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PREFACE

Fluid Mixing III continues the series of conferences which began at Bradford in March 1981. It is hoped to hold a fourth in the series in 1990. The conferences are intended to cover all aspects of mixing including the assessment of mixture quality, experimental and theoretical studies of mixing, chemical reaction and mass transfer, heat transfer, novel experimental techniques, scale-up and optimisation.

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Industrial Mixing Applications

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** This paper is printed out of page sequence*

PROBLEMS ASSOCIATED WITH THE HOMOGENISATION OF LIQUID METALS

D.S. Beishon* and T. Robertson*

Sub-surface injection of inert gas into liquid metal baths for the purpose of homogenisation (thermal and chemical) is an important part of many steelmaking processes. Design and assessment of such mixing arrangements has relied very heavily on the use of physical models, with water simulating liquid metal, though recently there have been attempts to apply the developing techniques of computational flow modelling in this area. A distinction can be made between the use of any model as a simple comparison tool and its use to make accurate predictions; it is with the latter application that this paper is concerned, and, primarily, with physical rather than computational modelling.

The basis for much of the work carried out using physical models to investigate mixing in liquid metals has been an assumption that supply of an equivalent power per unit mass (of stirred liquid), in a geometrically similar model, to that calculated as being supplied in the plant situation, will ensure similarity of the mixing process. By making reference to pilot plant studies using 4 tonnes of liquid steel and laboratory scale studies using 500 kg of mercury, it is shown that the power-based modelling criterion should not be applied when water is used to simulate liquid metal. A probable explanation for the breakdown is given, again based on comparative observations in vessels containing water and liquid metal, and empirical methods currently being used to apply physical model derived results are described. Finally, the paper indicates the lines of further work intended to resolve the problem of making useful predictions in an important area for steelmaking dealing also with some implications for computational flow modelling.

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INTRODUCTION

The paper is concerned with the use of sub-surface gas injection as a method of homogenising large volumes of liquid metal, and with the application of modelling techniques to optimising such processes. Firstly it is necessary to indicate the scale of the homogenisation problems which can be encountered on steelplants. Thus, the mass of liquid metal involved might be as great as 350 tonnes, the density is approximately 7.10^3 kg/m^3, and the temperature can be in the range 1350-1750 °C; at the low end of the range the metal is carbon saturated iron and at the high end it is steel. Thermal homogenisation is necessary because normal heat transfer processes result in cool, denser liquid accumulating near the floor of any vessel containing the liquid metal. Chemical homogenisation is necessary whenever treatment or alloying materials are added to the liquid metal, and since common additives range in density from 2.10^3 kg/m^{3}to 11.10^3 kg/m^3, it will be clear that considerable buoyancy or negative buoyancy forces may oppose the circulating flows induced in an effort to achieve homogenisation.

Figure 1 shows the process route most used for bulk steelmaking with liquid iron emerging from a blast furnace, being converted to steel in a BOS furnace, further refined in a secondary steelmaking plant, and delivered as a solid product at the end of a continuous casting plant. The points on that route where measures are taken to achieve homogenisation are indicated in the diagram. Until recently two methods of homogenising each batch of liquid metal were employed at various stages, namely pouring from one vessel into another, and sub-surface gas injection, but a third method is now in use, namely electromagnetic stirring. Assessment of the success of a homogenisation process is possible on plant by chemically analysing the product where an addition has been made, or by measuring pouring stream temperatures during emptying. However, other factors such as periods of standing tend to obscure the picture, and it is not surprising that there has been a demand that physical modelling techniques should be applied to this category of processes for purposes of assessment, optimisation of operation and improvement of design.

Physical modelling and specifically the use of water to simulate flowing liquid metal has been very effective in the steel industry and the design and operation of many of the units shown in Figure 1 have been considerably influenced by such work. The advantages of using water in this type of work are many:- it is easy to contain and pump; it is non-hazardous; it is transparent thus allowing observation of flows throughout the volume; and the critical flow parameter, kinematic viscosity, has a similar value to that for liquid steel at temperatures substantially above the melting point (liquidus). Accordingly, it was inevitable that physical modelling investigations of homogenisation processes would be undertaken using scale models of relevant containing vessels, with water simulating liquid metal and with gas injected beneath the liquid surface at a rate calculated to give similarity of the mixing process. It is the purpose of this paper to show that while this approach is useful (and an example of satisfactory results is given,) it is not adequate in a number of areas, particularly if there is a desire to quantify the process.

