VOLUMETRIC FLOW MEASUREMENT INSIDE A WATER LADLE MODEL WITH SHAKE-THE-BOX SYSTEM

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ABSTRACT

The ladle furnace plays a critical role in the secondary steelmaking stage, where many processes take place in the ladle such as steel property and temperature homogenization, inclusion removal, degassing, and desulfurization. Although many research has been conducted to study these aspects, due to the complicated heat and mass transfer process inside the ladle, many details about the physical process are still not quite clear. For example, the efficacy of plug/injector designs in turbulent mixing of molten steel were not fully understood. Due to its complex three dimensional flow phenomena inside the ladle, previous two dimensional flow measurement of water ladle models provided little insight into understanding the three dimensional flow phenomenon of turbulent mixing. Therefore, to achieve a better understanding on the efficacy of plug/injector designs in turbulent mixing, we implemented an advanced volumetric flow measurement instrument of Shake-the-Box system to measure the three-dimensional flow field inside a water ladle model. Totally, three different plug/injector designs were tested under two different flow rates (8 LPM and 11.5 LPM) of gas injection within a volumetric flow measurement region of 4.8 cm × 4.8 cm × 2.4 cm. The flow measurement results suggest the double slits injector produces the highest turbulence kinetic energy comparing the three injectors.

KEY WORDS: Multiphase flow, Turbulence, Ladle Metallurgy, Shake-the-Box

1. INTRODUCTION

Because high-quality steel products are a keystone part of fundamental transportation, construction, communications, defence systems, and high-tech applications, the demand for high-quality steel continues rising with the prosperity of the economy. Many processes happen in the ladle, such as steel property and temperature homogenous, inclusion removal, degassing, and desulfurization, making the ladle an important part of the steelmaking process. Many researchers have interest in studying the processes inside ladle furnaces. However, because of complicated heat and mass transfer phenomena in the ladle, its detailed process is not clear yet. As water in room temperature and molten steel have equivalent kinematic viscosity [1], the equivalent scaled water ladle experiment is carried by many researchers to study flow phenomena.

In 1975, Szekely et al. [2] first modelled and studied the flow characteristics of a ladle based on a simplified water model. Gas was injected from bottom, and bubble size was assumed as constant. All the boundary conditions were coming from physical measurement. By using Spalding's k-ω model, the Navier-Stokes equations were solved in order to predict velocity and turbulence inside of water model. In 1978, DebRoy et al. [3] improved Szekely et al.'s model by revising the bubble model from disperse bubbles constrained in single plume with diameter only related to volume fraction to injection gas flow rate. Johansen et al. [4] adopted the experiments by using a bottom injection water model. In his work, he found that the bubbles can create turbulence, and the turbulence will affect the flow velocity in bubble plume region. Peranandhantan et al. [5] conducted the experiment to find out an expression of slag eye size in a simplified water model. Several variables such as gas flow rate, slag thickness, liquid depth and so on were test in the work. Top slag eye was captured and measured through camera observation. Mazumdar et al. [6] reviewed several studies on physical

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models and empirical correlation of gas-stirred ladle. Simplified expressions of several variables including gas flow rate, ladle dimensions and so on were well reviewed in his work. As for plug location, several researchers changed the plug positions in their water ladle model and observed better mixing and wall shear stress distribution [6, 7, 8]. It is argued that plug design can change the bubble size distribution close to the plug, but not the average size and distribution in the whole ladle [5, 10, 11, 12]. More detailed plug design experiment is conducted by Trummer et al, [13] they test hybrid, slot, and porous plugs in their water model experiments. But the discussion of the flow caused by plug design is limited. In 2019, Owusu, et al, [14] used Particle Image Velocimetry (PIV) and image processing methods to measure and calculate the turbulence kinetic energy and bubble distribution in the cross-sectional plane of their water ladle. They conducted different plug design studies to examine the mixing and turbulence kinetic energy distribution. They conclude that the porous plug shows the best mixing and more intensive bulk convection, but the difference between the injectors are small. So far, many researchers have used PIV method to study the flow field in the ladle, but PIV method can only give the results in two-dimensions. The measurement of velocity and turbulence distribution in three-dimension space is still undeveloped in the ladle system.

