

Mixing in Ladles by Vertical Injection of Gas and Gas-Particle Jets — A Water Model Study

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The composition of a liquid metal alloy can be adjusted by additions to the metal in the ladle before casting. The productivity of such operations can be optimized if the time required for completely mixing the addition in the ladle is known. The mixing time is usually defined as the time required for the concentration of the tracer of one location to reach 95 pct of the steady state concentration after an addition at another location. In a stirred vessel, this time is related to the intensity of the stirring. The results of several studies relevant to metallurgical processing have been successfully correlated by equations of the form of Eq. [1]:

$$t_{\text{mix}} = A\epsilon^{-B} \quad [1]$$

In Eq. [1], t_{mix} is the time required for mixing in seconds, ϵ is the specific rate of dissipation of turbulent energy in the vessel in watts per ton, and A and B are constants which depend on the nature of the mixing process, the dimensions of the vessel, and the procedure by which the mixing time is measured.¹⁻⁸ In most studies, the exponent B has been found to have a value between 0.25 and 0.5.

In metallurgical processes, the power for stirring a vessel is often supplied by injecting gas below the surface of the vessel. The buoyancy of the gas bubbles drives the recirculating flow of the liquid. In injection processes, this gas stream can be used to carry particles into the melt. When the velocity of the injection and the loading of particles in the jet are high, then the kinetic energy of the gas and particles can contribute to the mixing. While the effect of gas injection on the mixing of ladles has received considerable study, the possible effects of particles on the time required for mixing have not been addressed. In this study, a water model has been used to determine the effects of changes in injection parameters on the time required for mixing by gas-particle injection.

The mixing energy supplied to a bath by a gas-particle jet comes from two sources. Under most conditions, the largest source of mixing energy is that due to the rise of gas bubbles through the melt driven by buoyancy. In an isothermal system, this is given by Eq. [2].⁹

$$\epsilon_B = 854 \frac{QT}{W} \log \left(1 + \frac{\rho_l g h}{P_a} \right) \quad [2]$$

In Eq. [2], ϵ_B is the specific power density due to buoyancy (watts t^{-1}), Q is the volumetric flow rate of gas ($m^3 s^{-1}$), T is the temperature (K), W is the mass of the bath (tonnes), g is the gravitational constant ($m s^{-2}$), h is the height of the liquid bath above the tip of the lance (m), ρ_l is

the density of the melt ($kg m^{-3}$), and P_a is the ambient pressure above the bath (Pascals).

The rate at which the gas jet transfers kinetic energy to the bath is given by Eq. [3].¹⁰

$$\epsilon_{K_g} = \frac{1}{2} \frac{\rho_g Q^3}{W A^2} \quad [3]$$

In Eq. [3], ϵ_{K_g} is the specific power density due to kinetic energy of the gas in the jet (watts t^{-1}), ρ_g is the density of the gas ($kg m^{-3}$), and A is the cross-sectional area of the lance (m^2).

If the particles travel at the same velocity as the gas, the rate at which the particles in the jet transfer kinetic energy to the bath is given by Eq. [4]

$$\epsilon_{K_p} = \frac{1}{2} \frac{\dot{m} Q^2}{W A^2} \quad [4]$$

In Eq. [4], ϵ_{K_p} is the specific power density due to the kinetic energy of the particles in the jet (watts t^{-1}) and \dot{m} is the mass flow rate of particles ($kg s^{-1}$). Compressibility effects are neglected in Eqs. [3] and [4] so that the ratio Q/A corresponds to the linear velocity of the jet. ϵ_{K_g} and ϵ_{K_p} vary with the square of the linear velocity of the gas leaving the jet.

In this study, a water model has been used to determine the effects of changes in injection parameters on the time required for mixing by gas and gas-particle injection. Seventy-six liters of water were contained in a cylindrical polyethylene vessel, which tapered from 48.5 cm in diameter at the top to 42 cm in diameter at the bottom. The vessel was filled to a depth of 48 cm.

