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Experimental and Numerical Modeling of Mixing and Settling in Continuous Metal Production

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Abstract

Metal is now produced from ore in novel single reactors. These converters provide substantial improvement in fuel efficiency and much better pollution control than common practice.

The reactors are operated essentially in a horizontal mode to permit staging of fuel and oxygen potential in the bath along the reactor by utilizing bottom-blowing of oxygen and fuel through injectors directly into the liquid bath. The submerged injectors must create sufficient turbulence to provide excellent heat and mass transfer between gas and liquid in the bath, but this turbulence must be localized to provide zones for separation of metal and slag between the active turbulent mixing and chemical reaction zones. For the design and refinement of these processes it is important to know the behavior of gas and liquids in the plume created by submerged gas injection, the nature of liquid entrainment into the plume, the extent of the mixing zone and the effect of baffles on the confinement of said mixing zone. Experimental and numerical work was conducted to study stirring of single liquid reactors and mixing and settling in a bath of a two liquid reactor stirred by submerged gas injection.

Introduction

Metal is now produced directly from ore concentrates in modern single elongated reactors using submerged gas injection in a great variety of both ferrous and nonferrous smelting and refining operations. These novel reactors promise substantial fuel savings in metal production and much better control of pollutants than common practice, such as the blast furnace for steel production or the reverberatory furnace for copper production. Tonnage oxygen and bottom blown oxygen converters are now employed for lead production in several QSL reactors worldwide [1], Figure 1. These reactors are suitable for the simpler copper production and can be modified for continuous steel production [2]. The horizontal operation permits staging of the oxygen in the bath from an oxidation to a reduction zone along the reactor. This requires a multitude of injectors into the bath along the reactor. Oxygen and fuel are bottom injected through these injectors into the molten bath in such volumes to assure proper reaction rates. This submerged injection gives rise to local intensive mixing of the slag and metal or matte layers in the bath and increases heat and mass transfer between the gas and the metal and slag respectively. High gas inlet velocities through the injectors are necessary to prevent metal from clogging the injectors but care must be taken to prevent jetting of the gas through the bath, because this will result in a short residence time of the gas in the bath, little interfacial area between the gas and the bath and thus insufficient reaction rates. Afterburning in the gas phase above the bath and in the gas-uptake will be the result and the reactor will work more in the mode similar to a reverberatory furnace. Best performance of the process is probably achieved when the metal level is low in the reactor such that slag can reach the mouth of the injectors and so called mushrooms are permitted to form [3]. These mushrooms will protect the injectors and break-up the incoming gas jet.

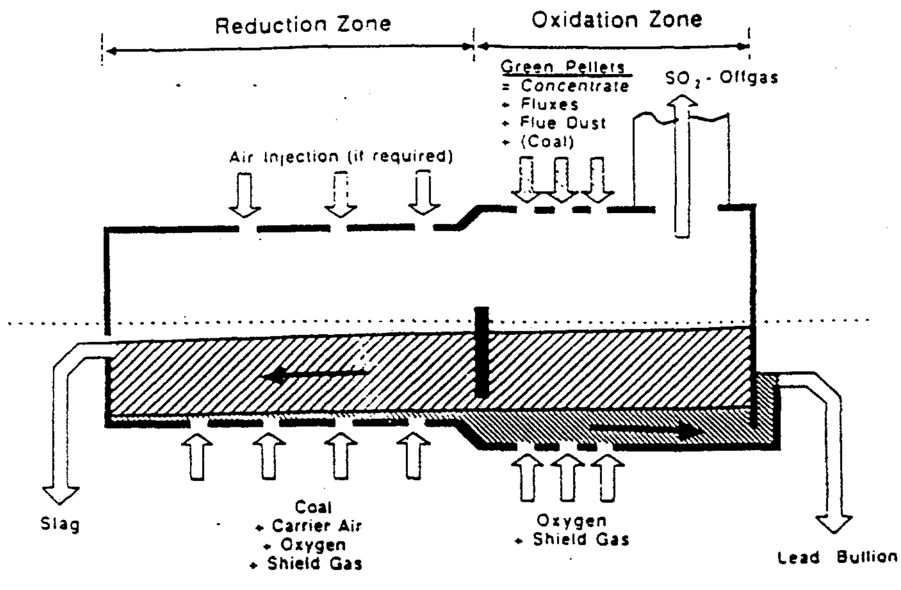


Figure 1 - QSL Reactor from [4]

The rate at which the gas is injected needs to be controlled to localize turbulence and mixing near the injectors and permit sufficient time for separation of the slag and metal reaction products between injection zones. Thus calm regions between the injectors are needed; this reactor operating mode is often referred to as mixer-settler [4].

The design of these reactors requires knowledge of the behavior of the gas, the slag and the metal in the mixing and settling zones of the reactor. It is also important to know the behavior of gases and liquids in the bubble plume, the nature of liquid entrainment into the plume and the shape and composition of the mixing zone in the two liquid bath.

The effects of changing design parameters such as gas flow rate and thickness of the slag and metal layers on the overall behavior of the reactor need to be studied. Analytical models capable of predicting the behavior of the plume and the mixing between the phases are essential in the design and refinement of these processes.

While a fair amount of work has been done on recirculatory flow induced by submerged injection of gas bubbles in ladle shaped vessels, [5-8] one very important topic has received much less attention. In ladle mixing one is usually concerned with homogenization of one liquid, while in these modern single reactors oxidation and reduction reactions are occurring within the bath of slag and metal or matte due to submerged gas injection. The efficiency of these reactors is greatly dependent on the "rate at which reactants may be supplied to the reaction zone," [9]. Thus, for prediction of heat and mass transfer between the gas and the liquids as well as between the liquids it is important to obtain volumetric void fraction data and observe flow velocities in the three-phase flow. Of particular interest is the overall flow behavior in and around the plume created by gas injection.

Research of submerged injection of gas into two liquids has relevance to situations besides metal production. One such situation is nuclear reactor accidents where failure of coolant systems could potentially cause degradation of the reactor's concrete containment walls. The chemical interaction between core melt and concrete would result in the release of gas that rises through two layers of core metal and molten concrete. Information regarding whether these two layers remain distinct or become partially mixed or even homogeneous due to gas bubbling would allow validation of assumptions made in the current modeling of these accidents [10,11].

In this paper experimental and numerical results are presented of gas injection into one liquid and into two layers of two different density immiscible liquids. These liquids have similar density ratios as slag and metal or matte and similar viscosities. The experiments give more insight into the three-phase mixing and separation phenomena and the results are used to validate predictions of numerical models [12,13].

Background and Literature Review

The behavior of bubble plumes in metal production reactors has been of interest for several decades. The research has focused primarily on bubble plumes in cylindrical ladle reactors. Typically, the metal in the reactor is fairly uniform thus can be treated as one liquid with effects of the slag being neglected. The majority of research has been conducted using "cold" models of the reactor with water representing the molten metal [14-17].

There are three distinct regions within the gas plume with different dynamics and different relevant parameters [18]. The three regions are: the development region where jetting and bubble formation are important; a uniform plume region where buoyancy forces dominate and stable bubble sizes exist; and a surface region where the plume's vertical motion is directed radially outward. In the first region for air/water systems, gas velocities close to the sound velocity will lead to jetting, e.g. [19-22], but jetting can be avoided if mushroom formation is permitted [23]. The latter researcher found that gas leaving these mushrooms does not jet but forms bubbles immediately. This information is very important for the assumptions in numerical modeling of the flow.

