The scale-up of high shear processing for the purification of recycled molten scrap aluminum alloy: key features of fluid flow

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In order to remove impurities in scrap aluminum alloys, hence increasing their value, a laboratory-scale high shear processing (HSP) unit for mixing the molten alloy was developed, which makes it possible to remove iron-based contaminants using physical conditioning, at relatively low cost. In order to make this technology applicable in the industrial environment, we are now investigating the scale-up of HSP by using computer simulation. The computational research quantitatively predicts a variety of key features of fluid flow, which determine the feasibility of the scale-up. These include the mass flow rate through the mixing head, the effective agitation of the melt in the bulk crucible, and the shear rate that can be achieved. Based on the configuration of HSP that we review in this paper, we predict that it is feasible to achieve a factor of four scale-up in the volume of liquid alloy treated.

Keywords: high shear processing, materials purification, aluminium alloy, materials recycling

1. Introduction

Significant reductions in energy, and environment costs can be achieved by manufacturing high performance aluminium alloy using recycled aluminium instead of the primary aluminium that is produced from bauxite ores. Because scrap aluminium is normally contaminated by harmful elements e.g. iron, at relatively high level, a key challenge to the recycling process is the purification of recycled materials. Physically conditioning molten scrap aluminium by using high shear processing (HSP) was recently found to be a promising technology for this type of purification [1]. It was found that HSP can significantly fragment the solid oxide films and clusters of the molten aluminium alloy into individual fine oxide particles, which act as potent sites for the nucleation of Fe-rich intermetallic phases. The solidified intermetallic particles can subsequently be removed by the downstream sedimentation process, and hence recycled aluminium alloy is purified by removing the harmful elements.

The original design of the high shear mixer is shown in Fig.1. It consists of closely coupled stator and rotor, which are coaxial and separated by a very small gap. The impeller of the rotor has four flat blades, which is connected to a long shaft. The stator is a tube, which has a series of circular holes in the wall near its end. The outer diameter of the stator is 42 mm, and there are 72 holes of 2.5 mm diameter in the stator which are aligned along four rows.

In the former experimental and computational research, this mixer proved to be capable of successfully shearing the molten aluminium alloy in a cylindrical crucible of 300 mm diameter and 300 mm deep, which accounts for about 50 kg liquid metal. In order to investigate the feasibility of the scale-up of the HSP, computational simulation was employed in the recent research trying to predict the performance of the HSP in a scale-up case. In this paper, we call the former trial of HSP by using the original 42 mm diameter mixer the baseline case.