A solution of 75 pct H_2SO_4 was used as the tracer, and the concentration of tracer in the solution was monitored using a pH meter. Approximately 3 ml of tracer was added during each experiment. This contains sufficient H^+ to reduce the pH of the water to 3, and the mixing was considered complete when the pH of the solution had stabilized to within ± 0.01 pH units. This corresponds to a degree of mixing of 97.7 pct.

The bath was mixed using gas injection through a lance directed vertically downward in the center of the tank. Mixing was performed by injection of air and helium through nozzles 0.12, 0.254, and 0.4 cm in diameter located 6, 26, and 46 cm below the surface of the liquid. Air was also used to inject silica sand with an AFS grain fineness number of 106 and resin coated silica sand with an AFS grain fineness number of 60 through the 0.254 cm diameter lance from 26 cm below the surface of the liquid. These particles are inert and denser than the liquid into which they are injected and therefore these experiments have been performed with a particular type of gas-particle jet whose behavior may not be the same as that of most gas-particle jets used in steel processing.

The pH of the solution was monitored using an electrode placed 2.0 cm below the surface of the bath and 0.5 cm from the circumference. In different experiments, the tracer was injected (1) very near the pH electrode, (2) diametrically opposite the pH electrode near the surface, (3) 0.5 cm from the bottom of the tank directly below the pH electrode, (4) directly below the injection lance, and (5) 0.5 cm from the bottom of the tank diametrically opposite the pH electrode. The time required to reach 97.7 pct

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mixing for each set of experimental conditions was measured as a function of the flow rate of gas, and the effect of changes in the injection parameters on the time required for mixing was noted.

The time required for 97.7 pct mixing for cases in which the lance was submerged 46 cm at the center of the vessel and the tracer was injected at different positions is plotted in Figure 1 as a function of the rate at which turbulent energy due to buoyancy forces was supplied for mixing. The data for each condition were fit to a straight line by the least squares method so that they could be represented by an equation of the form $t_{\text{mix}} = A\epsilon^{-B}$, and the values of the coefficients A and B are included in the figure. In general, the experimental values of the exponent B were found to be substantially larger than the values observed in other studies.¹⁻⁸

The position at which the tracer was added was found to have a significant effect on the time required to produce complete mixing. The locations near the top of the bath gave much more rapid mixing than the locations near the bottom of the bath, and the location near the tip of the lance gave longer mixing times when the rate of gas injection was low, but mixing time approaching those observed for shallow tracer injection when the rate of injection of gas was high.

These results are consistent with the theoretical profiles of turbulent viscosity as a function of position reported by and Guthrie and co-workers which indicated higher turbulent viscosities near the top surface of the bath.^{11,12,13} Shorter mixing times would be expected when the tracer is injected into a region with a high turbulent viscosity, and hence a high eddy diffusivity. The mixing of the tracer injected into other locations would be expected to be delayed until the

circulation of the bath carried the tracer into regions of higher turbulence.

For injection at a particular depth in the water model, the rate at which a gas stream supplies potential energy for mixing to a liquid bath depends only on the volumetric flow rate of the gas, while the rate at which kinetic energy is supplied also depends on the linear velocity of the stream, the density of the injected gas, and the mass flow rate particles in a gas-particle jet. In this study, the effect of changing the kinetic energy of the gas stream was investigated by varying the diameter of the lance and the density of the injected gas. For a given gas, the kinetic energy of the gas stream is higher when it is injected through a smaller lance, and the kinetic energy is higher when a denser gas is injected through a given lance. The addition of particles increases the kinetic energy of the gas stream at any fixed volumetric flow rate of gas. For any combination of injection parameters, the contribution of kinetic energy to the total rate of supply of energy for mixing increases as the volumetric flow rate of the jet increases. For small diameter nozzles and for jets containing entrained particles, the kinetic energy is the principal source of energy for mixing at high injection rates.