The paper begins with a description of the process of homogenisation by sub-surface gas injection and of the similarity criteria normally considered. The next section gives an example of circumstances where a water-based model has proved adequate to produce the information required. Thereafter, the paper concentrates on cases where the water-based model has proved inadequate and demonstrates this with reference to laboratory scale experiments using 500 kg of mercury and pilot scale experiments using 4 tonnes of steel. The penultimate section deals with the implications of the results and with the program of work proposed to put physical (and mathematical) modelling on a firmer basis in this area.

SUB-SURFACE GAS INJECTION

Figure 2 shows the context in which homogenisation by sub-surface gas injection will be considered in the remainder of the paper. The containing vessel is a refractory lined steel ladle and the gas is introduced by way of an immersed lance. Gas bubbles leave the lance orifice(s) and rise towards the surface carrying liquid with them. The gas then leaves the liquid accompanied by splashing and clearance of the surface slag cover, while the liquid moves outwards towards the walls, then travels downwards, and finally moves across the base towards the lance to complete the circulation, (in fact this description is a simplification as will emerge later in the paper).

The problems which the temperature ($\sim$1600 °C) and the liquid density (7.10^3 kg/m^3) would create for any mechanical stirring method are fairly obvious, but the advantages of sub-surface gas injection appear when the stirring energy made available is calculated. Effectively the appearance of gas in the liquid at the lance orifice results in the displacement to the liquid surface of an equal volume of liquid metal, and this potential energy is released as kinetic energy as the gas rises to the liquid surface. The fact that the gas expands as it rises because of the reduction in the ferrostatic pressure adds to the release of energy (though some recent work has cast doubt on the usefulness of all of this energy in the context of homogenisation[1]). The effect of the high temperature of the liquid metal is to increase the temperature and thus volume of the injected gas and this in turn results in an increase in the energy made available by the rise of the gas to the surface. Thus, it can be argued that the characteristics of liquid metal which make mechanical stirring almost impossible, namely temperature and density, actually increase the effectiveness of sub-surface gas injection with the extra energy coming from an increase in the pressure of the gas supply and cooling of the liquid metal.

Physical modelling of the homogenisation process shown in Figure 2 has been carried out with a number of objectives, namely, to consider problems of blockage and erosion of injection orifices, to consider problems of surface disturbance and splashing, and to consider the effectiveness of homogenisation. Work local to the injection point has rested heavily on criteria identified by Wraith et al[2,3] and is not discussed in this paper. Both surface disturbance and homogenisation were thought to depend primarily on the energy input, though it was assumed that gas bubble size would also be important in the former case.

The parameter which has been used to match models to plant from the viewpoint of energy input is often described as the energy density though actually it is the power input by injected gas per unit mass of stirred liquid ($\sum$). Since this parameter is dimensional its application builds in a relationship between homogenisation times (T) and the model scale, namely;

$$T_p/T_m = (L_p/L_m)^{2/3*}$$

A number of experimenters have produced relationships between 'T' and '$\sum$' indicating the successful use of models to predict homogenisation times[4,5] but experience to be described in this paper does not agree with this view.

Calculation of the power input per unit mass for a plant sub-surface injection process is not a trivial exercise, principally because the total energy release depends critically on the rate of temperature increase of the gas when it enters the metal and this obviously depends on the dynamics of the bubble formation process. Again, Wraith has been responsible for the work which has obtained information in this area[6], and based on this a formula was derived by workers at BSC Teesside Laboratories[7]. In fact it is now possible to check the accuracy of this formula with regard to the way in which account is taken of temperature effects by employing a technique developed independently by two sets of workers for another purpose[8,9], i.e., to simulate frozen accretions of liquid around the injection point. The method involved cooling the gas to a temperature close to that of liquid nitrogen prior to injection into a number of liquids e.g. water, white spirit and wax. Injection into mercury which would allow the calculation method of accounting for temperature to be tested has not yet been carried out.

In summary, physical modelling of sub-surface gas injection into liquid metal was assumed to require obedience to normal rules of scaling, i.e., achievement of geometric similarity, and the use of a criterion which matched power inputs per unit mass. There was thought to be a need for some consideration of the gas bubble formation process particularly as will be seen when surface disturbance was of interest. The results of taking this approach are the subject of the succeeding sections of the paper.

INVESTIGATIONS INTO THE EFFECT OF INJECTION POINT LOCATION

Over the past 15 years a number of variants of the arrangement shown in Figure 2 have been investigated using the modelling approach detailed above, i.e., a geometrically scaled model, water as the working liquid and the power per unit mass modelling criterion. Injection of gas by way of a deeply immersed lance and through one or more porous plugs in the base of the ladle have been looked at and it was considered that, within rather wide limits of measurement accuracy, the efficiency of homogenisation was not dependent on the method of injection[10].