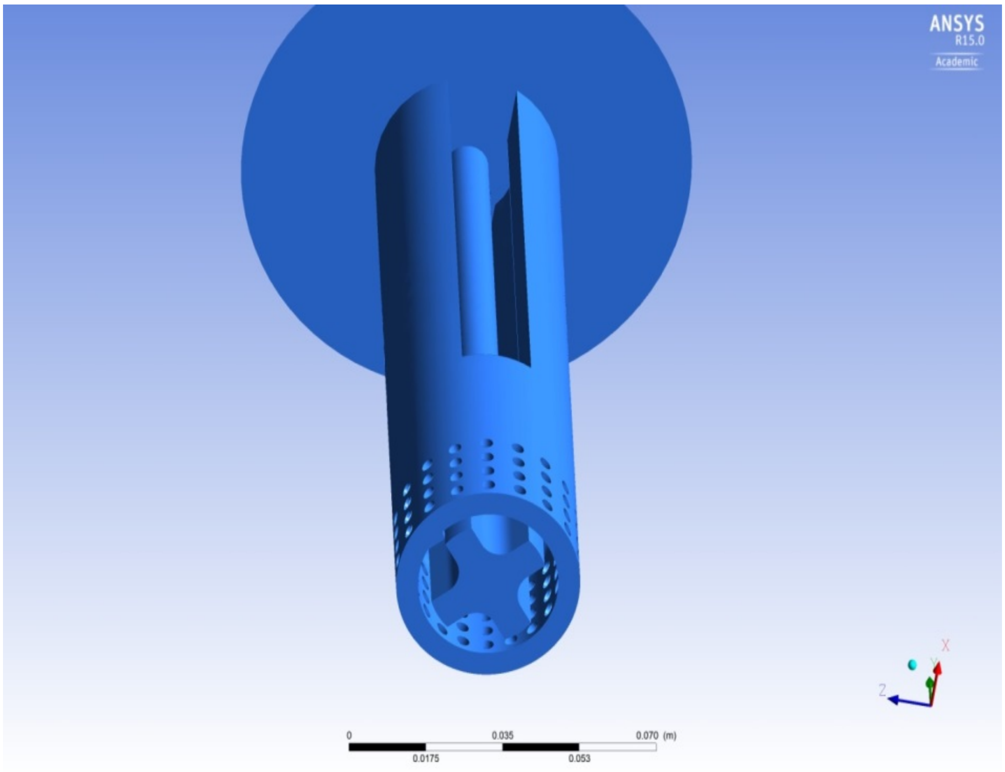


Fig.1 Geometry of the original high shear mixer

In the case study of the scale-up of the HSP, the design of the high shear mixer is adjusted. The outer diameter of the new mixer is 80 mm and there are 280 radial holes in the wall near the end of the stator, which are aligned along seven rows. This diameter of the new mixer is almost twice the diameter of the old mixer. The rotor of the new mixer runs at the speed of 2000 rpm and the mixing head is 150 mm below the free surface of liquid metal. The crucible that is employed in the scale-up case of HSP is 650 mm in diameter and 650 mm deep. In the computation, the crucible is filled with the liquid AA6060 alloy of 550 mm deep. The total mass of liquid metal in this scale-up case is around 493 kg. Compared with the former case of HSP using the 42 mm diameter mixer, this accounts for the factor of ten of the scale-up of HSP, in terms of the mass of the liquid metal.

2. Simulation results

The overall fluid flow problem is mathematically formulated with the conservation equations of mass and momentum, in 3D Cartesian coordinates. The turbulence feature of fluid flow is taken into account by using the realizable $k-\varepsilon$ model [2] with enhanced wall treatment [3]. The interface between the liquid metal and air is implicitly captured by the volume of fluid method [4]. The overall simulation domain is discretized with tetrahedral mesh of adaptive resolution, in order to resolve the geometrical features of different sizes at different places of the domain. The mesh size varies between around 0.4 mm and 15 mm. Sliding mesh is employed in order to take the rotational movement of the impeller and its influence on the fluid flow into account. The overall governing equations are solved with the SIMPLE method [5], in order to find the transient solution of the target problem. The size of the time step is 5×10^{-4}s. The computation was implemented by using the FLUENT module of ANSYS.

2.1 Mass flow rate

The temporal evolution of the mass flow rate of liquid metal through the different rows of holes in the wall of the stator is illustrated in Fig.2. While the flow rate through the rows of holes near the bottom of the mixing head (e.g. Row 1-4 counting from the bottom of the mixing head upwards) is comparatively low, the mass flow rate through the top rows of the holes (row 5-7) is comparatively high. At the steady state, the total mass flow rate through all the holes in the wall of the stator is around 3.1 kg/s. Because the fluid flow reaches its steady state by the time of 2 s of shearing, we analyse the respective features of fluid flow at the time of 2 s in the rest parts of this paper.

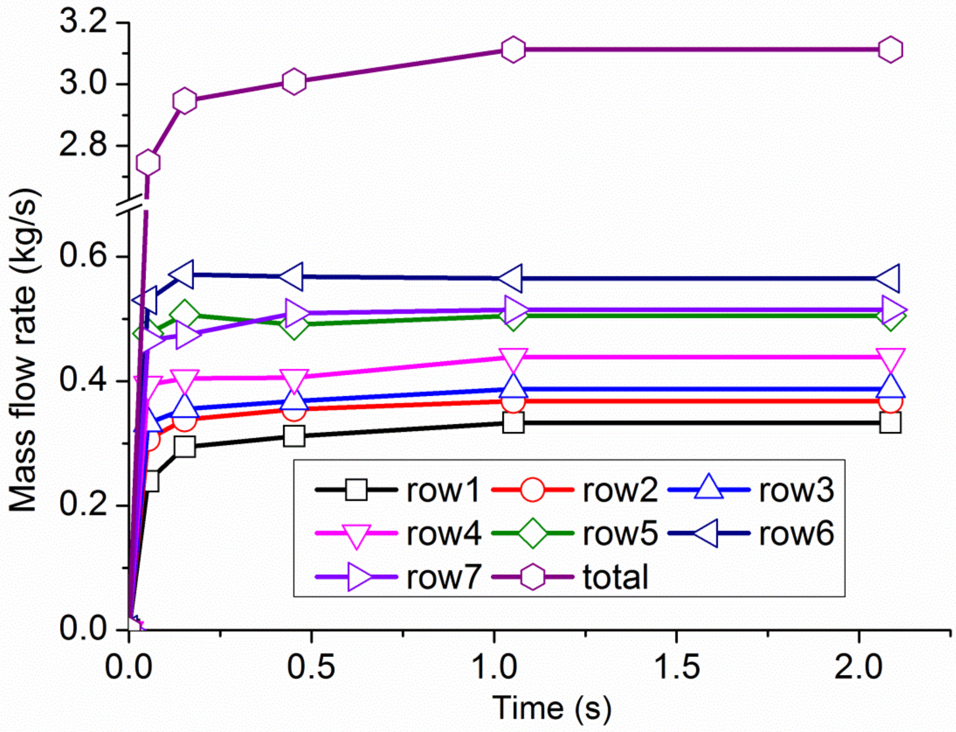


Fig.2 Temporal evolution of the mass flow rate through the holes at the side of the stator

