser pulses was optimized, where the average pixel movement was between 4 and 8 pixels, following the guidelines provided by Keane and Adrian.¹⁶⁾

The LDV system consisted of a 500 mW argon ion laser and a dual-beam Dantec optical head with blue (488 nm) and green (514.5 nm) wavelengths for radial and longitudinal velocity components, respectively. After laser beam splitting, it was emitted from the different positions of the probe (9869-750, focal length is 758 mm), and then converged at one point after the probe lens acts. To optimize data of sample rates and signal-to-noise ratios, the system was operated in the forward scatter mode. A pinhole of approximately 0.1 mm diameter in the receiving optic was used to collect the scattered light. The measuring locations corresponded with representative regions of the downstream spray to ensure all locations associated with the PIV closely. The mean sampling frequencies for the LDV signals for the different locations of the flow examined were in the range between 25 and 70 kHz for the longitudinal velocity component (green wavelength) and between 8 and 17 kHz for the radial velocity component (blue wavelength).

The PIV and LDV measurements depend upon the presence of small particles to trace the flow. The suitable tracer particles, which require good fluid following and small enough size for high light scattering efficiency, were related to the display accuracy of the measured velocity result. Since the water droplets were entrained in the gas flow and they were distinguishable, they could be tracked, detected, and recorded by a camera. In this paper, water droplets themselves were functioned as tracer particles, which can be well scattered by the laser. Therefore no other tracer particles were introduced during the experiment, and the velocities of the droplets themselves measured the velocity of the flow field.^{9,17)}

3. Results and Discussion

3.1. Pressure-mass Flow Rate Curve of the Nozzle and Velocity Structure of Air-mist Jet

The measured relationships between the air flow rates and water flow rates as a function of the inlet nozzle pressures, *i.e.*, P_a and P_w , are displayed in Fig. 2. This *operating diagram* shows solid lines were determined under a constant air inlet pressure and dashed lines were determined under a fixed water inlet pressure. The solid and dashed lines imply the corresponding changes in the flow rates of both fluids (*i.e.*, air and water), respectively, at the constant inlet pressure of water and air. It was clear that the water flow rate increased with the increasing water pressure at constant

Fig. 2. Operating diagram of the air-mist nozzle determined in the laboratory. (Online version in color.)

Fig. 3. An image of PIV frame (water pressure 0.4 MPa, air pressure 0.2 MPa).

air pressure. At a constant water pressure, the water flow rate slightly decreased with increasing air flow rate. To investigate velocity characteristics of the air-mist jet, the researchers performed PIV and LDV measurements with water pressures of 0.3, 0.4, and 0.5 MPa and air pressures of 0.1, 0.2, and 0.3 MPa.

As described in section 2.1, the laser sheet has been set to illuminate the plane containing the injector axis. Water droplets released at high pressure are tiny enough to be tracking particles by themselves. An image of the PIV frame for this work is presented in Fig. 3. The liquid membrane was fully transformed into a spray jet by air pressure. Then the drops interacted with the surrounding air and were entrained by air to expend the jet. It was also interesting that particle concentration was very high at the outlet (*i.e.*, 0–80 mm along the axis). The visible area of the fanlike spray with an image was $425 \times 320 \text{ mm}^2$.

The researchers have obtained an average contour map and velocity distribution structure at air pressure 0.2 MPa and water pressure 0.4 MPa, as shown in Fig. 4. The bell shape of the air-mist jet's velocity distribution indicated the existence of a central core with higher velocity droplets. Furthermore, the contour map was not fully symmetrical

Fig. 4. Average contour map and velocity distribution structure of air-mist jet at air pressure 0.2 MPa and water pressure 0.4 Mpa. (Online version in color.)

Fig. 5. Comparisons of velocity profiles of air mist measured with PIV and LDV in the same position below the nozzle. (Online version in color.)

along the centerline, and the spray bent, forming the reflux region close to the left side. Since the left side of the setup was a wall, creating a forced jet, this work has focused on right side, where a free jet had formed (In order to compare the differences between forced jet and free jet, the asymmetric method was designed). The contour map of velocity vector in Fig. 4 suggests a nearly uniform acceleration of the water particles and decreases in terms of varying H from nozzle orifice. This accelerating behavior was likely caused by the continuous acceleration of droplets within the air jet core. It also showed a decrease as the horizontal distance to the centerline increases. The velocity distribution structure of the air-mist jet was divided into two parts: the potential core and the main region. The researchers considered the transition interface to be the maximum centerline velocity. The centerline velocity distribution increased to the maxi-

um velocity (to the transition interface), and this part was the potential core. Then the velocity decreased, and this part was the main region.