The intent of this work is to achieve a better understanding about the efficacy of plug/injector designs in turbulent mixing. The advanced volumetric flow measurement instrument of Shake-the-Box system is implemented to measure the three-dimensional flow field inside a water ladle model. In total, three different plug/injector designs were tested under two different flow rates of gas injection with a volumetric flow measurement region of 4.8 × 4.8 × 2.4 cm. The flow measurement results suggest the double slits injector will produce the higher turbulence kinetic energy under both flow rates of 11.5 LPM and 8 LPM.

2. EXPERIMENTAL METHOD

2.1 Water Ladle Model

Because of the extreme ladle operation conditions in steel manufacturing, direct measurements are difficult to achieve in the actual ladle. The water ladle experiment, however, can take the advantage of the similar kinetic viscosity of water and molten steel to understand the flow phenomena in Argon/Nitrogen-steel ladle systems. In this study, to measure the 3D particle displacement without image distortion, a water ladle model is developed with six pieces of flat optical glass (Glass dimensions are labeled in the figure). In the water ladle model, the porous plug is placed at 1/4 position of the longest diagonal. Compressed air is injected to the water ladle through the porous plug. Totally, three different plug/injector designs were tested under two different flow rates of gas injection. The detail physical dimensions / property are provided at Table 1.

Table 1 Important physical dimension and properties

Property / Condition	Unit	Water ladle
Water density	kg/m^3	1000
Water viscosity	$Pa \cdot s$	1.0×10^{-3}
Air density	kg/m^3	1.2
Air viscosity	$Pa \cdot s$	1.8×10^{-5}
Gas flow rate	LPM	8 or 11.5
Liquid height	M	0.1778
Room temperature	℃	25

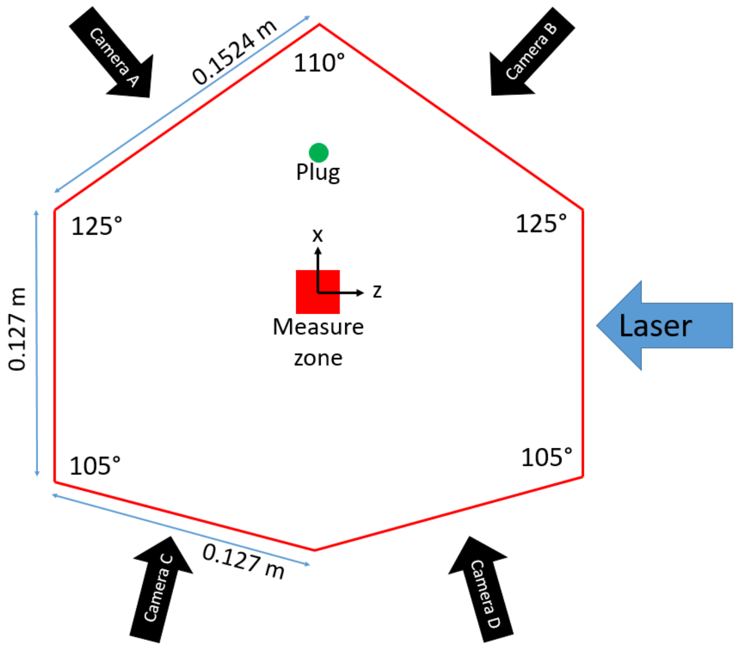


Figure 1 Sketch of experimental setup (top view)