The area integrated absolute value of mass flux of the melt across the diameter of the crucible is illustrated in Fig.3, which characterises the effective vertical mass flow rate of liquid metal in the crucible along its depth. In this figure, it can be found that the effective vertical mass flow rate has a maximum value at around 50 mm below the bottom of the mixing head. Within the range of above the top of the mixing head by 50 mm and below the bottom of the mixing head by 200 mm, the effective vertical mass flow rate is above 3.1 kg/s. The effective vertical mass flow rate mathematically formulates the significance of the vertical agitation of the liquid metal in the crucible. As only the vertical agitation of liquid metal has the capability of redistributing the liquid metal in the depth of the crucible through the mixing head and get effectively sheared, the effective vertical mass flow rate can be used to approximately characterise the effective agitation of liquid metal in the overall crucible.

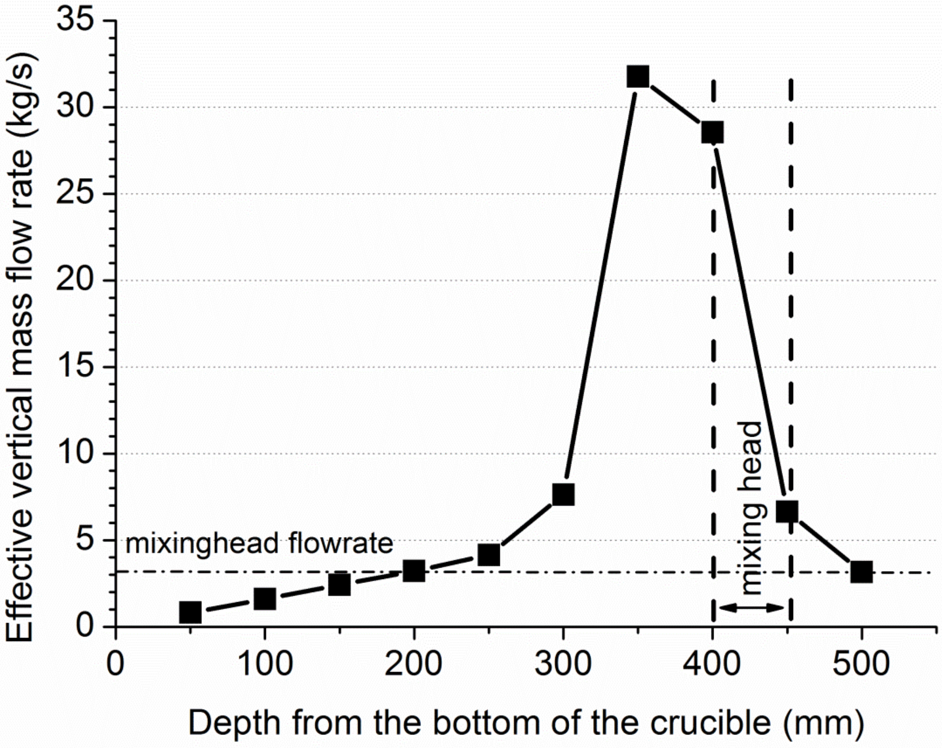


Fig.3 Profile of the effective vertical mass flow rate along the depth of the crucible at 2 s of shearing

Because the mixing head can only treat the liquid metal at the mass flow rate of 3.11 kg/s (shown in Fig.1), the liquid metal that is within the range of 200 mm to 500 mm deep in the crucible can be effectively redistributed through the mixing head and sheared. The liquid metal that sits at the bottom 200 mm of the crucible or at the top 50 mm relative to the free surface is hard to be effectively redistributed through the mixing and sheared. This means that approximately 269 kg liquid metal can be effectively processed at the mass flow rate of the order of 3 kg/s in this crucible.

2.2 Radial agitation of the liquid metal

The effective vertical mass flow rate is only characterising the vertical component of melt flow that is averaged across the diameter of the crucible. When sampling the contour of melt velocity along a plane through the rotor shaft as shown in Fig.4, it can be seen that the magnitude of melt velocity is relatively high in the close vicinity of the mixing head and it decays rapidly away from the mixing head. The liquid metal near the wall or bottom of the crucible is relatively stagnant. The radial profile of the velocity of the melt is very nonuniform. If we define the value of melt velocity of 1 cm/s to be the threshold value that defines the volume of well agitated melt, we can get the geometry of effective agitation as shown in Fig.5.