Equations of the form of Eq. [1] have been successfully used to correlate mixing times with mixing power densities in systems with very different means of mixing.¹⁹ This implies that mixing energy from all sources can be added to give a total mixing energy. Figure 2 shows the effect of the total turbulent energy for mixing calculated from Eqs. [2], [3], and [4] on the time required for 97.7 pct mixing when the tracer was injected at positions (3) and (5) near the bottom edges of the vessel. A least squares fit of these data gives Eq. [5] with a correlation coefficient of 0.83.

$$t_{\text{mix}} = 501\epsilon^{-0.46} \text{ sec} \quad [5]$$

Figure 3 shows the times required for 97.7 pct mixing in the same experiments plotted as a function of the rate of addition of potential energy calculated from Eq. [2] alone. A least squares fit of these data gives Eq. [6] with a correlation coefficient of 0.875.

$$t_{\text{mix}} = 692\epsilon^{-0.89} \text{ sec} \quad [6]$$

Exponents in Eqs. [5] and [6] and those in Figure 1 are all much higher than the exponents which have been measured in similar experiments.¹⁻⁷ This may be due to the somewhat different specification of complete mixing used in this study than in other studies. When the system is very near to a state of complete mixing, the last stage of solute redistribution into poorly mixed regions of the bath may occur primarily by molecular diffusion rather than turbulent diffusion. The values of the exponents observed in this study are consistent with values of the exponents observed in other studies where the flow was dominated by molecular viscous forces.¹⁴ Furthermore, the probe and tracer injection sites in this study were located very near the walls of the vessel and so the results may have been influenced by viscous boundary layers near the walls.

The correlation of experimental results is significantly better when the contribution of the kinetic energy to the rate of energy supplied for mixing is not included. Examination of Figure 2 shows that at low velocities of injection, the data fit a single line, but at higher velocities of injection, the data

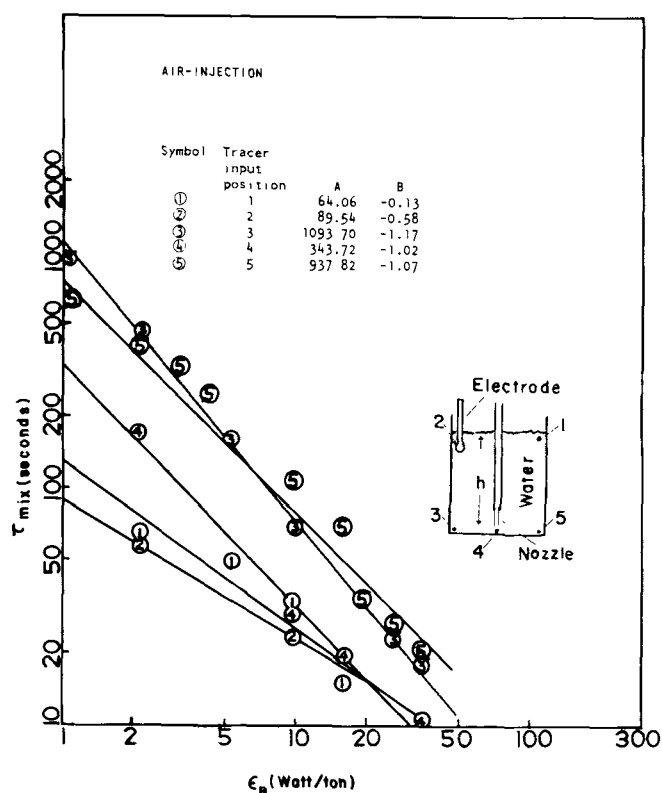


Fig. 1 — Effect of location of tracer injection on time required for complete mixing vs rate of dissipation of turbulent energy by buoyancy forces