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*L is scale, subscripts 'm' and 'p' refer to model and plant.

However more recent work, still employing the same approach, has modified these views to some extent and is discussed here because it illustrates the usefulness and the limitations of the modelling method.

Steel ladles are drained through a sliding gate valve in the floor and it is important that the outflow should begin whenever the valve is opened. Unfortunately, a build-up of cold steel in the neighbourhood of the outlet, and freezing, will prevent 'first-time opening' and the measures which must be taken to establish a flow are both slightly hazardous and detrimental for product quality. Gas injection is undertaken in order to homogenise the ladle contents and thus prevent the accumulation of cold steel near the outlet, but the question arose as to whether an alteration in lance location might confer benefits.

The ladle concerned has a capacity of 320 tonnes of liquid steel and the dimensions are given in Figure 3. At the time, the lance was centrally located and injection took place 300 mm above the floor through either one or two ports, at a rate of 400 Nl/min of argon. The simulation was with a 1/7 scale perspex model, geometrically similar to the plant and filled with water. The power per unit mass of liquid criterion fixed the model gas flow rate at 30 l/min. Concern was with the floor region rather than homogenisation of the whole contents so arrangements were made to visualise the flow in this region. Slit light sources illuminated the horizontal plane immediately above the base, a mirror allowed this plane to be viewed through the base and tracer particles rendered the flow visible.

Figures 4 and 5 present the results obtained with a central lance and a lance displaced by half the ladle radius towards the wall as shown in Figure 3; the injection ports were at the same level in each case so the power input was the same. In the photographs, long streaks indicate high velocities while particle build-ups denote stagnant zones. The diagrams interpret the photographs. With the central lance the flow across the base is variable with build-up possible anywhere including the outlet region. With the lance off-set a consistent flow across the floor was established as shown in Figure 5, and it appeared that any cooled steel arriving near the outlets would be quickly dragged away towards the lance. The use of a lance with two outlets did not affect the patterns of flow but it was found that increasing the separation of the lance from the ladle floor, as happens in practice as a result of wear, increased the advantage of the off-set lance in terms of flow activity near the floor.

Vigorous stirring near the ladle floor is not only important for the thermal reasons advanced so far, but also to aid utilisation of heavy alloying materials such as lead. Recent investigations of the ISID side wall injection device enhance the view that off-set injection is desirable and suggest that maximisation of the off-set, which is achieved by this device, should be recommended. Figures 6 and 7 again compare the flow in lower regions of the ladle, this time for a central lance and ISID device. The power inputs from injected gas were the same but in each case a heavy simulated slag cover lay on the water surface. Remembering that settled particles imply that a region is stagnant, while streaks imply significant velocities, the advantage of the ISID device is very clear.

It should be made clear that recommendations have been made on the basis of the results described above, with confidence that the improvements observed on the model will carry over to the plant. However, the limitations of the modelling approach have affected the recent work. The dramatic effect of heavy slag cover on the flow in the lower regions of the ladle is evident when Figures 4 and 6 are compared; in each case a central lance was used, the difference was caused by the slag cover. It was anticipated that such differences would be reflected in an increase in overall homogenisation time and Figure 8 shows that this proved a correct assumption. These results were obtained by adding an acid tracer and producing a time record of pH from which the homogenisation time was estimated. Locations for tracer addition and pH measurement which maximised the sensitivity of the method were determined on the basis of observations of indicator colour changes in the model ladle. Figure 8 shows clearly that the type of slag cover has implications for the gas injection rates required for homogenisation and the process time. Unfortunately, in spite of the fact that Figure 8 is presented as a graph of plant homogenisation times against plant gas injection rates, the information to be presented in the next section of the paper makes it clear that recommendations cannot be made on this basis, i.e., the power per unit mass criterion is unsound.

HOMOGENISATION TIMES AND CIRCULATION RATES FOR LIQUIDS OF DIFFERENT DENSITY

Problems associated with the prediction of homogenisation times and circulation rates for steelmaking processes, using the power per unit mass criterion, have been known to exist for some time. Earlier work, concerned with identifying mixing times for a gas stirred ladle, found that the model predictions were considerably lower than the actual plant operation with regard to required gas injection rates[10]. Surface disturbance, always much greater in water than liquid steel for a given power input per unit mass, also raised suspicions that the modelling criteria were inadequate. This was thought to be due to the differences in behaviour between gas bubbles in water and in liquid metals and has suggested that whilst qualitative investigations, similar to those described in the previous section could be carried out with some success, exact quantitative predictions of parameters such as homogenisation times would not be possible. In this section, further evidence is supplied as to why the power per unit mass criterion is thought to be inadequate.