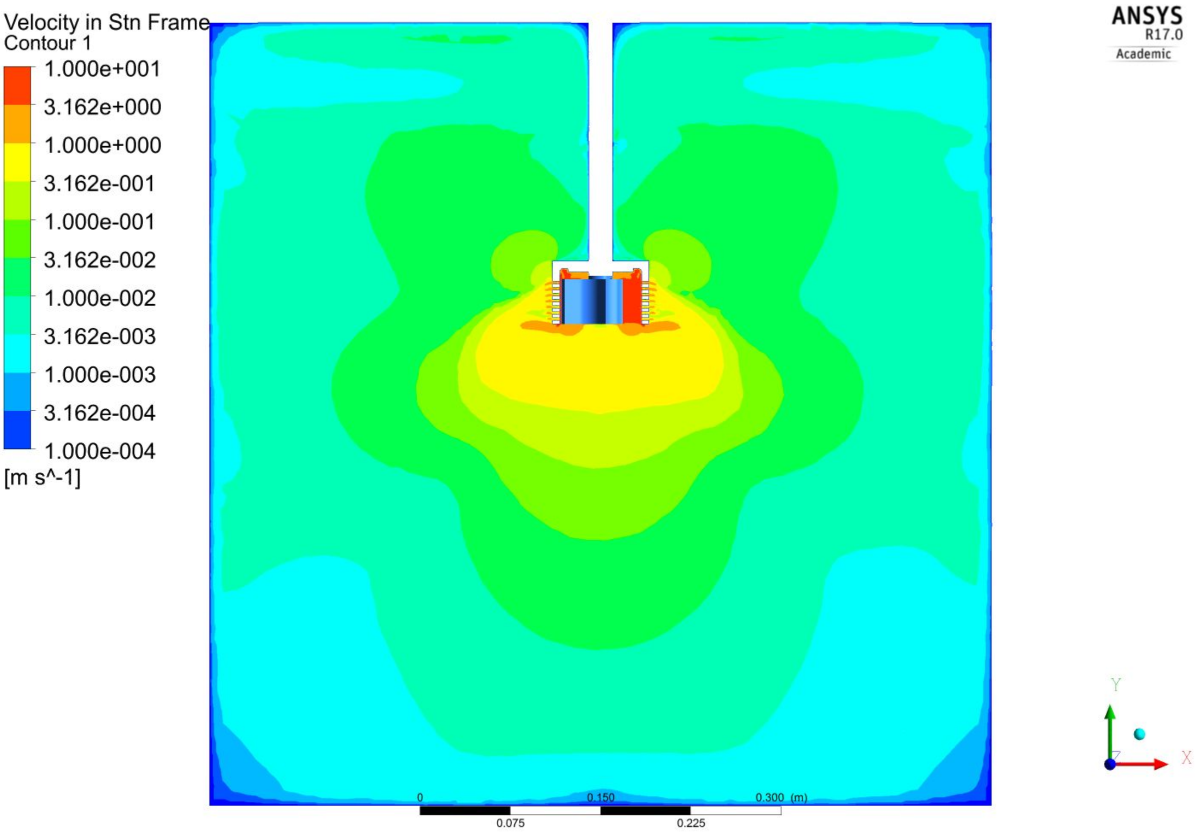


Fig.4 Contour of the melt velocity in a plane through the rotor shaft at 2 s of shearing

The diameter of this volume is around 450 mm and it extends from the free surface of liquid metal continuously downwards by around 400 mm. This means that this 80 mm diameter mixer can effectively agitate the whole liquid metal in a 450 mm diameter and 400 mm deep volume when running at the impeller speed of 2000 rpm.