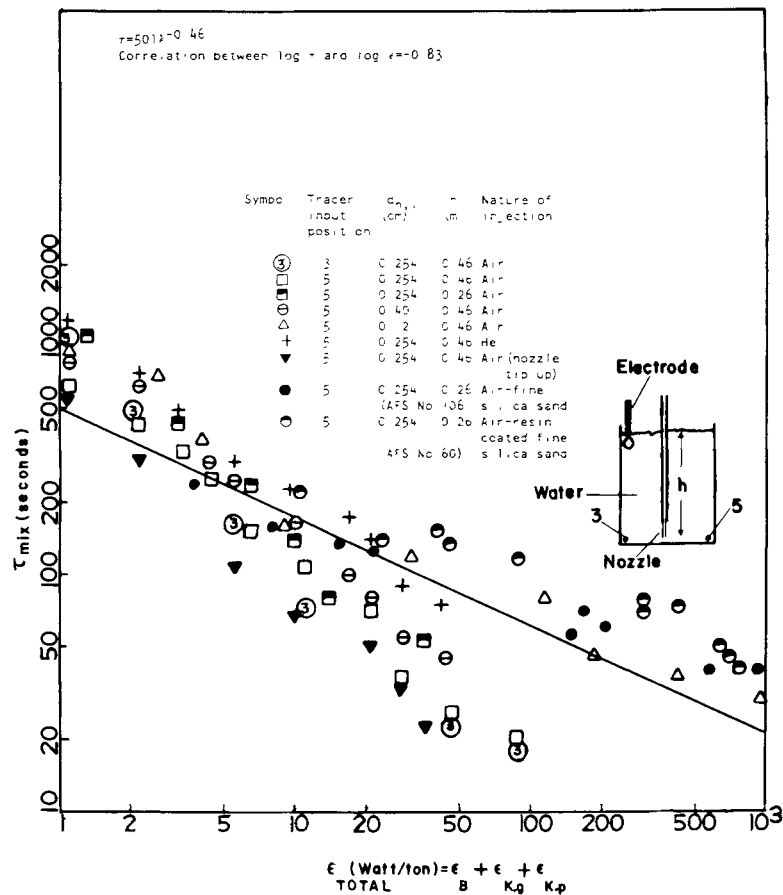


Fig. 2—Effect of total kinetic energy for mixing on time required for mixing

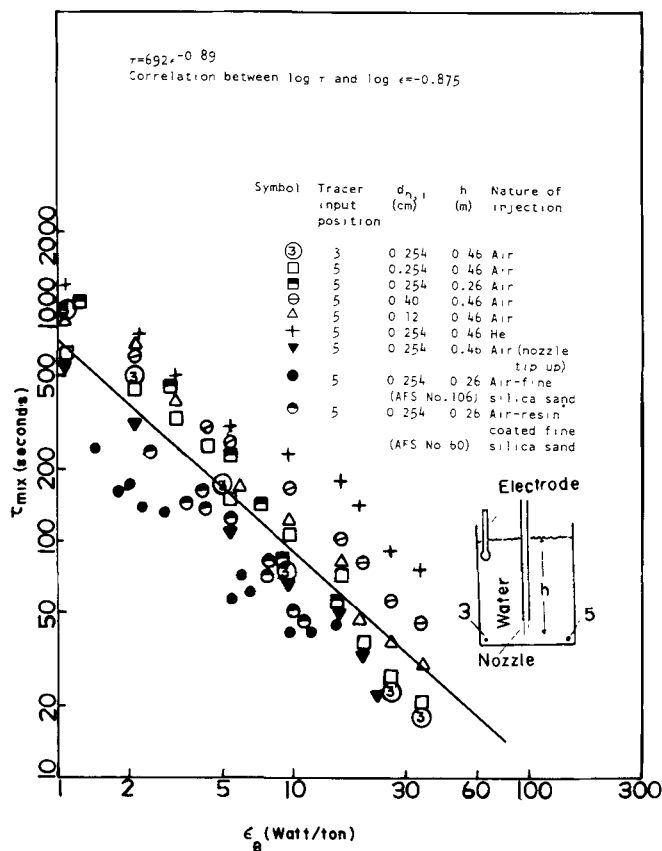


Fig. 3—Effect of energy from buoyancy forces on time required for mixing.

for gas-particle injection and for injection through the smallest nozzle indicate longer mixing times than for other systems. These are the conditions where the contribution of kinetic energy is greatest, and indicate that the effect of kinetic energy on the time required for complete mixing is disproportionately small. This result is consistent with the results of several other recent studies of this phenomenon which indicate that kinetic energy does not contribute to mixing in the same way as buoyancy.^{15,16}

The small effect of kinetic energy on mixing in gas stirred systems has been attributed to the rapid dissipation of kinetic energy near the point of injection.¹⁶ Jets containing entrained particles penetrate much more deeply than jets which do not contain entrained particles.¹⁷ When the gas jet is injected vertically downward in the center of the vessel, this increased penetration is likely to have little effect on the overall circulation in the bath. The kinetic energy associated with particle injection or high velocity gas injection may play a more important role in mixing when the jet is injected in a non-axisymmetric orientation. Further water modeling experiments are under way at the University of Illinois at Chicago to investigate this phenomenon.