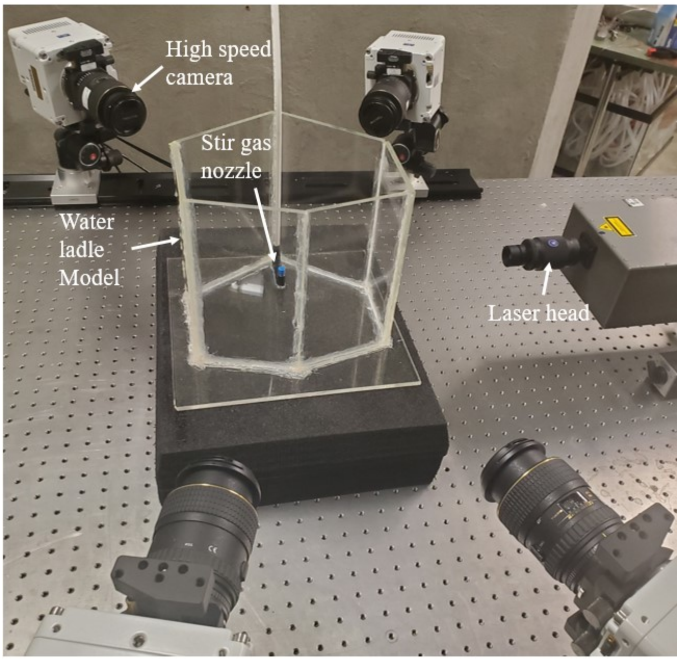


Figure 2 Shake-the-box system setup

2.2 Porous plug

There are many types of Ladle Porous Plug, which can be roughly categorized into: diffuse, through-hole, and slit type. In this study, two through-hole type nozzles and one slit type nozzles are investigated. The nozzles are 3D printed using MakerBot Replicator with material of polylactic acid (PLA). As shown in Figure 3, Nozzle 1 has a single hole with a diameter of 5 mm at the center, while Nozzle 2 has 4 smaller holes of 1 mm. Nozzle 3 has two 5 mm long slits.

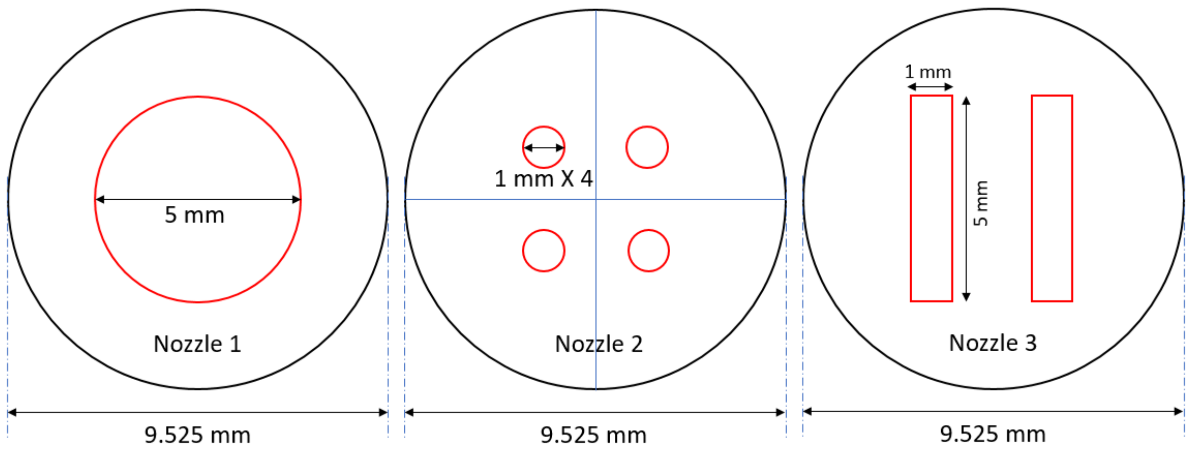


Figure 3 Sketch of plug designs

2.3 Time resolved volumetric flow measurement with Shake-the-Box system

In the water ladle model, the three dimensional flow field of a 4.8 × 4.8 × 2.4 cm volume is measured and quantified using the state-of-the art 3D Lagrangian particle tracking velocimetry (PTV) system: Shake-the-Box (LaVision, Inc Göttingen, Germany). As shown in Figure 1, the origin is set at center of measuring volume. The x-direction and z-direction point to the nozzle and the laser, respectively. The Shake-the-Box system uses particles' spatial information from previous time steps to predict particle positions in the future time steps. Then, the predicted particle positions are corrected from an image matching technique (particle 'shaking' in space). By associating the additional temporal information of particle positions to the particle tracking algorithm, the occurrence of ghost particles is significantly minimized while the data processing speed is significantly improved. Hollow glass spheres (diameter of 8~12 μm) are used as seeding particles in the ladle model to track the gas stirred water flow. A Nd: YLF high repetition rate laser (Photonics Industries) and 4 high speed cameras (Phantom VEO 640L) are synchronized to illuminate the seeding particles at 200 Hz while filming the particle images. DaVis 10 (LaVision, Inc Göttingen, Germany) was used to process the particle images during volumetric self-calibration, particle detection/ tracking and velocity interpolation. Finally, the volumetric velocity field is screened by a 252 × 252 × 252 voxel sub volume with 75 % overlap to produce a 23 × 23 × 12 velocity vector field.