A large amount of research has been focused on determining parameters of importance for the stable bubble size region. It has been shown that bubbles formed initially, rapidly disintegrate and coalesce due to the turbulence in the plume to achieve a stable bubble size distribution, e.g., [24-26]. In the latter paper, it is stated that "a stable distribution of small-sized bubbles is established ... practically independent of injection conditions." Several researchers showed that the gas void fraction and vertical velocity profile in the plume can be represented using a Gaussian curve [27-28]. The centerline bubble void fraction decreases with height as the bubble plume widens. The bubble plume angle is generally about 20^o for air/water plumes but depends somewhat on flow parameters. The magnitude of gas fraction and velocity were found to be dependent on the gas and liquid densities, gas flow rate and distance from the injector.

A buoyant gas plume rising through a single liquid bath creates a toroidal shaped recirculating flow as liquid becomes entrained into the plume, moves radially at the bath surface and is then driven down by the confining walls [29]. The speed and energy of this flow is critical to achieving metallurgical mixing requirements. Liquid entrainment into the plume is defined as the rate of change of liquid in the plume with height. The bulk of entrainment into the plume occurs in the fully developed region. Liquid is being drawn into the wakes of individual bubbles [30]. The volume of the liquid recirculating in the bubble wakes can be from five to twenty times that of the bubble [31].

Modeling of metal reactors requires extrapolation from the common water models to actual reactors. This has led several researchers to study the differences between metal and water reactors. In [30] it is reported that bubbles forming in a metal bath are significantly larger than in a water bath due to higher surface tension and non-wetting nozzles. From computer simulations these researchers conclude that bubbles formed in a liquid iron bath from a 6 mm diameter nozzle have a volume about three times larger than bubbles from the same nozzle in a water bath.

Recently, plume velocity profiles were obtained for a wood's metal reactor that also followed the Gaussian profile in water plumes [32]. The work shows that the behavior of plumes in liquid metals is generally the same as for water models, which gives confidence that results from cold water studies can be applied to molten single liquid metal reactors which do not have slag layers.

Very little experimental or modeling work has been focused on submerged gas injection into two fluids. In [33] it is stated that: "...numerical modeling of such systems (gas stirred metal reactors)...has so far tacitly ignored the presence of any overlaying slags." The authors studied the effects that such a slag layer can have on the flow field. A thin layer of oil was placed on the water in a test tank. The oil was found to significantly dissipate the kinetic energy of the fluid. The dissipation of the kinetic energy was attributed largely to the deformation of the oil/water interface. This casts doubts on the ability of single fluid water models to accurately model the fluid dynamics in actual metal/slag reactors.

A simple model to describe the transport of the heavier liquid with gas bubbles into a lighter liquid was developed by [34]. It was concluded that when the heavier liquid's density is more than three times that of the lighter liquid no heavy liquid transport takes place across the interface. In contrast, it was observed by [35] that even in a mercury, water bath a thin film of mercury is dragged up into the water by the gas. For a higher viscosity upper liquid layer the mercury drained smoothly from the bubble, but large globules of mercury were drawn up in the wake of the bubble. More detailed studies of the bubble wake behavior are discussed in [31]. The conclusion is that single bubble models cannot accurately model the effect of multiple bubbles or a swarm of bubbles rising through two fluid mixtures [35].

Model results of a continuous counter-current slag metal reactor are presented by [36], but the work concentrates on the longitudinal mixing and optimum conditions for heat and mass transfer between the two liquids i.e., metal and slag for refining purposes. Similarly, in [37] studies of longitudinal mixing in a channel reactor with two liquids as well as recirculation in both liquids due to submerged gas injection are presented. In that model, the plume is considered to be a well-mixed continuously stirred reactor, but the conclusion is drawn that there is a need for careful studies of this plume to provide a better understanding of gas injection into two liquid systems [38].

Experiments of gas injection into both single and two liquid baths simulating direct metal making reactors are presented by [12,28]. In these reactors the slag layer is much thicker than those in a ladle reactor. Different ratios of slag/metal thickness were studied using oil and water in a rectangular channel reactor. In the two liquid baths, the gas plume entrains heavier liquid and draws it upward into the lighter liquid where it is discharged radially. The heavy phase then drops down due to gravity forces creating a limited size recirculation zone.

Numerical models are a very useful tool in predicting and improving the performance of such complicated metal processing in a single reactor [39,40]. Numerical modeling of single phase flow has developed into a mature discipline. But multiphase flow occurs in many natural and industrial processes. The major difference between single and multiphase flow is the existence of an interface between the different phases. The interface can move, deform, break-up, which makes it much harder to model than single phase flow. Discontinuities in flow and material properties exist across these interfaces. The equations of motion for single phase are obeyed within each phase but one must develop methods to account for the interfaces and their effect on the flow. In these models it is assumed that the continuum approach will be valid for each of the phases present in the flow. One of the simplest and most general of these methods is the local instant formulation of a two-phase flow field which can be divided into distinct single phase subregions where the continuum model for single phase flow is applicable [41]. Appropriate boundary conditions and jump conditions must be specified at the interface between the different single phase regions. But, when the void fraction or concentration of one of the phases is very low, it is not necessary to treat each of the phases as a continuum. It is possible to track the motion of the dispersed, low void fraction phase by tracking individual particles as they move through the continuous phase. This method is referred to as the Lagrangian method since the Lagrangian coordinate system is a natural choice with which to track the motion of the particle or bubble. Interaction between the phases is accounted by coupling the momentum exchange between the particles and the liquid. Detailed descriptions of the method are presented by [42, 43]. As the particle is tracked through the domain, the momentum exchange is added to the computational cells that the particle passes through. Generally, it is not possible to track each of the particles in a given flow. Several different particles are tracked to form a statistical representation of the actual flow. The Lagrangian method provides a simple and flexible method of calculating the flow behavior in low void fraction flows. For flows in which the void fraction of the dispersed phase is greater than 10 percent, a different method is required.

The local model formulation is limited in its applicability, but it illustrates the basis on which the majority of two phase models are developed. The two fluids are treated with the assumption that the continuum approach is valid for describing the two phases as long as the interaction that occurs at the interface is accounted for. For most applications, an averaged or macroscopic flow field would be sufficient as a model. Equations can be developed which do not require microscopic details of the flow. The method utilized is similar to a process used in turbulent flow, where the equations of motion are time-averaged removing the problems associated with fluctuating velocities. The equations are then in a form which can be solved. The averaged equations remove the microscopic detail from the flow and allow the flow to be calculated in a practical manner.

For multiphase flow, the equations developed in the local instant formulation are first averaged. The development of averaged two phase flow equations is not a trivial matter and detailed discussions of the process can be found in [41] and [43]. Several different averages can be used in the averaging of the equations. The most commonly used collection of averages is called the Eulerian average. In the equations of motion, the spatial and time coordinates are taken as the independent variables. The Eulerian averaging is based on the averaging of the equations with respect to these independent variables. One problem that occurs with the above methodology is that the averaging process has added new terms which are not specified, the heat, mass and momentum exchange terms between the phases. The situation is simplified for the case of modeling the submerged gas injection into a bath of liquid without heat or mass transfer between the phases, but there are still several terms in the momentum equation which must be defined by the use of constitutive equations. These constitutive equations are sometimes called closure laws. When these laws are applied, the equations of motion become "closed" and can then be solved for the flow fields of the two phases. A general form for the closure laws still escapes us and as is stated in [44]: "...the development of the closure relations for the macroscopic two-phase flow formulation presents one of the most difficult problems ever encountered in fluid mechanics and heat transfer." Thus, prediction of multiphase flows is still one of the most difficult fluid dynamic problems but solutions to these are possible if the right model is used.