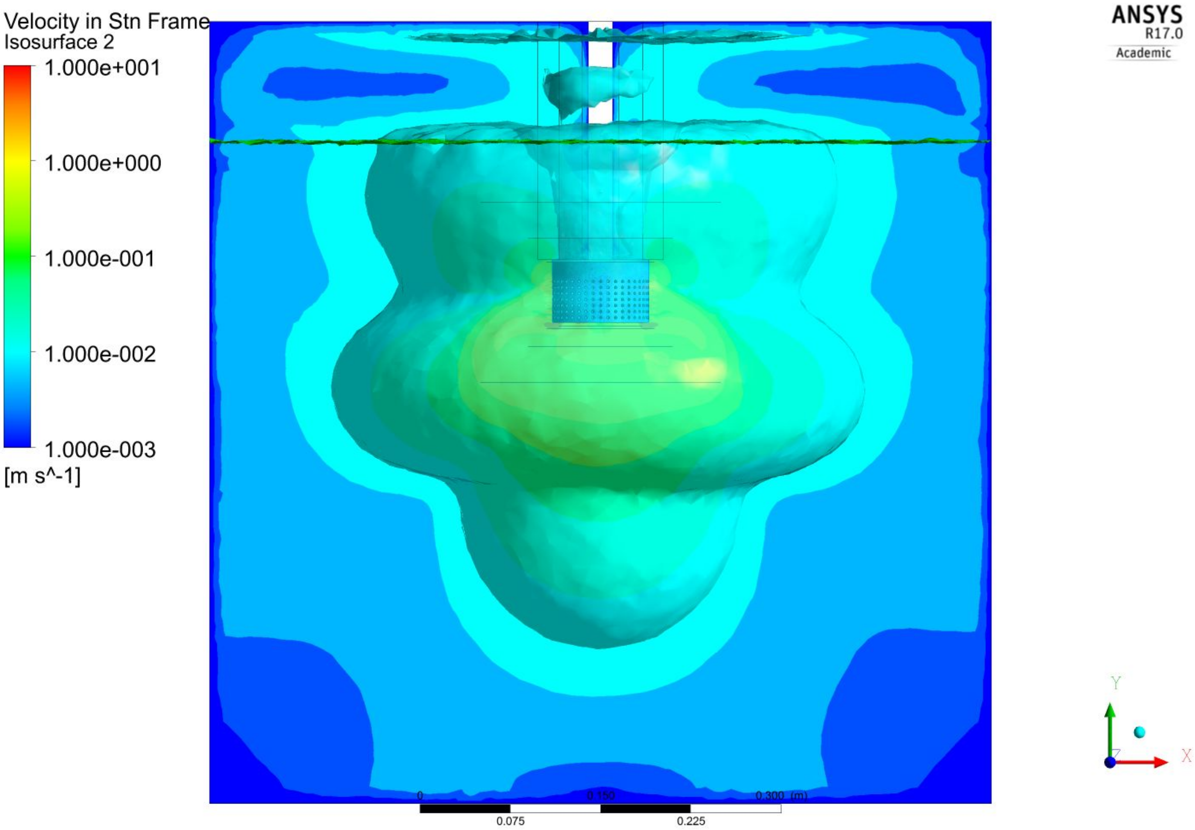


Fig.5. Contour of melt velocity of 1 cm/s at 2 s of shearing

The vector shown in Fig.6 demonstrates the tangential velocity of the liquid metal at a plane through the rotor shaft at 2s of shearing. It can be seen that there is a very localised strong recirculation of liquid metal near the bottom of the mixing head. Such recirculation entrains the outshooting melt jets immediately back into the mixing head through the large opening at its bottom. This strong and localized melt recirculation makes the liquid metal in the far field difficult to effectively agitate. Above the mixing, however, the outshooting melt jets through the holes in the wall of the stator are acting as a highly energetic barrier that obstacles any chance that the liquid metal above the mixing head can flow into the mixing head at all.