3. RESULTS

4.1 Averaged velocity field

Figure 4 shows one example from the volumetric flow measurement results and plots the averaged volumetric velocity vector field with Nozzle 1 (single hole) under the two different flow rates: 11.5 LPM and 8 LPM. As expected, the higher gas injection rate introduces higher flow velocity inside the ladle. On Nozzle 1, the averaged flow velocity magnitude ranges from 0.0048 m/s to 0.0619 m/s at the flow rate of 11.5 LPM and ranges from 0.0046 m/s to 0.0595 m/s at the flow rate of 8 LPM. To better visualize the volumetric velocity field, in Figure 5, the averaged velocity results are plotted on four horizontal planes with a distance of 0.96 cm between two adjacent parallel planes. Regardless the shape of the nozzle and gas flow rate, the high velocity region generally locates at upper part of the measurement volume while the details of average velocity magnitude varies significantly in different cases. Meanwhile, the averaged velocity magnitude over the entire measured volume are calculated and listed in the table 2. Under the gas injection rate of 11.5 LPM, the nozzle 3 (double slits) produces the highest averaged velocity of 0.054 m/s while the nozzle 1 (single hole) produce the lowest averaged velocity of 0.0445 m/s. At the gas injection rate of 8 LPM, the nozzle 2 (four hols) produce the highest average velocity of 0.0436 m/s while the nozzle 3 produce the lowest average velocity of 0.0399 m/s.

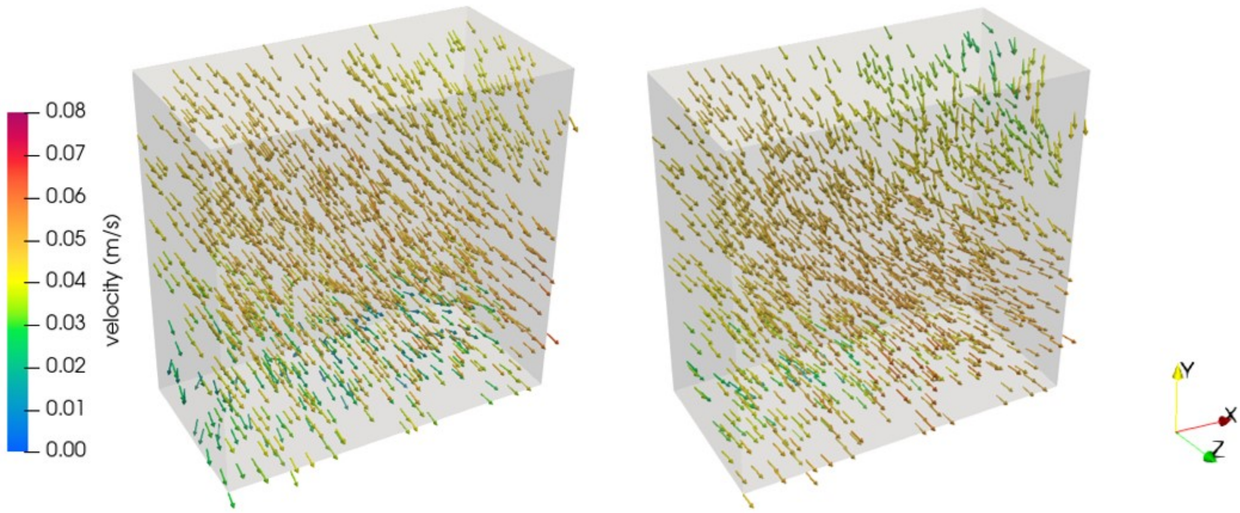
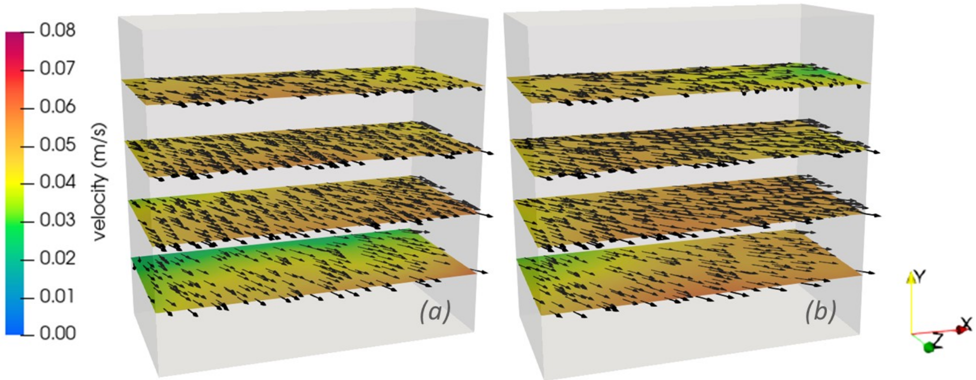