Experiments

In order to get a better understanding of mixing and settling due to gas injection into a liquid bath with two immiscible liquid layers a test facility was constructed out of plexiglas 2.4 m long, 1.2 m high and with a width which can be varied. Initial experiments were performed with a reactor width of only 2.5 cm. Even though these experiments cannot be considered truly representative of the behavior in a full scale reactor they permitted excellent opportunity for observation and easy velocity measurements in the fluids with the Laser-Doppler Velocimeter (LDV). This arrangement was considered a slice through the bath and plume. But this narrow channel affects liquid entrainment of the bubbles since the bubble shape was distorted in the narrow channel. Wall effects are important in such a narrow channel, thus the results can only be used as a first test if three-dimensional computer simulations are capable of predicting such wall effects correctly.

In these initial experiments the test facility was filled first only with water and LDV measurements were performed along the center plane of the bath. Figure 2 shows a front and top view of the test facility including instrumentation which will be discussed below.

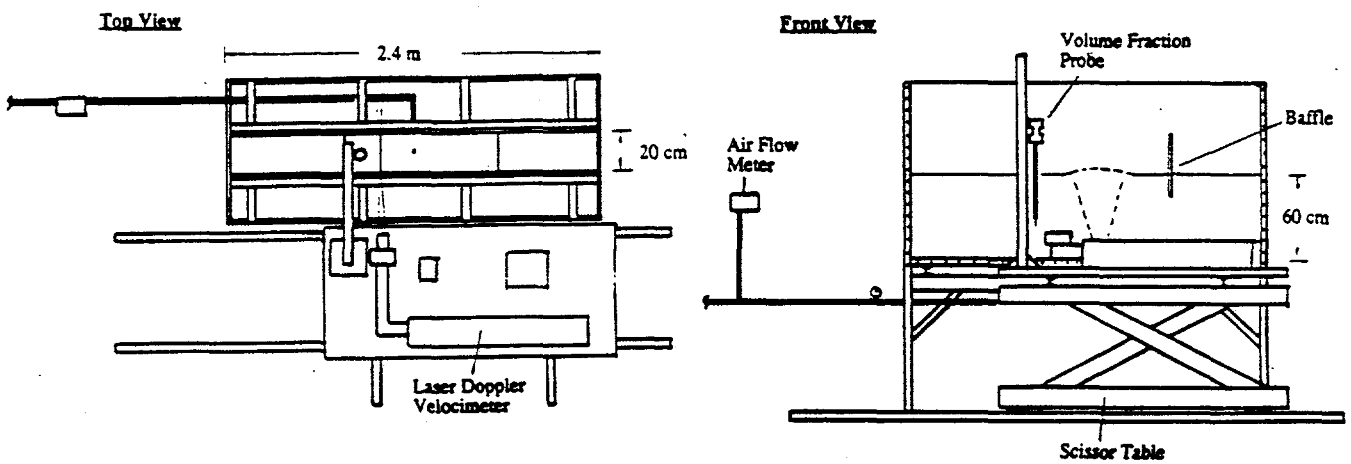


Figure 2 - Test Facility

In a second phase of the experiments the width of the test channel was increased to 20 cm. Even though wall effects are still present, this width represented a compromise between a more realistic three-dimensional behavior, manageable amounts of liquids in the channel, but there were already restrictions in flow velocity measurements due to the limited transparency of the two liquid mixture.

A single gas injector was installed at the bottom of the test facility exactly in the center of the flow channel. Air was injected through that nozzle with gas velocities from about 60 m/s to 300 m/s, the latter being close to sound velocity.

In considering the mixing within the bath due to submerged gas injection a critical variable is the liquid entrainment into the plume. This quantity gives a measure of the plume's pumping action and the mixing between different depths in the bath. Although the entrainment varies with height in the plume a summation in height quantifies the total liquid interaction with the plume. Since in real metallurgical systems the gas in the plume contains chemically active species such as fuel and/or oxygen, total liquid entrainment is an important parameter. In order to measure liquid entrainment into the plume, liquid velocity measurements were performed with LDV in close increments over the whole depth of the bath in a radial distance from the nozzle axis dictated by the need to keep bubbles from interfering with the LDV.

The evaluated volumetric liquid entrainment rate was found to be proportional to the third root of the volumetric gas flow rate as was concluded by [24].

Two liquid studies are required for a more realistic comparison with a modern metal converter. The difficulty in performing two liquid studies involves matching the ratio of density, viscosity and interfacial tension of metal and slag with light and heavy liquid fluids at room temperature. Besides these desirable fluid properties toxicity was of major concern. Using these criteria, the combination of choice was a sodium-chloride/water solution and soybean oil. The maximum achievable density ratio was 1.25 and the viscosity ratio is about 0.03 while a copper/slag bath would have a density ratio of roughly 1.3 with a viscosity ratio of about 0.01. The latter of course is a strong function of the bath temperature. Although these ratios do not exactly agree with the model fluids it was thought that basic information about the flow fields would be similar and comparison with numerical modeling results would be a valid test if such models can predict single as well as two-liquid behavior with submerged gas injection.

More than fifty separate tests were performed with data including measurements of the velocities for the whole flow field in single liquid experiments, velocities at the boundaries of the plume for entrainment evaluation, mixing zone size measurements and volume fraction data in the plume with a newly developed volume fraction probe, capable of measuring the local void fraction of the three phases, gas and the two-liquids, in and around the bubble plume.

Significant conclusions were drawn already from the one-liquid experiments. A large fraction of the input kinetic and buoyant gas energy is dissipated already in the plume itself. This agrees well with work by [32], but shows that plume losses in the energy balance cannot be neglected [30,41].

Since multihole nozzles are used in practice different nozzles were tested as well but the results indicated that overall entrainment of the multihole and single hole nozzles was within the uncertainty limit for the same gas flow rate. It was suggested to insert shallow baffles in the vicinity of the bubble plume to restrict the mixing and recirculating zone in the bath [38]. Experiments with such baffles show that these decrease not only the width of the mixing and recirculation zone but also the overall entrainment rate. This was due to the fact that the baffles increase the turbulence, thus also the energy dissipation. At higher gas flow rates even bubbles recirculate since the overall liquid downflow at the baffles is sufficiently high to trap the bubbles in the flow.

Experiments in two liquids produced new data relating the mixing zone's shape and size to various bath depths and injection parameters. It was observed qualitatively and measured quantitatively that the mixing zone becomes smaller with an increasing density ratio between the two liquids, see Figure 3. Most fundamentally, in relation to the question for the need of baffles to create limited mixing and settling zones, the data show very defined zones of mixing and settling created only by the density differences between the two liquids even without baffles. Other important findings were gathered with a volume fraction probe. It was found that heavy liquid entrainment and the mixing zone width increased with increasing submerged injection gas flow rate, see, e.g., Figure 4.