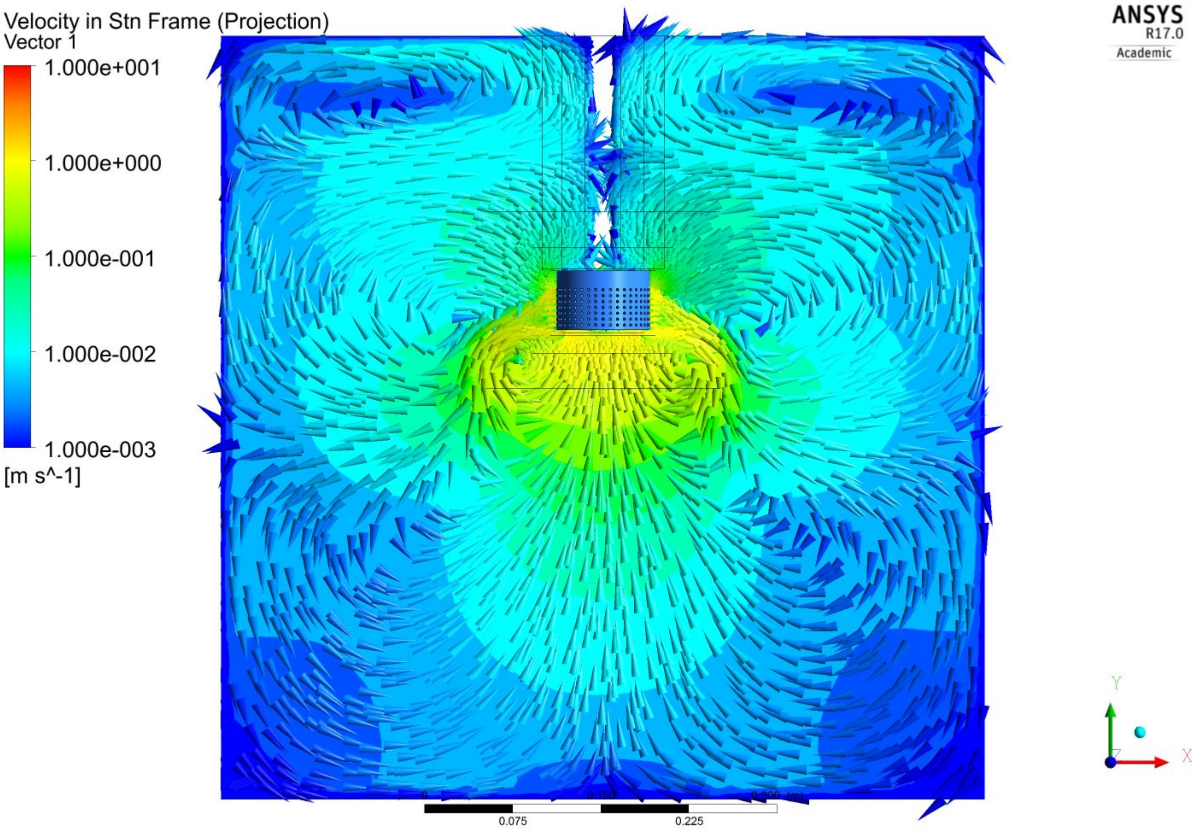


Fig. 6 Vector of melt velocity at 2 s of shearing

The streamline shown in Fig.7 can help understand the overall flow pattern of the liquid metal in the crucible. Within the range of above and below the mixing head by approximately 100 mm, there is a very strong recirculation of the melt in the far field