3.2. Combining the PIV and LDV Measurements for Air-mist Jet

During mixing of water and air, liquid membranes cannot be completely atomized into small water particles. This liquid membrane in the vicinity of the nozzle may not be detected by a PIV setup, resulting in a considerable error on the velocity field reconstruction. To identify and solve this problem caused by PIV measurement, the researchers used laser Doppler velocimetry (LDV) technique in this work also. Figure 5 shows average velocity profiles of air-mist measured, respectively, with PIV and LDV at nearly the same position from the nozzle orifice. The comparison of

results between PIV and LDV measurement indicates (1) the flow field recorded by PIV (right side including frame) provided more quantitative detail of the velocity field structures than that by LDV (left side to the center coordinates), where a little information on the velocity field structures can be observed and (2) the velocity by LDV measurement was higher than that by PIV at the nozzle outlet. This is believed to be caused by the different measurement principles and distinct technical features between PIV and LDV. PIV images were typically stored in two different frames in the same picture. The authors applied a cross-correlation analysis in PIV image treatment. The frames were then subdivided into a number of fields (interrogation windows). Movement of the water droplets was calculated by cross-correlation of the pixel intensity in the interrogation areas from the two frames. Since the intensities of single pixels were also considered in the data processing, the algorithm is, therefore, sensitive to droplet size (a larger droplet gives a higher intensity than a small droplet).

In this work, the aim was to measure the velocity of the water droplets. This poses a challenge because droplets of different sizes will move with different velocities, especially when the droplets are at positions close to the nozzle. The velocities in the PIV measurements were not linked to the specific drop sizes. When the number of small droplets was equal to that of larger ones, PIV could bias toward the velocities of the larger droplets because they reflected more light. Since PIV only gives one velocity measurement for each interrogation window, it is impossible to identify which droplet velocity is measured. Nevertheless droplet velocities could be more uniform in the area away from the nozzle orifice.

LDV measurement provided velocities near the wall point by point. At each location 3 000 LDV data points correspond to approximately 100 PIV images. However, PIV measurement can figure out a complete velocity profile of the air-mist jet, and it was in good agreement with the LDV in the area far from the nozzle orifice (see Fig. 5). On the other hand, LDV is qualified for excellent time resolution and online data processing. For a very dense air-mist jet with large particle volume, it might be time-consuming for LDV measurement. As mentioned earlier, the LDV technique can only provide point measurement, which is another limit of the LDV.

In summary, both LDV and PIV are capable of measuring air-mist flow and providing quantitative information about major flow features. PIV can figure out a whole and precise velocity profile in the area away from the nozzle, but little information at positions close to the nozzle outlet. Meanwhile, LDV is qualified with excellent time resolution, which enables obtaining more detailed velocity field information in the vicinity of the nozzle outlet, but the point-by-point measurement is time-consuming, specifically for a dense air-mist jet. Taking into account the advantages and limits of PIV and LDV, an optimized method with combination of LDV and PIV can be proposed to accurately measure the velocity field of the air-mist jet, therefore describing better the flow characteristics. This is by using PIV to measure the velocity of the area away from nozzle, and by using LDV in the vicinity of the nozzle outlet.

Figure 6 shows the distribution of the dimensionless axial

Fig. 6. Comparisons between PIV and LDV data: (a) distribution of horizontal dimensionless velocities at different cross sections of PIV and LDV; (b) distribution of axial dimensionless velocities at different cross sections of PIV and LDV. (Online version in color.)