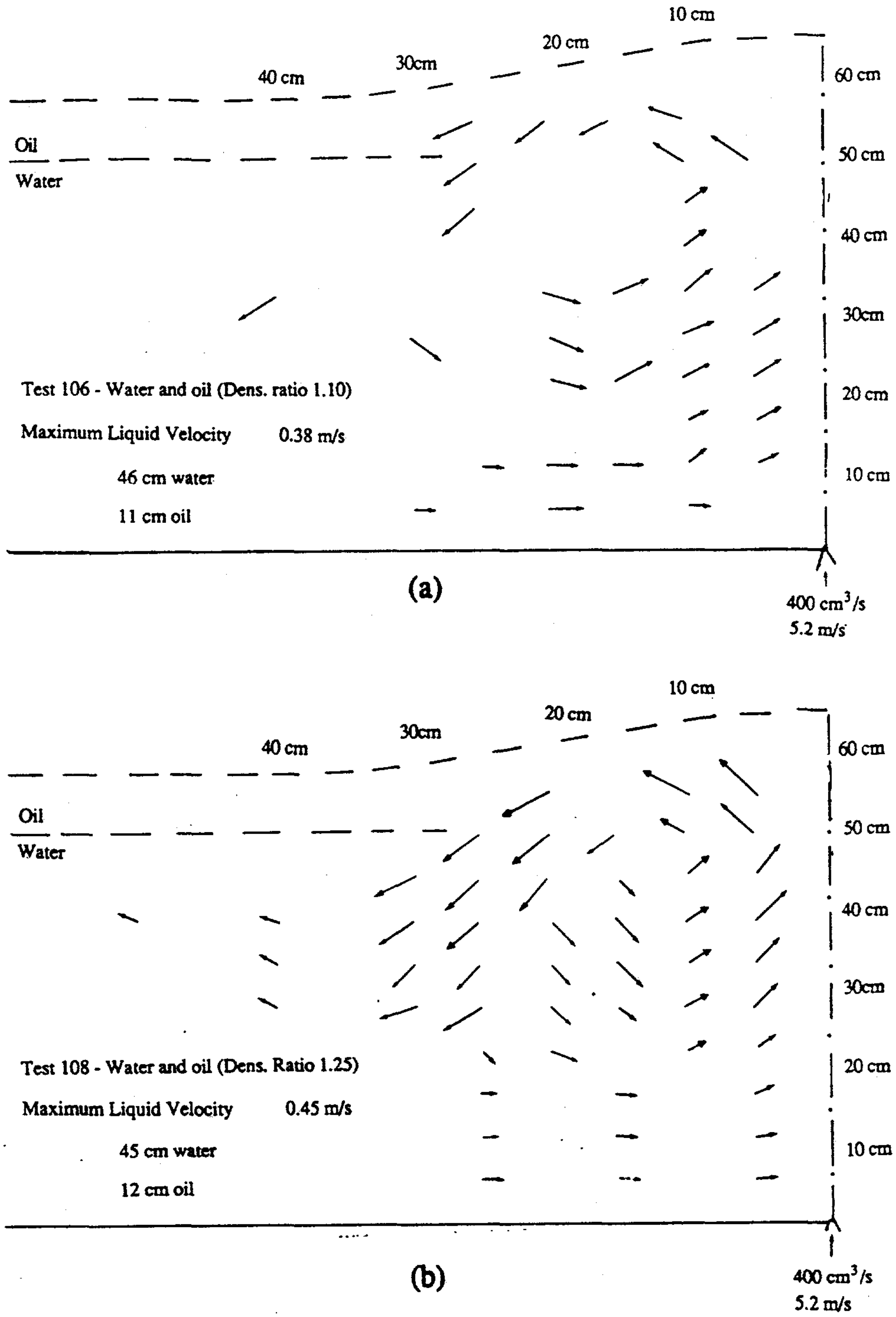
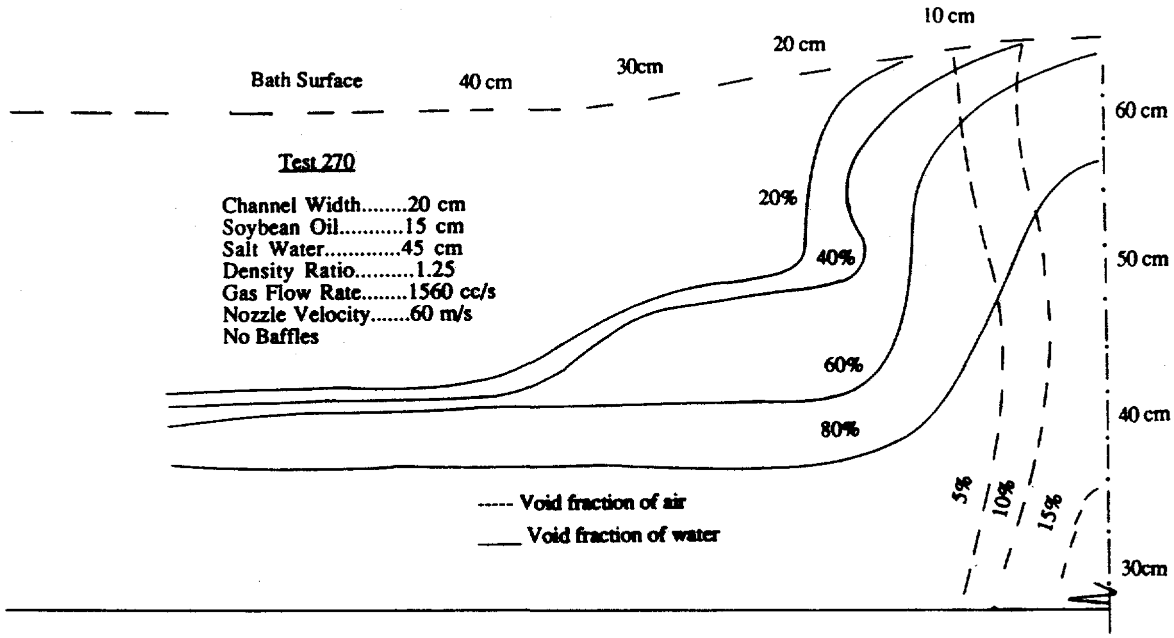


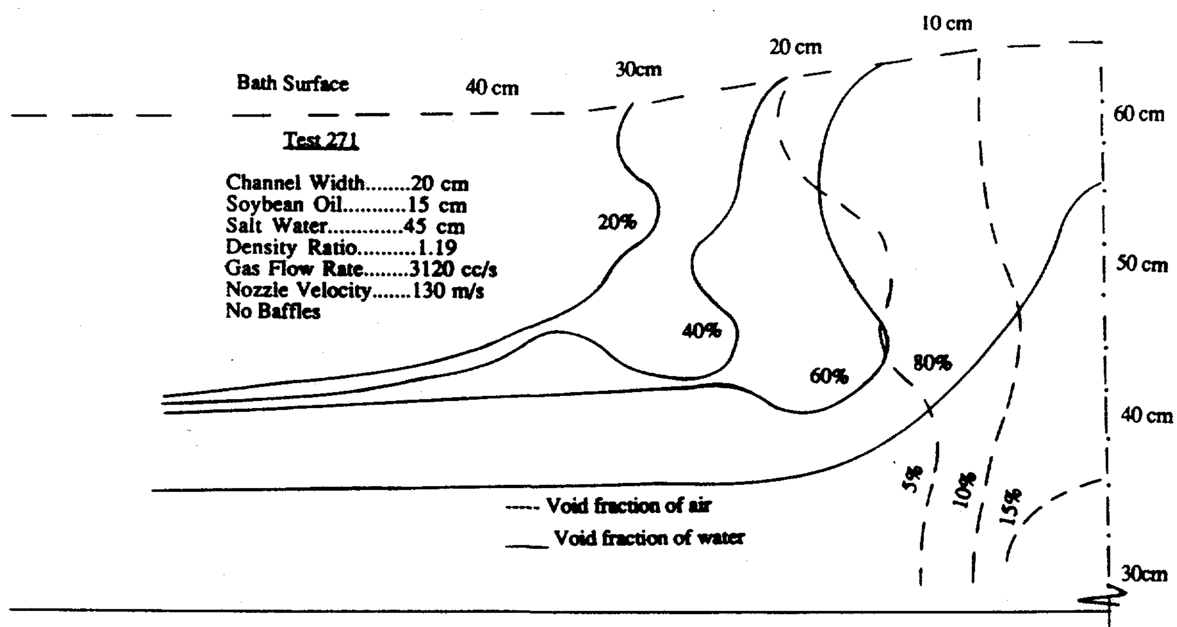
Figure 3 -Liquid Circulation in a Two-Liquid Bath in the Vicinity of the Bubble Plume for Different Liquid Density Ratios

Numerical Modeling

In the first phase of this study gas was injected into only one liquid. Researchers have shown that the average gas void fraction in the fully developed portion of the plume is lower than 10 percent [22] which allows the use of the Lagrangian method. At these low void fractions, individual bubbles can be tracked as they move through the bath. The Lagrangian method can also be extended to three dimensions without difficulty. Thus, this method was selected for the modeling of the single liquid baths. The computer code [45], has the capability of tracking a dispersed phase in the Lagrangian framework as part of the standard package. This code was used to compute the modeling with only one liquid. The trajectory of the bubble is calculated from a force balance on the gas bubbles. The most important aspect of this model is the momentum exchange that occurs between the rising gas bubbles and the liquid. As a bubble is tracked through the computational domain, the momentum exchange is calculated for each cell that the bubble passes through. To simulate the injection of the gas into the bath, several injection points for the bubbles are placed across the nozzle. Any number of stochastic tracking can be applied to each injection point. It is important to track enough bubbles to adequately represent the plume.