Figure 4 Averaged velocity vector field with one-hole Nozzle (Left: Flow rate: 11.5 LPM, Right: Flow rate: 8 LPM)



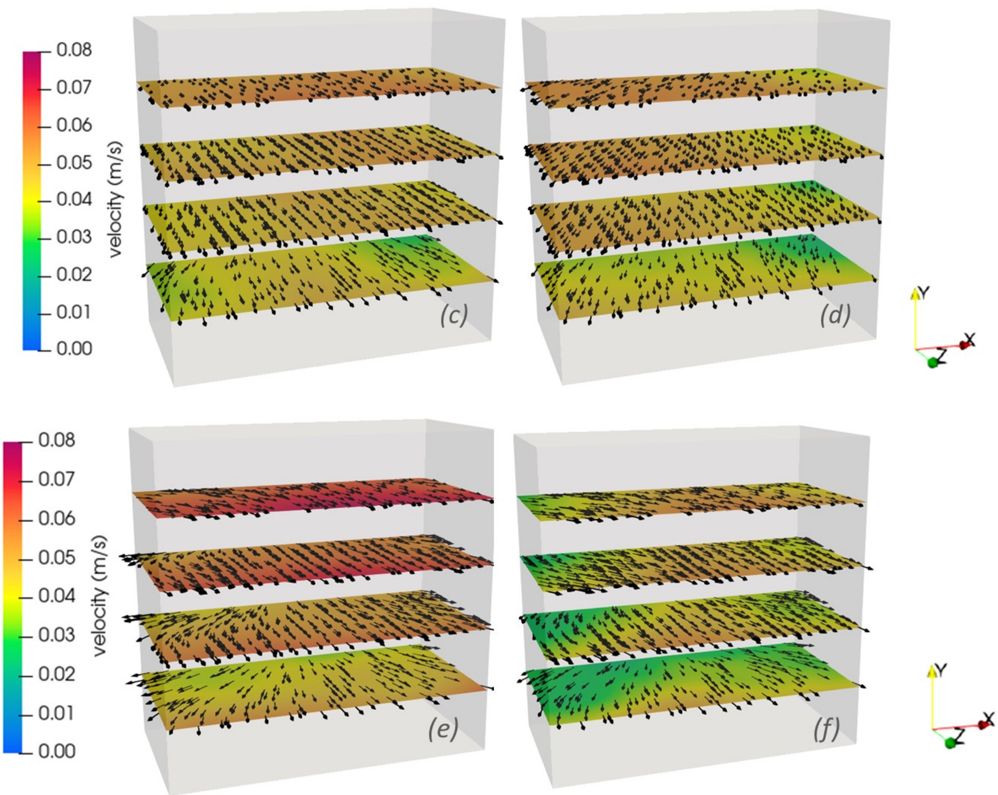


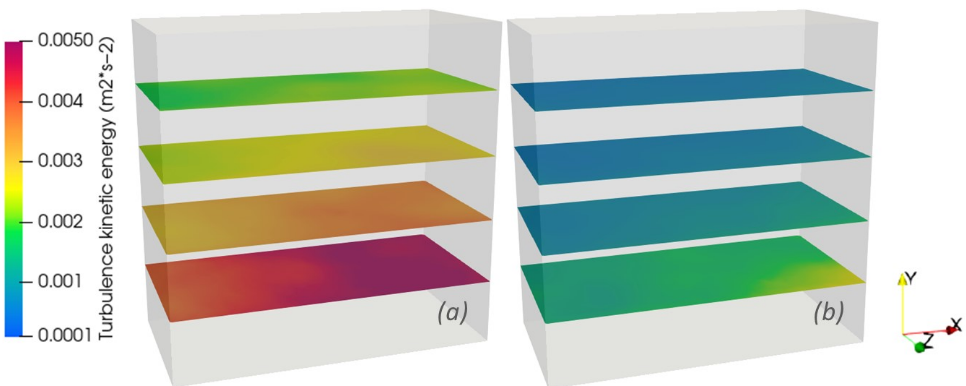
Figure. 5 Averaged velocity plot on horizontal planes. (a, b) averaged velocity results with one-hole Nozzle under gas injection flow rates of 11.5 and 8 LPM. (c, d) averaged velocity results with four-hole Nozzle under gas injection flow rates of 11.5 and 8 LPM. (e, f) averaged velocity results with double slits Nozzle under gas injection flow rates of 11.5 and 8 LPM

4.2 Turbulence kinetic energy and intensity

Inside steel ladles, the gas injection is mainly used to increase the turbulent mixing for the steel property and temperature homogenous while bulk convection and eddy diffusion can significantly affect the mixing inside the ladles [14]. Therefore, it is to our great interest to quantify the turbulence mixing when studying the