and horizontal velocities with the maximum velocity u_m as a function of the dimensionless distance from the nozzle orifice with $x_{0.5}$. The latter was the horizontal distance from nozzle outlet, at which the velocity was equal to half of the maximum velocity. The red circles and black squares in Fig. 6 stand for the data measured by PIV and LDV technique, respectively. As seen in Fig. 6(a), the dimensionless average velocity of the air-mist jet v/u_m decreases with $x/x_{0.5}$ and reaches a minimum value at around $x/x_{0.5} = 2.0$. PIV data agreed well with the result of LDV measurement. With respect to the dimensionless axial velocity (u/u_m) in Fig. 6(b), however, the PIV and LDV data agreed with each other only at the positions farther than 180 mm from nozzle outlet (*i.e.*, $H = 180$ mm, 288 mm). A large difference between the PIV and LDV results has been observed at positions closer than 126 mm from the nozzle (*i.e.*, $H = 18$ mm, 72 mm) and the value of LDV measurement was higher than that of PIV data. The axial and horizontal components might be assumed as significant at the nozzle outlet, and the horizontal component tended to rapidly convert into the axial, moving downwards along the axial coordinate. The axial component was definitely predominant in the air-mist

spray. The much smaller horizontal component compared to the axial component and the differences between the two techniques caused a large difference between horizontal dimensionless velocities of PIV and LDV.

3.3. Velocity Distribution

Figure 7 shows the profiles of the velocity at different cross sections. The velocity changed with downstream distance with the central region showing at first an increase and then a decrease in velocity. For all cross-sections of the air-mist jet, the velocities of droplets attained their maximum values in the spray center and decreased toward both sides of the spray. The large droplets at the edge of the spray lost their momentum due to the drag force and collisions. In addition, the mixing of air and water and the instable spray might result in a large range of water droplet size and velocity. It is possible that the large and small droplets in the air-water jet move with same velocity. At the location 315 mm further away from the nozzle orifice, the spray was fully mixed and the distribution of droplet velocity was nearly the same in the center and at the sides of the spray. These results suggested that this could be used to set the height of the nozzle to the surface of the steel plate.

The velocity distribution was normalized with the maximum velocity of the same cross section as seen in Figs. 8 and 9. The expressions $\frac{v}{u_m} \left(\frac{u}{u_m} \right)$ and $\frac{x}{x_{0.5}}$ represent the horizontal and vertical coordinates, respectively, and $x_{0.5}$ is distance to the test point of $v=0.5u_m$ or $u=0.5u_m$. The normalized axial velocity was identical to a free jet when $x/x_{0.5} > 0$ in Fig. 8(b), but the axial velocity was different and lower at distances close to the nozzle orifice when $x/x_{0.5} < 0$ to confined jet as observed by PIV in Fig. 8(a). The dimensionless horizontal velocity showed wing shape profiles by PIV and LDV in Fig. 9. The dimensionless horizontal velocities increased with $x/x_{0.5}$ and reached a maximum at $x/x_{0.5} = 1.0$, and then decreased rapidly. As the distance from the nozzle increases, the velocities decreased until 180 mm then unchanged by LDV in Fig. 9(a). While as the distance from the nozzle increased, the velocities first increased to 180 mm and then decreased, as observed by

Fig. 7. Velocity distribution at different cross sections at air pressure 0.2 MPa and water pressure 0.4 MPa using PIV. (Online version in color.)

Fig. 8. Distribution of axial velocity component v at different cross sections using PIV (a) confined air-mist jet; (b) free air-mist jet. (Online version in color.)

Fig. 9. Distribution of horizontal velocity component u at different cross sections using LDV and PIV for free air-mist jet. (Online version in color.)

PIV in Fig. 9(b).

In the following discussion, we ignored the forced jet of the left part, and only the free jet was considered. By monitoring axial cross sections, the researchers further illustrated the dimensionless velocity distribution, as shown in Fig. 10. As expected, at all nozzle distances the water droplet velocities were equal. The dimensionless velocity distributions in various cross sections were self-similar and satisfied the Gaussian distribution. The dimensionless velocity distributions of each cross section were identical in the air-mist jet. The theoretical Gaussian profile (black solid line in Fig. 10) was fitted to the measured data with a resulting R-square of 0.9912. This implied the fundamental profile shape was independent of the distance from nozzle. The Gaussian distribution function is expressed as follows:

$$\frac{v}{u_m} = e^{-\frac{1}{2} \left(\frac{x}{Cx_{0.5}} \right)^2} \dots\dots\dots (1)$$

where v is the time-average velocity at a point (x, y) in the air-mist jet; u_m is the centerline velocity (*i.e.*, the maximum velocity of cross section); x is the horizontal distance to the center line; $x_{0.5}$ is the distance to the test point of $v=0.5u_m$; and C is empirical constant $C = 0.807$. The formula (1) is the analytical solution based on phenomenological theories supplemented by experimental observations.