(a)



(b)

Figure 4 - Measured Void Fraction of Water and Air in a Two-Liquid Bath in and around the Bubble Plume as a Function of Gas Injection Rates

Initial comparisons with experimental results of [17] showed very good agreement of experiment and numerical predictions in an axisymmetric vessel with submerged gas injection. Thus, the model was expanded to 3-D and flow velocity measurements in single liquid bath were compared with numerical predictions. As shown in Figure 5, agreement of measured and predicted horizontal and vertical velocities at the centerline of the bath as a function of distance from the plume axis is very good.

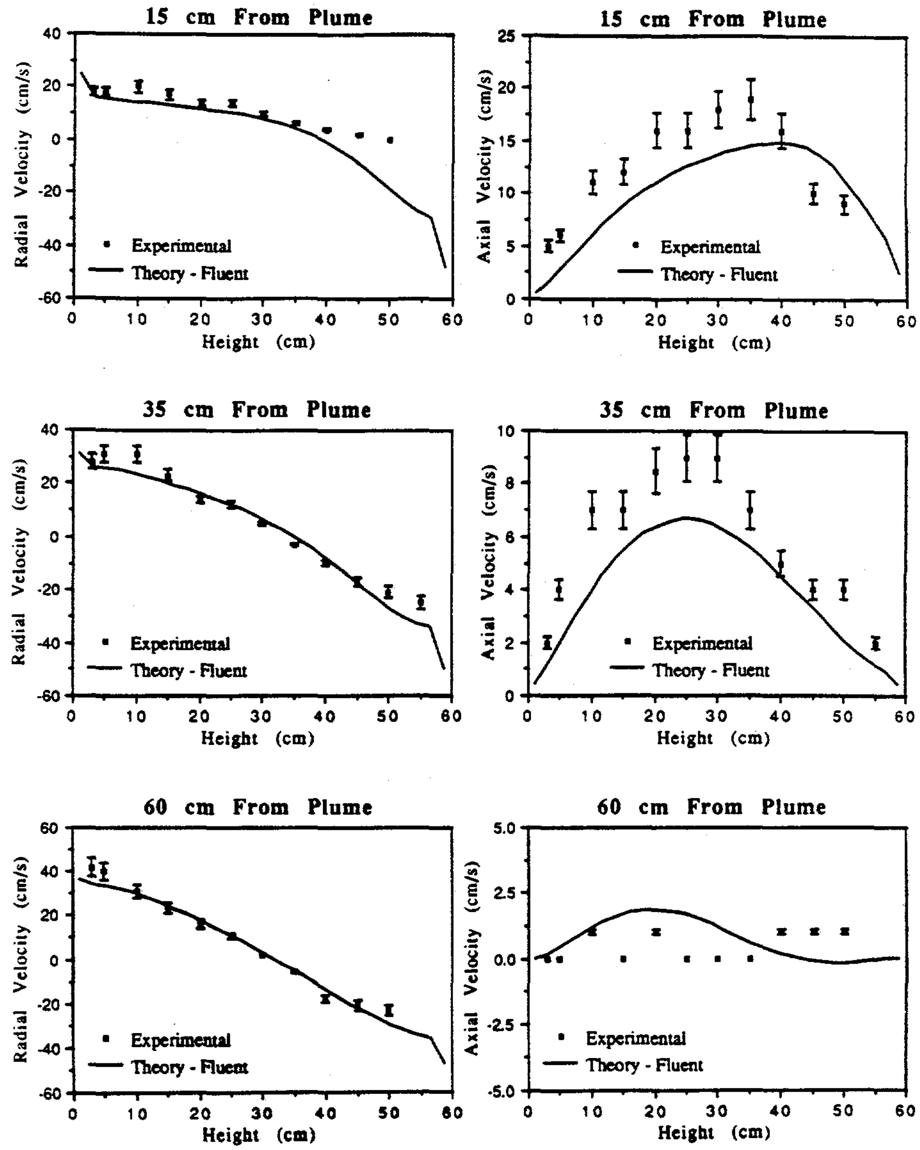


Figure 5 - Comparison of Measured and Computed Axial and Radial Velocities in the Test Channel with One Liquid as a Function of Distance from the Plume Axis and Plume Gas Flow Rate

This indicates that two-phase dispersed flow (such as bubbles) can be predicted quite well with presently available computer codes. The behavior of the system becomes much more complicated with the addition of a second liquid into the tank. As shown in the literature review very little work has been done in this area with the exception of [12, 28, 33] who conducted experimental studies of air injection into baths of oil and water. The behavior of a gas stirred two liquid system is complicated by the fact that several different flow patterns exist within the reactor. In the plume region, a somewhat homogeneous mixture of air, water and oil develops but away from the plume, the oil and water remain primarily separated. The submerged gas injection into two liquids combines the whole range of flow regimes encountered in multiphase flow into one problem.

Several Eulerian based two phase codes have been discussed in the literature [47]. The author utilized the finite volume code, K-FIX developed at Los Alamos National Laboratory(LANL) [48] to model the single liquid gas stirred bath. A new module was added which is designed for multiphase flow.

The governing multiphase equations are developed through the ensemble averaging of the local instantaneous equations. Detailed discussion of averaging of the equations and more information relevant to the following description of the code can be found in [49].

The multiphase flow problem is solved for the velocity and void fraction for each of the phases and the average pressure of the mixture. The equations are numerically integrated by stepping through time using a finite difference fully implicit scheme. For flows where the velocities are much smaller than the sound velocity and where pressure waves are not important, the implicit formulation is the method of choice due to its efficiency. For the flows of interest in this study, the fully implicit method is the most stable and efficient method for solving the averaged multiphase equations. The ability of an Eulerian code to model the dynamics of a gas stirred bath depends heavily on the formulation of the momentum exchange. The two phase drag, lift and virtual mass formulation was extended to three phases. All the coefficients above for drag, lift, and virtual mass interactions between each of the phases can be customized by the user. This was important because very little is known about the interaction of two fluids.

The problem that one encounters in the injection of gas into two liquids is that the interaction between the fluids can vary greatly throughout the domain. In one region there might be oil droplets in water or vice versa while in other regions the two phases could form two distinct separated layers which are not coupled, e.g., the density used in calculating the drag force on a bubble or drop depends on which phase is continuous. A mean fluid density was used to represent the continuous phase density in the drag interaction.

The code was used to model four different experimental cases, two different oil/water configurations and two different flow rates. Each case was run for 7.5 seconds in simulation time. Volume fraction data for each of the phases was evaluated at 0.25 second intervals. These files were used to create animation files that show the development and unsteady nature of the flow. Waves at both the surface of the tank and at the oil water interface could be seen as they moved back and forth from the center of the tank to the wall. Figure 6 displays oil void fraction at three different times calculated after initiation of gas injection. These figures show how the oil and water interface moves. The water is drawn upwards by the gas phase into the lighter oil where it is then forced to settle due to the density between the fluids.