of the crucible, along which the liquid metal flows along the radial and circumferential direction simultaneously. Below this region, there is a counter rotating recirculation of the liquid metal, along which the liquid metal flows at relatively low velocity.

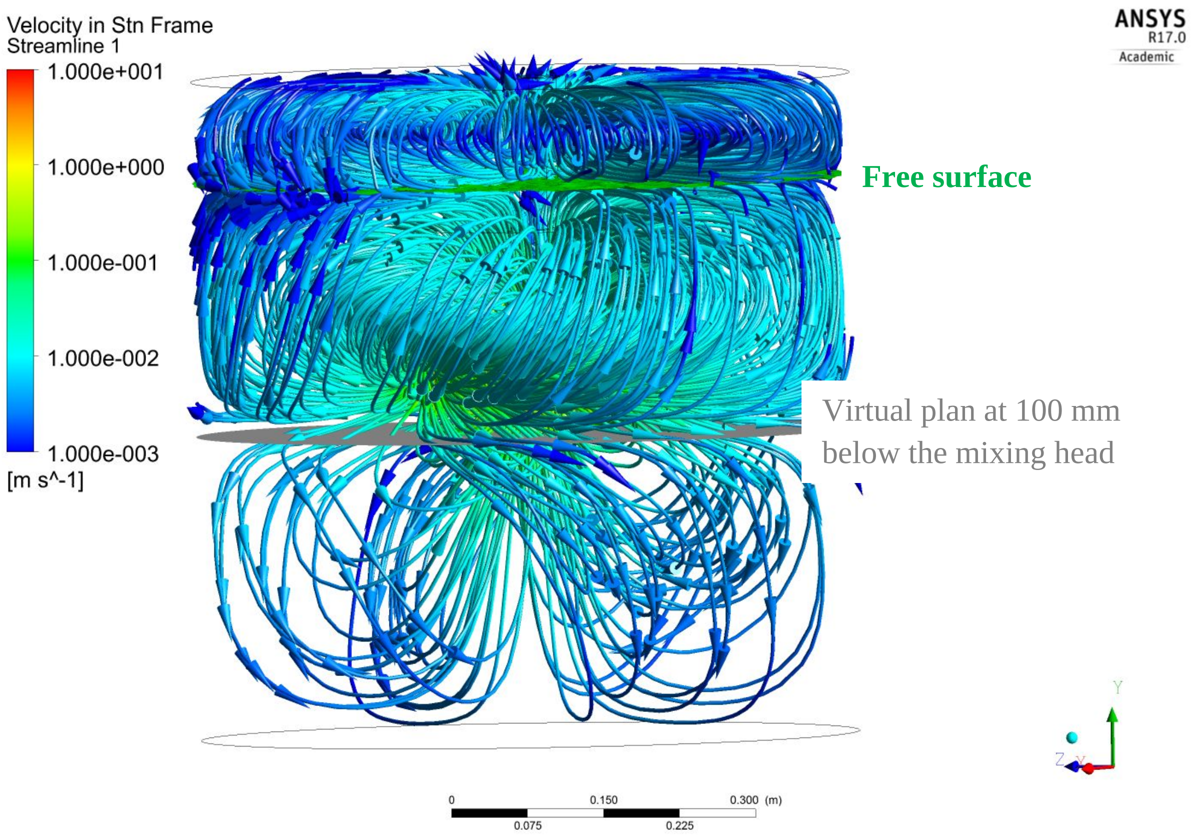
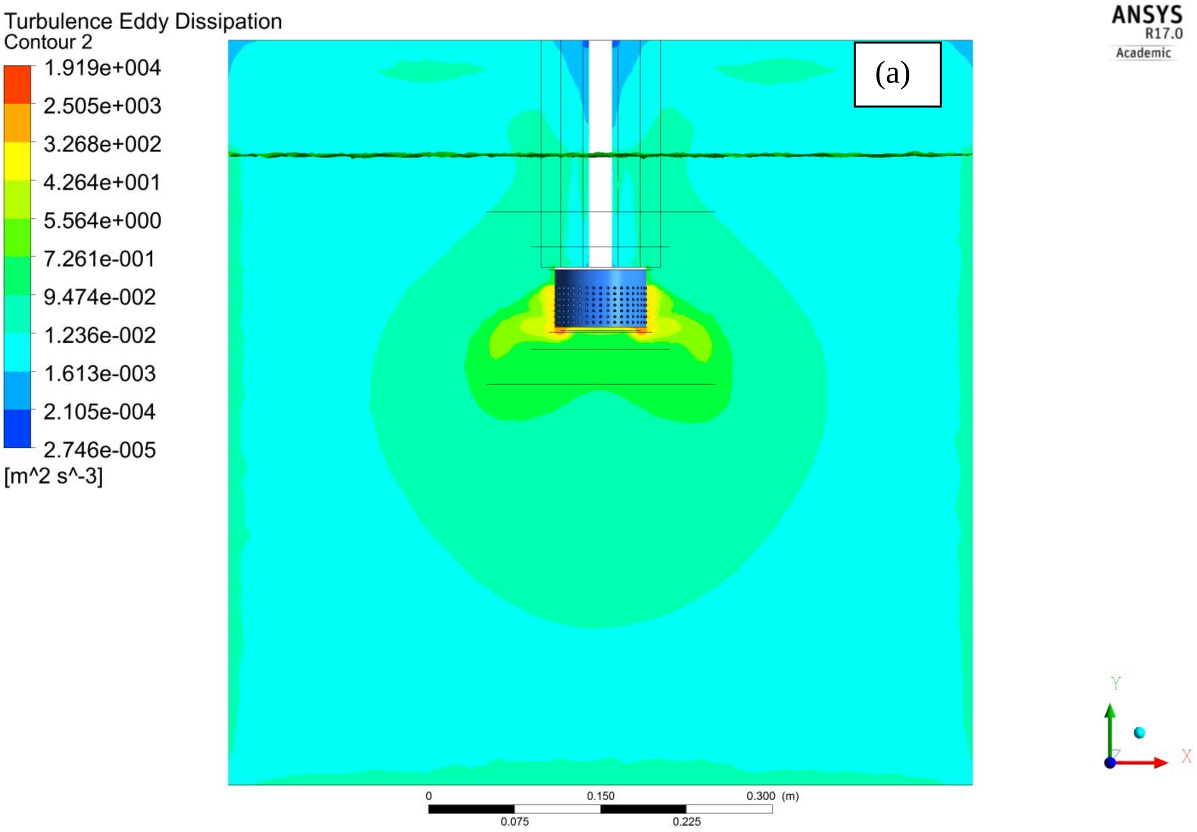