efficacy of the different injector/plug designs. Thus, in this study, turbulence kinetic energy is estimated from the collected volumetric flow velocity data to investigate mixing efficiency on different gas injector/plug designs. The turbulent kinetic energy is estimated from calculating the sum of the velocity root-mean-square (RMS) using the equation in below:

$$k = \frac{1}{2}({u'_x}^2 + {u'_y}^2 + {u'_z}^2)$$

Where u'_x, u'_y and u'_z are the RMS values of each velocity component estimated in the time domain.



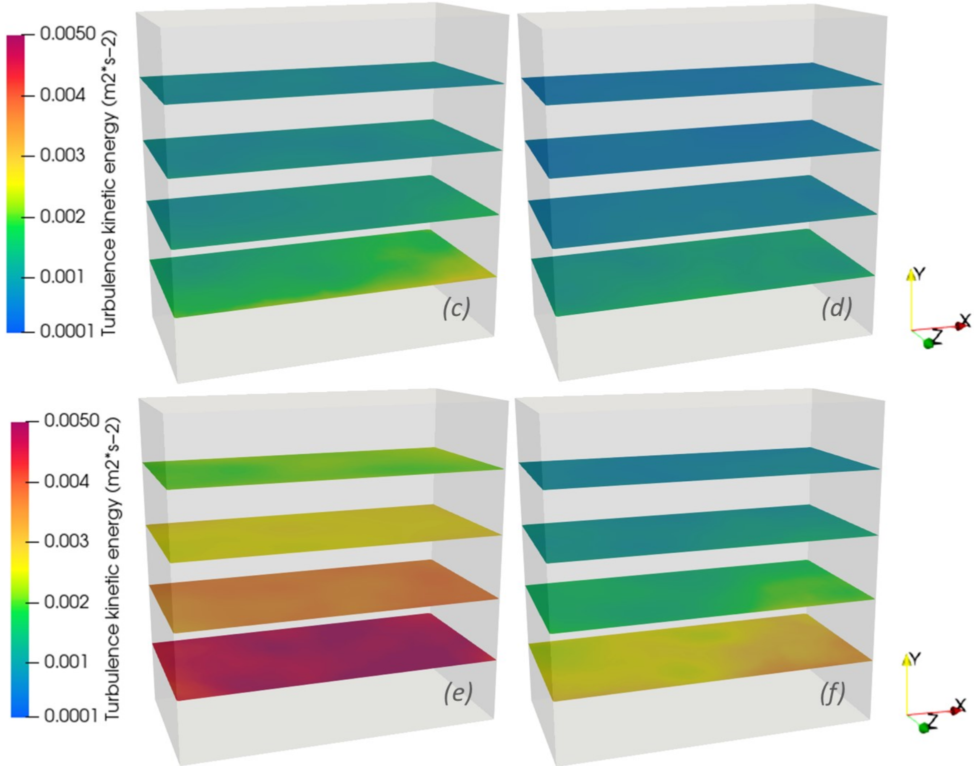


Figure. 6 Turbulent kinetic energy plot on horizontal planes. (a, b) averaged velocity results with one-hole Nozzle under gas injection flow rates of 11.5 and 8 LPM. (c, d) averaged velocity results with four-hole Nozzle under gas injection flow rates of 11.5 and 8 LPM. (e, f) averaged velocity results with double slits Nozzle under gas injection flow rates of 11.5 and 8 LPM