Figure 7 shows contour plot of the oil volume fraction for the same case taken after the flow field has developed. Figure 8 displays the contour plot of the time averaged experimental oil volume fraction. The theoretical prediction for the oil and water distribution is quite similar to the experimental profile. The spreading of the experimental contours is caused by the formation of emulsion due to the intense mixing that occurs which the model is not yet capable of handling. At the higher gas injection velocity of 130 m/s, more water is entrained by the gas upwards into the oil which pushes the mixture zone farther out. Figure 9 shows theoretical predictions for the oil volume fraction as compared with figure 10, the experimental oil volume fraction. The behavior of the oil in this case is much more unstable due to the higher flow rate and due to more oil/water emulsion. The time averaged experimental contour plots filter out the unsteady nature of the flow which can be seen in the animated results of the model where the interface location fluctuates laterally. The general shape and location of the mixing zone predicted compares fairly well for both flow rates.

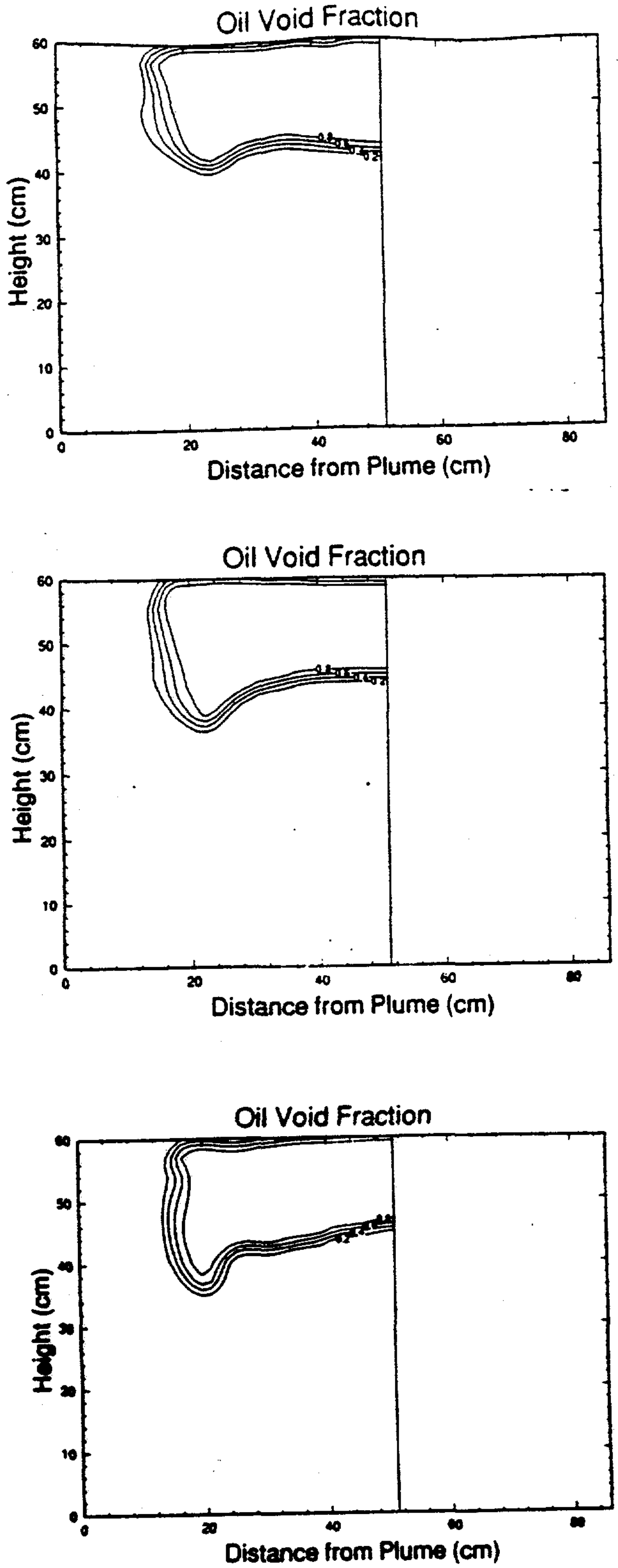


Figure 6 - Numerical Prediction of Lighter Liquid (Oil) Void Fraction Profile as a Function of Time 2.0, 2.2 and 2.4 sec after Initiation of the Gas Injection. Gas Injection Velocity 65 m/s.

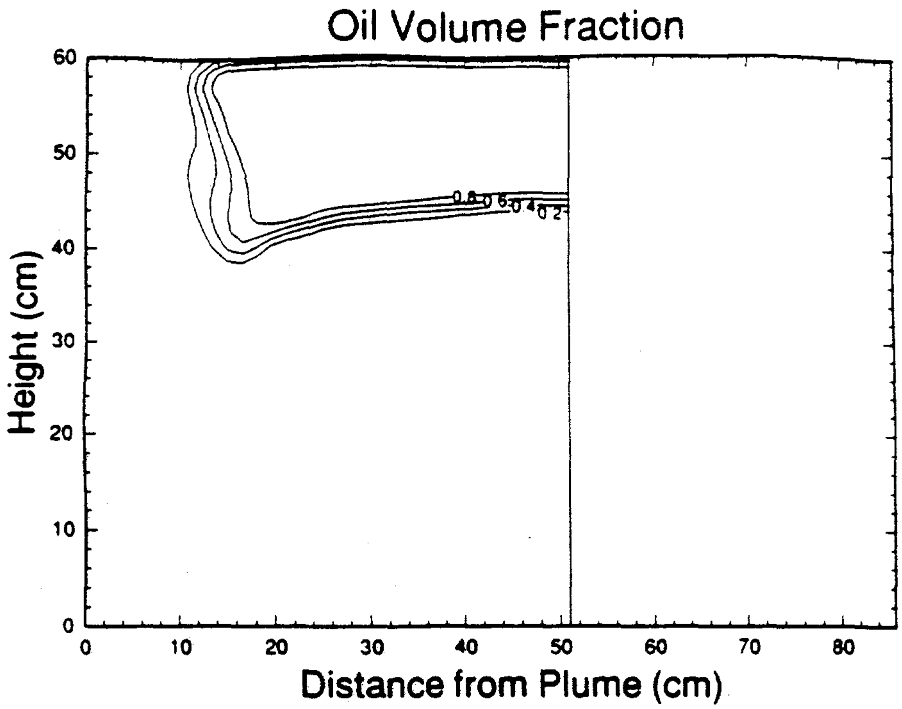


Figure 7 - Numerical Predictions of Lighter Liquid (Oil) Void Fraction Profile.
15 cm Oil Depth, 45 cm Water Depth, Gas Injection Velocity 65 m/s