Fig.7. Streamline of the liquid metal at 2 s of shearing

2.3 Shear rate

As shown in Fig.8, the turbulence eddy dissipation rate is highly nonuniform along the depth (a) and diameter (b) of the crucible. The characteristic shear rate can be calculated by using the squire root of the turbulence eddy dissipation rate divided by the kinematic viscosity of the melt. At the time of 2 s of shearing, the maximum shear rate in the whole crucible is 6.56×10^5/s.


Turbulence Eddy Dissipation
Contour 2
1.919e+004
2.505e+003
3.268e+002
4.264e+001
5.564e+000
7.261e-001
9.474e-002
1.236e-002
1.613e-003
2.105e-004
2.746e-005
[m^2 s^-3]
(a)
ANSYS
R17.0
Academic
Y
X
0
0.150
0.300 (m)
0.075
0.225

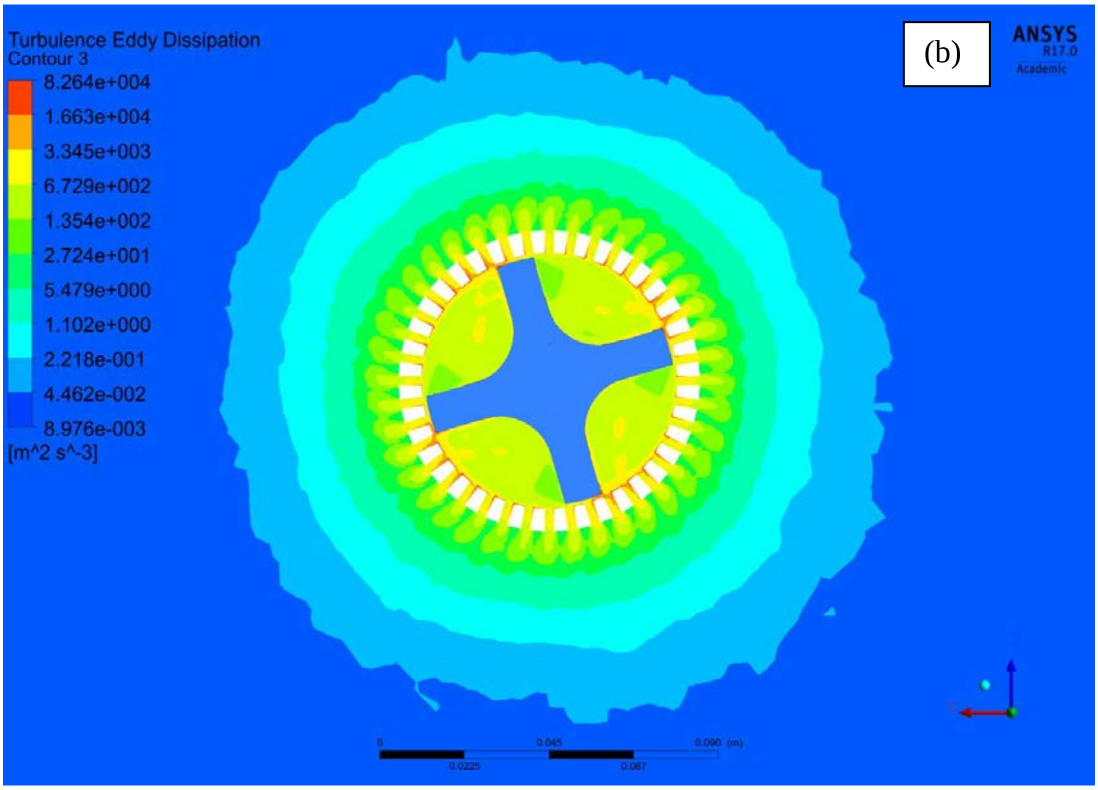

Turbulence Eddy Dissipation
Contour 3
8.264e+004
1.663e+004
3.345e+003
6.729e+002
1.354e+002
2.724e+001
5.479e+000
1.102e+000
2.218e-001
4.462e-002
8.976e-003
[m^2 s^-3]
(b)
ANSYS
R17.0
Academic
0
0.045
0.090 (m)
0.0225
0.067

Fig.8. Contour of the turbulence eddy dissipation rate at a plane along the rotor shaft (a) and at a plane that is normal to the rotor shaft and sectioning a row of the holes in the wall of the stator (b) at 2 s of shearing

3. Discussion and conclusion

According to what was calculated by using the CFD modelling, in the scale-up case of the HSP treatment of molten aluminium alloy, we can get the mass flow rate of around 3.1 kg/s through the mixing head. This value is less than the corresponding value (10.3 kg/s) of the baseline case (when formerly using the 42 mm diameter mixer). The key reason is that we sheared at 5000 rpm in the baseline case and sheared at 2000 rpm in the scale-up case. However, it was found that a relatively larger volume of liquid metal is effectively agitated in the scale-up case. Specifically, within the range of 300 mm deep around the mixing head, the effective vertical mass flow rate across the diameter of the crucible can match the mass flow rate through the holes at the side of the stator (Fig.2). It is reasonable to conclude that the 80 mm mixer can effectively agitate and shear the whole bulk liquid metal in a 450 mm diameter and 300 mm deep crucible. This accounts for around 129 kg AA6060 alloy.

While the scale-up case has a lower value of mass flow rate through the mixing head, its maximum value of shear rate (6.56×10^5/s) is higher than that of the baseline case (1.95×10^5/s). This is probably because the larger size mixing head has larger space for the turbulence of fluid flow to develop. While using either the baseline case or scale-up case setup of HSP, the high shear rate only exists in the close vicinity of the mixing head and the liquid metal is only strongly agitated within the order of centimetre above and below the mixing head.

The overall conclusion is that the scale-up case can be expected to effectively treat the liquid metal in a 450 mm diameter and 300 mm deep crucible (holding around 129 kg aluminium alloy) within the time order of minute, using the 80 mm diameter mixer running at 2000 rpm. Compared with the baseline case of HSP, this accounts for the scale-up of around factor of three. Because only a moderate rotor speed of 2000 rpm was employed in the computation, and the mass flow rate through the mixing head was found to be strongly and positively dependent on the impeller speed by our recent research, it is reasonable to estimate that the

80 mm mixer has the potential to be effectively applied in the four time scale-up of HSP (i.e. treating 200 kg liquid metal at a time running at 5000 rpm or so) instead of three time scale in reality. If an even high factor of scale-up of HSP is to be achieved, besides using an even larger size mixer in diameter, adjusting the length of the stator below the bottom of the mixing head is an option. The extension of the length of the stator can dramatically enlarge the volume of well agitated liquid metal without needing a higher power motor to drive the rotor.

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