Figure 6 shows the pseudo color plot of turbulence kinetic energy on the four horizontal planes calculated from the instantaneous velocity field. As expected, on the same nozzle design, higher gas flow rate produces higher turbulent kinetic energy. Comparing different nozzles, the double-slits nozzle is most effective in producing turbulence with the bottom plane having high turbulence kinetic energy of about 0.005 m^2/s^2. Moreover, on all the three nozzles, the high turbulence is mainly located in the lower part of the flow field, suggesting the more turbulence can be produced in the flow field closed to the nozzle/gas injection. For a better comparison about the turbulence mixing on different nozzle designs, the averaged turbulence kinetic energy is calculated over the entire flow measurement region on all the six cases. Table. 2 lists the calculated average turbulence kinetic energy with three different nozzle designs under two different gas injection flow rates. As expected, higher gas flow rate produces higher turbulence kinetic energy. At the flow rate of 8 LPM, the double slits, four-hole and single hole Nozzles produce averaged turbulent kinetic energy at 0.0018 m^2/s^2, 0.0010 m^2/s^2, 0.0011 m^2/s^2, respectively. At the flow rate of 11.5 LPM, the Nozzle the double slits, four-hole and single hole Nozzles produce averaged turbulent kinetic energy at 0.0034 m^2/s^2, 0.0014 m^2/s^2, 0.0033 m^2/s^2, respectively. Therefore, when evaluated from the turbulent kinetic energy, the performance of the injector/plugs depends on not only the injector types but also the gas injection flow rate and the calculation results suggest that the double slits nozzle produces highest turbulence kinetic energy in the ladle with the cases investigated.

Table 2 Average velocity magnitude and turbulence kinetic energy for difference nozzle type and flow rate

Nozzle	Nozzle 1 (Single hole)		Nozzle 2 (Four holes)		Nozzle 3 (Double slits)	
Flow rate (LPM)	11.5	8	11.5	8	11.5	8
Average velocity magnitude (m/s)	0.0445	0.0421	0.0451	0.0436	0.0540	0.0399
Average turbulence kinetic energy (m^2/s^2)	0.0033	0.0011	0.0014	0.0010	0.0034	0.0018

4. CONCLUSION and DISCUSSION

A preliminary study was conducted on a water ladle model using an advanced volumetric flow measurement instrument: Shake-the-Box system. Three different gas injector/plug designs: single-hole, four-hole and double slits are investigated under two different gas injection flow rates: 8 and 11.5 LPM. With the instrument, the volumetric velocity field within a 4.8 cm × 4.8 cm × 2.4 cm volume was measured at a sampling frequency of 200 Hz. From the collected volumetric velocity data, the averaged velocity magnitude and turbulent kinematic energy are calculated and compared, suggesting the double-slits nozzle produces the highest turbulence kinetic energy, therefore, should have the best performance in turbulence mixing for the steel property and temperature homogenous. In this study, an irregular shaped water ladle model was used to eliminate the potential image distortions and velocity mal-calculations from the Shake-the-Box system. However, the shape of the water ladle model deviates significantly from the actual ladle, therefore will impact and alter the gas stirred flow field considerably. To better simulate the flow inside a steel ladle, the method of refractive index match can be implemented in the future and sodium iodide solution will be used with a small cylindrical container inside a large flat wall container to eliminate the images distortion while keep the same boundary geometry at the same time.

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NOMENCLATURE

k	Turbulence kinetic energy	(m^2/s^2)
I	Turbulence intensity	(-)
u'_x, u'_y, u'_z	RMS velocity is each direction	(m/s)
u'	Turbulence RMS velocity fluctuation	(m/s)
U	Mean velocity	(m/s)

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