The velocity distribution in the fully developed region was given by Reichardt (1943)¹⁸⁾ for the single-phase submerged jet as

$$\frac{u_x}{u_m} = e^{-\frac{1}{2} \left(\frac{x}{Cs} \right)^2} \dots\dots\dots (2)$$

where u_x is the axial velocity at a point (x, y) in the jet; u_m is the centerline velocity; s is the distance from the nozzle outlet; and C is an empirical constant. Values of $0.071 < C < 0.080$ are found in the literature (*e.g.*, Albertson¹⁹⁾), x is the horizontal distance to the centerline coordinate. And then G. Hetsroni²⁰⁾ found that a two-phased jet could be described by formula (2) too; notice that the spreading coefficient was not necessarily equal or not to be constant. The data of air-mist jet were processed by this method as shown

Fig. 10. Dimensionless axial velocity curve of air-mist jet. (Online version in color.)

in Fig. 11. The dimensionless axial velocity and the value $(x/s)^2$ were not equal at different cross sections, especially before 180 mm, which means formula (2) does not apply to an air-mist jet for secondary cooling of continuous casting, whereas formula (1) could well describe the velocity characteristics of the air-mist jet for secondary cooling of continuous casting.

3.4. The Optimizing Flow Field of Different Working Conditions

In gas-liquid two-phase flow nozzles, the flow rates and pressures of the gas and liquid changed as a result of gas-liquid interaction under different nozzle-operating conditions. According to this, the average centerline velocities are plotted against the distance from nozzle using PIV in Fig. 12. It is clear that (1) both air and water pressure affect the centerline velocity and the influence of air pressure was more significant; (2) except for the test with 0.3 MPa air and water pressures, the centerline velocity firstly increased to reach maximum value at approximately 100 mm axial

Fig. 11. Dimensionless axial velocity profiles versus $(x/s)^2$ at different cross sections (from G. Hetsroni *et al.* 1971). (Online version in color.)

Fig. 12. Distribution of average droplet velocities along centerline (*i.e.*, axial direction) for operative pressures at water pressures of 0.2–0.5 MPa, air pressures of 0.1–0.3 MPa. (Online version in color.)

distance from nozzle and then decreased with distance; (3) for a given air pressure, the velocities decreased with increasing water pressure; (4) the velocity exhibited a fluctuation at the air pressure 0.3 MPa, but it was stable under the air pressures of 0.1 MPa and 0.2 MPa, where there was no significant velocity change with increasing water pressure. According to the finding in Fig. 12, the better velocity distributions of different working conditions and optimized operating nozzle condition were determined to be air pressure 0.2 MPa and water pressure 0.4 MPa or 0.5 MPa, where a stable and large centerline velocity of the air-water jet can be achieved for the nozzle.

Additional experiments under different water and air pressures were performed to optimize by using the aforementioned dimensionless method. The dimensionless axial velocity distributions were obtained under operating conditions of air pressure (0.1, 0.2, and 0.3 MPa) and water

pressure (0.3, 0.4, and 0.5 MPa) at different cross sections. The velocity distribution of the right side of **Fig. 13** shows the characteristics of the free air-mist jet under different operating conditions using PIV. It was clear that the dimensionless velocity profiles well satisfied the normal distribution and in different cross sections were self-similar only under the condition with air pressure 0.2 MPa and water pressure 0.4 MPa. Based on the experimental results, it can be determined that the condition was the optimizing velocity distribution of different working conditions, for which the dimensionless velocity distributions in different cross sections were self-similar, and for the same dimensionless location, the axial velocity of the same location was the same. That can be used as a suggestion to optimize velocity distribution of different working conditions of the air mist jet nozzle in the secondary cooling of continuous casting.

Fig. 13. Distribution of dimensionless axial velocities at different cross sections for operative pressures at water pressures of 0.2–0.5 MPa, air pressures of 0.1–0.3 MPa. (Online version in color.)

4. Conclusions

The velocity characteristics of air-mist jet during secondary cooling of continuous casting were studied by using PIV and LDV techniques. The main conclusions were as follows:

(a) The velocity distribution of air-mist jet were self-similar and well described for the whole flow field by

$$\frac{v}{u_m} = e^{-\frac{1}{2} \left(\frac{x}{Cx_{0.5}} \right)^2} \text{ with } C = 0.807.$$

(b) The air-mist jet was divided into two parts: the potential core and the main region. The velocity changed with downstream distance with an increase to decrease.