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Absorption of CO₂ Laser Beam by AISI 4340 Steel

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During laser welding the absorption of laser beam by the workpiece is affected by several factors such as the nature of the surface, joint geometry, and the amount and composition of plasma present in the vicinity of the molten pool. Clean surfaces of all metals and alloys at room temperature are highly reflective to the infrared radiation of carbon dioxide laser,^{1,2} and this poses a problem in the transfer of energy from the laser beam to the workpiece. The absorption of energy can be enhanced by appropriate surface modifications such as anodizing, sand blasting, and application of suitable coatings on metallic surfaces.³ For a given surface condition the absorption increases with temperature, and a liquid pool may form if sufficient amount of energy is absorbed by the solid surface. As a result of laser-material interaction, plasma and/or metal vapors may form de-

pending on the power density, the type of the shielding gas, and the temperature and composition of the molten pool.⁴ The absorption of laser beam in these cases is also influenced by the amount and composition of the plasma or metal vapor. The net amount of energy absorbed is affected by the interaction of various interdependent factors and is strongly dependent on the experimental conditions. An understanding of the energy absorption by the workpiece is important since the absorption is the principal method of energy transfer. The thermal cycles and the peak temperatures are significantly influenced by the absorption of the beam energy by the specimen. All heat transfer calculations on laser material processing require knowledge of laser beam absorptivity.

In the past several techniques were utilized to determine the absorptivity. Eagar *et al.*¹ determined the absorptivity of pure aluminum and aluminum alloys experimentally. The technique was based upon the evaluation of the amount of beam energy absorbed by a suitably designed cavity and by a flat surface. In this experimental technique the melting of the surface does not always occur and therefore the complexities associated with the presence of metallic constituents in the plasma can be avoided. The absorption of infrared radiation by metals largely depends on conductive absorption by free electrons and therefore the absorptivity can be calculated from the knowledge of the electrical resistivity of the substrate.^{5,6} Bramson⁵ related the absorptivity with the substrate resistivity and the wavelength of laser radiation. Arata *et al.*⁶ demonstrated that the absorptivity of various polished metallic surfaces is a linear function of the square root of the electrical resistivity of the respective metals. In these calculations the influence of plasma on absorptivity is ignored. Therefore the calculated absorptivity values represent the maximum possible value during laser welding, *i.e.*, in the absence of energy absorption by plasma.

The purpose of this documentation is to demonstrate an experimental technique for the determination of the absorptivity of the laser beam in steel samples under conditions of laser welding.

A Coherent Model #525-1 laser, capable of producing a maximum output power of 575 watts in the continuous wave mode, was used. Experiments were conducted with AISI 4340 steel samples typically about 4×10^{-2} m long, 1.5×10^{-2} m wide, and 0.045×10^{-2} m thick. The sample surface was ground with a 240 grit grinding paper. Samples were placed on a remotely controlled, electrically operated table capable of providing linear speeds in the range of 1×10^{-3} to 20×10^{-3} m per second. The table was placed inside a plexiglass box which arrested any stray reflected laser beam and provided controlled atmosphere during laser welding. Arrangements were made to supply a shielding gas (He) at a predetermined rate (100 ml per second) through a copper nozzle mounted coaxially with the laser beam. The laser beam was focused using a 2.54×10^{-2} m diameter, 0.127 m focal length Zn-Se lens with antireflection coating. Specimens were held in place by using suitable clamps, and welding was performed at preset values of laser power, welding speed, and shielding gas flow rate. Since the temperature in the base plate changed rapidly during welding, lightweight thermocouples made of 1.27×10^{-4} m diameter platinum and platinum-13 pct rhodium wires were

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