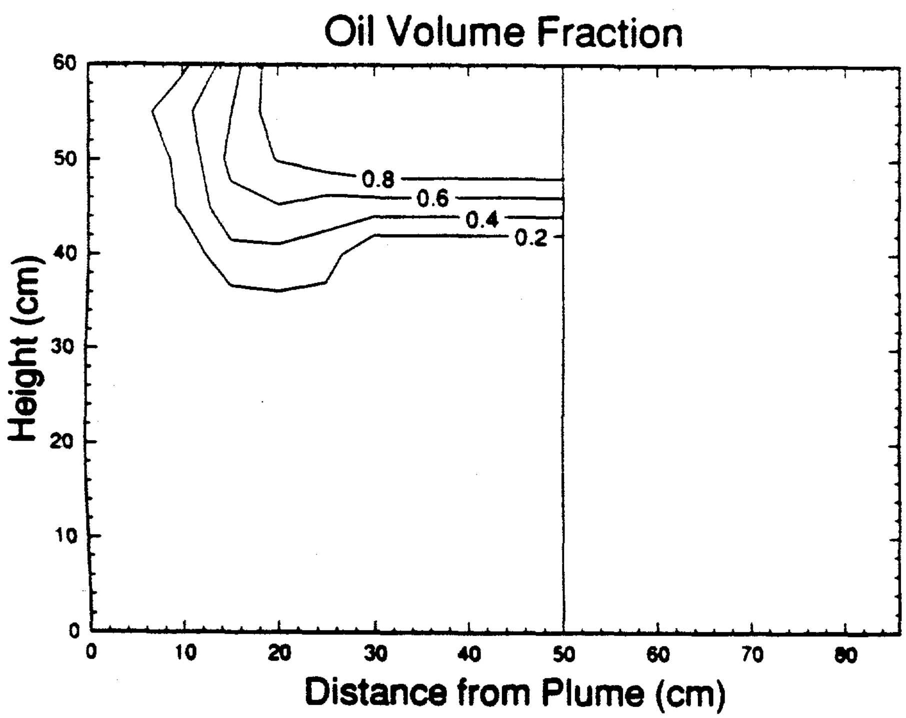


Figure 8 - Measurements of Lighter Liquid (Oil) Void Fraction Profile.
15 cm Oil Depth, 45 cm Water Depth, Gas Injection Velocity 65 m/s

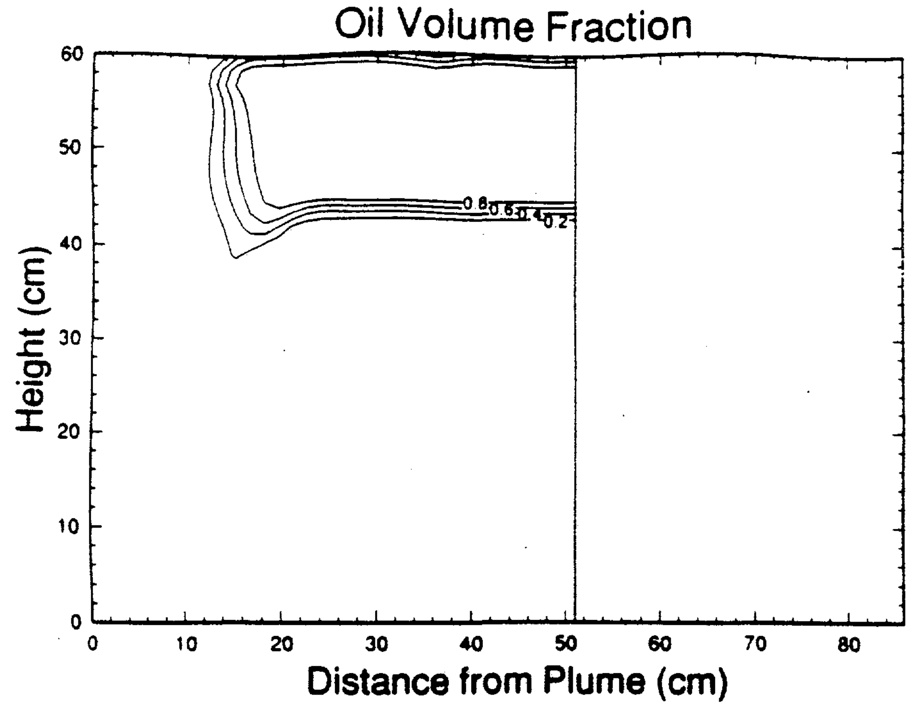


Figure 9 - Numerical Predictions of Lighter Liquid (Oil) Void Fraction Profile.
15 cm Oil Depth, 45 cm Water Depth, Gas Injection Velocity 130 m/s

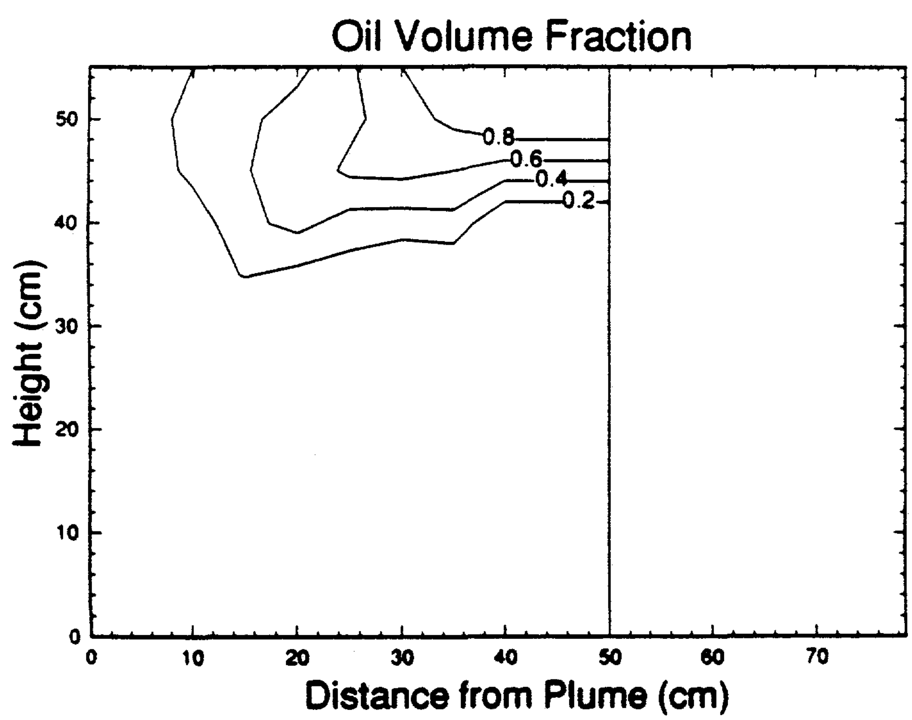


Figure 10 - Measurements of Lighter Liquid (Oil) Void Fraction Profile.
15 cm Oil Depth, 45 cm Water Depth, Gas Injection Velocity 130 m/s

The test configuration of equal layers of water was also studied. Figures 11 and 12 show the theoretical and experimental oil volume profiles for a gas injection velocity of 130 m/s The agreement between the model and the experiments is not as good as in the first two cases. The experimental results display a mixture zone in the plume region while the model predicts that the central plume is all water. A thin mixture zone is predicted at the outer edge of the plume. This is due to more fluctuation in the bath and plume which cannot be measured since the void fraction measurements are slow.

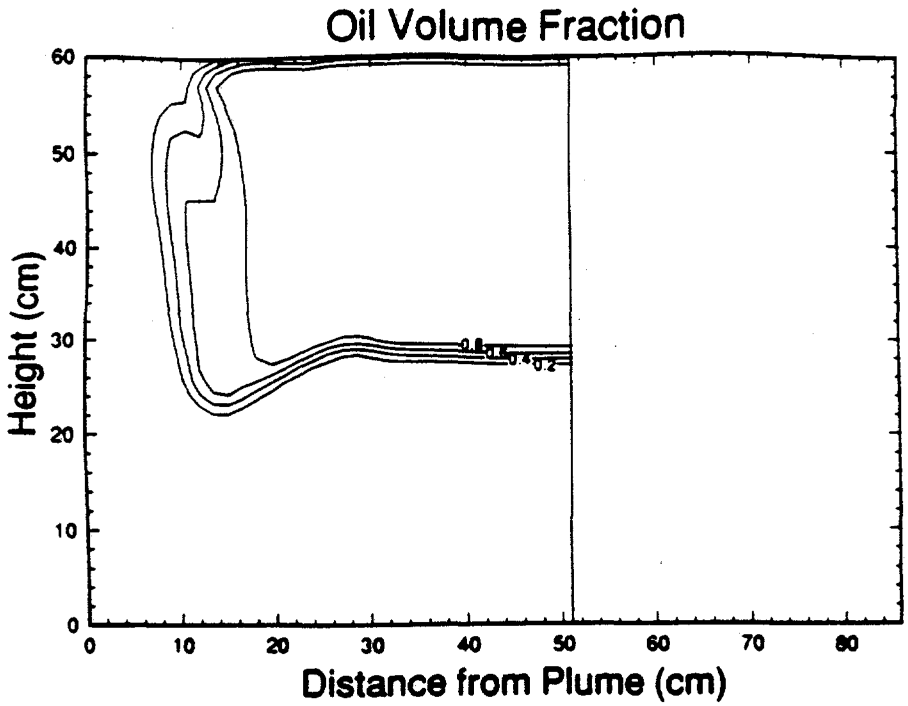


Figure 11 - Numerical Predictions of Lighter Liquid (Oil) Void Fraction Profile.
30 cm Oil Depth, 30 cm Water Depth, Gas Injection Velocity 130 m/s