(c) The dimensionless velocity distribution of each cross section was identical and could be suggested to optimize the flow field of different working conditions in the secondary cooling of continuous casting.

(d) To describe better the flow characteristics of air-mist jet, and taking into account the advantages and limits of PIV and LDV, an optimized method with combination of LDV and PIV can be proposed to accurately measure the velocity field of the air-mist jet. This is by using PIV to measure the velocity of the area away from the nozzle, and by LDV in the vicinity of the nozzle outlet.

Acknowledgments

The authors wish to thank professor Mu-Xing GUO (KU Leuven) for the guidance and helpful suggestions they provided throughout this work. The work was supported by the National Council of Science and Technology of China under Grant 51264030; National Key R & D Program of China under Grant 2016YFC0401201 and the Inner Mongolia Natural Science Foundation under Grant 2017MS (LH) 0534.

Nomenclature

A : air flow rate (L/s)
 P_a, P_w : manometric air-; water-nozzle pressures (MPa)

u, v : normal velocity components at virtual impingement plane; horizontal velocity, axial velocity (m/s)
 u_m : the maximum velocity
 W : water flow rate (L/s)
 x, y : rectangular coordinate axes (mm)
 u/u_m : axial dimensionless velocities
 v/u_m : horizontal dimensionless velocities
 C : an empirical constant
 $x_{0.5}$: the distance to the test point of $v=0.5u_m$
 S : the distance from the nozzle outlet

REFERENCES

- 1) C. A. Hernandez-Bocanegra, J. I. Minchaca-Mojica, A. H. Castillejos, F. A. Acosta-Gonzalez, X. X. Zhou and B. G. Thomas: *Exp. Therm. Fluid Sci.*, **44** (2013), 161.
- 2) N. Hatta, H. Takuda, R. Ishii and H. Fujimoto: *ISIJ Int.*, **29** (1989), 605.
- 3) N. Hatta: *ISIJ Int.*, **29** (1989), 695.
- 4) N. Hatta and M. Nakamura: *ISIJ Int.*, **29** (1989), 796.
- 5) Y. Ito, T. Murai, Y. Miki, M. Mitsuzono and T. Goto: *ISIJ Int.*, **51** (2011), 1454.
- 6) C. I. Hernandez, G. F. A. Acosta, E. A. H. Castillejos and M. J. I. Minchaca: *Metall. Mater. Trans. B*, **39** (2008), 746.
- 7) M. J. I. Minchaca, E. A. H. Castillejos and G. F. A. Acosta: *Metall. Mater. Trans. B*, **42** (2011), 500.
- 8) J. E. Naved: Ph.D. thesis, University of Central Florida, (2000), <https://stars.library.ucf.edu/rtd/1942/>, (accessed 2018-03-22).
- 9) P. Raul, V. Juan, P. W. Hua and M. Louis-Marie: *Int. J. Multiph. Flow*, **80** (2016), 69.
- 10) J. Popper, N. Abuaf and G. Hetsroni: *Int. J. Multiph. Flow*, **1** (1974), 715.
- 11) C. Presser, G. Papadopoulos and J. F. Widmann: *Fire Saf. J.*, **41** (2006), 580.
- 12) B. P. Husted, P. Petersson, I. Lund and G. Holmstedt: *Fire Saf. J.*, **44** (2009), 1030.
- 13) T. Saga, H. Hu, T. Kobayashi, S. Murata, K. Okamoto and S. Nishio: *J. Vis.*, **3** (2000), 145.
- 14) F. Kerhervé, J. Fitzpatrick and J. Kennedy: *Exp. Therm. Fluid Sci.*, **34** (2010), 34.
- 15) D. Marx, Y. Aurégan, H. Bailliet and J. C. Valière: *J. Sound Vib.*, **329** (2010), 3798.
- 16) R. D. Keane and R. J. Adrian: *Meas. Sci. Technol.*, **2** (1990), 1202.
- 17) M. Raffel, C. Willert and J. Kompenhans: *Particle Image Velocimetry*, Springer, Berlin, Heidelberg, (1998), 79.
- 18) H. Reichardt: *Aeronaut. J.*, **47** (1943), 167.
- 19) M. L. Albertson, Y. B. Dai, R. A. Jensen and H. Rouse: *Trans. ASCE*, **115** (1950), 639.
- 20) G. Hetsroni and M. Sokolov: *J. Appl. Mech.*, **101** (1971), 315.