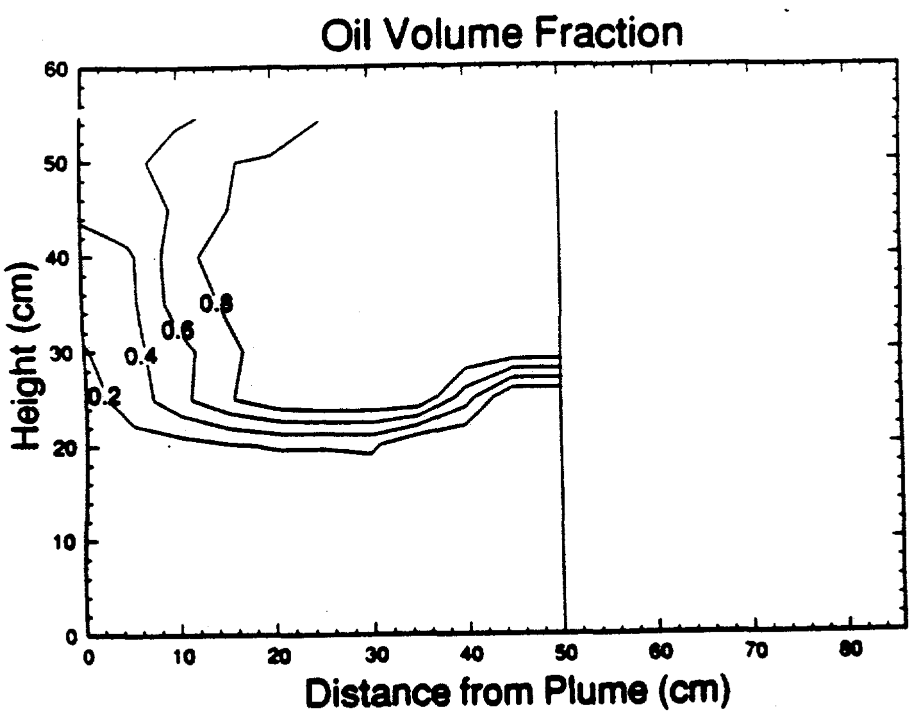


Figure 12 - Measurements of Lighter Liquid (Oil) Void Fraction Profile.
30 cm Oil Depth, 30 cm Water Depth, Gas Injection Velocity 130 m/s

After the model had been applied to the oil and water experimental tank, a reactor for producing lead was studied. The numerical model is able to provide basic information which cannot be obtained experimentally. The material properties of the two fluids were the only parameters in the model that were changed. The density of the lead was assumed to be 10000 kg/m^3 with a viscosity 10 cP, the density of the slag was estimated as 4000 kg/m^3 with a viscosity of 900 cP.

Figure 13 displays the lead volume fraction for a 30 cm of slag and 30 cm of lead depth configuration at the flow rate of 1560 cm^3/s, which is equivalent to 130 m/s injection gas velocity. The code predicts that entrainment of the lead will occur with a smaller diameter mixing zone. This result supports the experimental finding of [35]. The larger density difference between the lead and the slag causes the lead to settle much faster than in the oil/water tank.

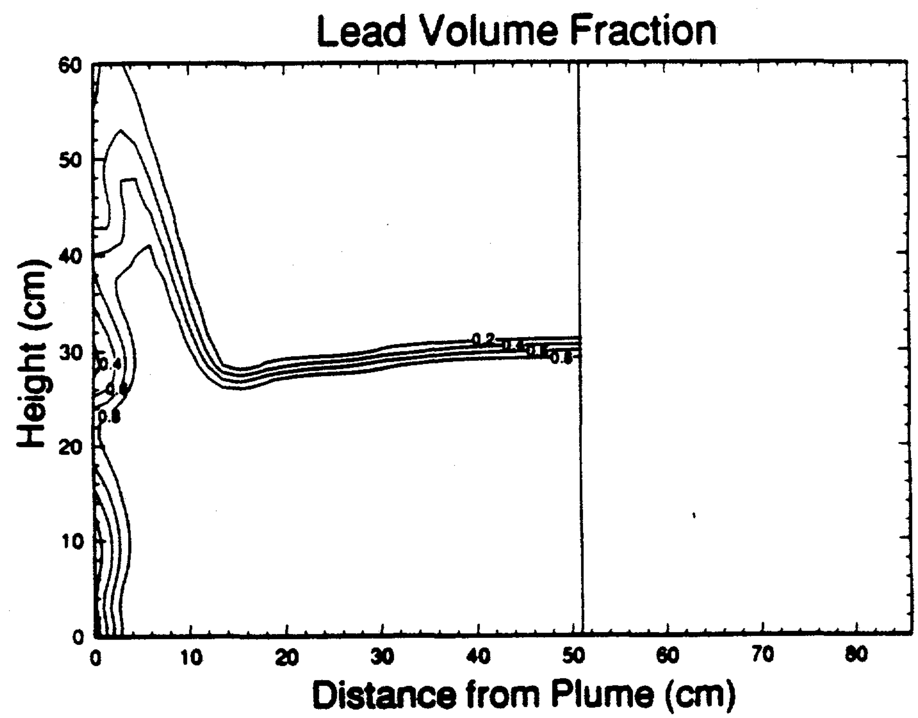


Figure 13 - Numerical Predictions of Slag Void Fraction Profiles in a 30 cm Deep Lead and 30 cm Deep Slag Bath. Gas Injection Velocity 130 m/s.

Conclusions

Significant progress has been made in experimental and numerical modeling of continuous metal production reactors. Submerged gas injection in both single liquid and two liquid baths has been studied with emphasis on the momentum transfer between the various phases.

The first phase of this study focused on the modeling of injection of air into water baths. Experimental data [12] were provided for a rectangular test facility with which to validate the predictions of the computer model [13]. Both theoretical predictions for velocities and turbulence intensities were compared to experimental results and were found to be in good agreement. The effect of baffles was studied in both axisymmetric and three dimensional domains. Baffles were found to significantly reduce the energy of the recirculation in the bath supporting the findings of [28].

The second part of this study concentrated on the gas injection into a two liquid bath. Previous researchers had neglected the presence of a second liquid in the metal reactors due to the complexity it brings to the system. A new two phase formulation for the interphase drag, particle lift and virtual mass forces was derived and found to provide good agreement with experiments with good numerical stability.

This formulation was then extended to three phases and implemented in the code replacing the existing momentum exchange routines. Computer modeling was conducted and it was found to show good qualitative agreement with experimental data.

The present work is a first step towards understanding and modeling the complicated flow behavior of a multiphase bath stirred locally by submerged gas injection. It is not surprising that in this first attempt heat and mass transfer have been neglected. The work concentrated on the momentum transfer between the phases. Not only the steady-state distribution of the phases in the bath are predicted well, but also the start-up when gas injection is initiated.

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