At Teesside Laboratories a pilot plant, 4 tonne, ladle unit has been developed for the purpose of secondary treatment of liquid steel. The unit is characterised by an elliptical cross-section and a baffle arrangement which effectively divides the volume in two. Gas stirring is used to homogenise the steel and heat can be supplied by arc electrodes. Pilot plant trials have been carried out on the unit to determine mixing times, for a range of gas flowrates, by making additions of copper and taking samples of steel over a ten minute period of time[11]. Mixing tests were also carried out on a 1/3-scale water model of the unit made from perspex and expanded polystyrene. The standard acid tracer technique was used to determine homogenisation

times for a similar range of power inputs, per unit liquid mass, to the pilot plant work.

Figure 9 shows the results from the mixing tests for the model and pilot plant, the power input being that supplied by the injected gas. The graph shows that the model predicts optimum homogenisation times when using a power input of about 0.5 W/kg whilst the pilot plant results show that better homogenisation is achieved with power inputs of at least 2.5 W/kg, a difference of a factor of 5 between model and pilot plant results. The model also predicts a minimum mixing time of about 320 seconds whilst plant mixing times as low as 130 seconds were achieved.

The effect of supplying greater quantities of gas, into the model, once the minimum homogenisation time has been reached is to increase the mixing time; a possible explanation for this is given later. The results presented support the view that energy, in the form of gas bubbles, is utilised differently in water and liquid metal, thus when gas is injected into water much greater surface disturbance occurs than in steel and less energy is utilised in bulk mixing.

Similar trends have been observed in other areas of modelling of steelmaking units which employ gas injection, the RH vacuum degasser being an example. The unit shown in Figure 10 consists of a chamber, capable of being evacuated, with two refractory lined nozzles extending from the base. In operation the two legs are lowered into a ladle containing steel until immersed well below the liquid steel surface, the steel is then drawn up the legs and into the chamber by applying a partial vacuum. Supply of gas into one leg then causes the steel to circulate upwards into the chamber, across the floor, and then down the other leg and into the ladle where mixing is generated by the return flow. Model tests were carried out on a 1/5-scale water model to establish the optimum gas flowrate for mixing in the ladle, the injection gas flow rate into the leg was scaled using the power per unit mass criterion and considered as the principal cause of mixing. The model results predicted an optimum gas flowrate of 162 l/min whereas plant flowrates are around 600 l/min, considerably higher than the model estimation. The question arose as to whether any recommendation could be made concerning the plant gas flowrate and it was decided to carry out small-scale laboratory tests on a system similar to the RH unit using water and mercury.

Figure 11 shows the experimental arrangement used which was relatively complex mainly due to the difficulties in the safe handling of mercury. The circulation tube, consisting of two vertical limbs and one horizontal limb, was positioned so that the ends of the two vertical limbs were submerged in two separate containers. Liquid in the containers was then drawn up the legs to the horizontal limb by applying a vacuum. Gas introduced near the base of one column of liquid then caused the liquid to circulate from one container to the other via the circulation tube. A constant supply of liquid was made to the inlet container so that it overflowed at a rate greater than the circulation rate, whilst the flow from an orifice in the second container allowed the circulation rate to be measured by keeping the

liquid in the container at a fixed level. By using different sizes of orifice the circulation rates for a range of gas flowrates could be obtained for water and mercury.

The results of this work are presented in Figure 12 and are plotted as volume circulation rate against power input per unit mass of liquid in the experimental arrangement. Using water, the circulation rate rises with increasing power, or gas injection rate, until a peak of around 12.5 l/min is reached with a power supply of 2.5 W/kg and thereafter it begins to fall. The mercury circulation rate rises to a peak of around 10 l/min, but with a power supply of 7 W/kg, and again decreases for a further increase in power input. Higher liquid circulation rates could be achieved with water than mercury for power inputs up to about 4 W/kg and the difference, in terms of power input, between the peak circulation rates for water and mercury is a factor of about 3. The most likely explanation for these results is that slippage of liquid in the gas bubble column is greater in heavy metals than in water. Thus, it is easier to increase the mean liquid velocities in the gas/water column and hence there is a more effective circulation as shown in Figure 12. However, as the gas supply rate is increased so is the resistance to flow as a result of blockage in the upward leg of the circulation tube and a stage is reached where the increase in power input cannot overcome the increasing blockage and hence a downturn in circulation rate occurs. In mercury, the increase in circulation rate occurs over a longer range of power input but again the blockage effect eventually outweighs the power supply. The point at which this occurs for mercury means there is more gas in the upward leg than at the corresponding point for water and it would be expected that the peak circulation rate would be lower, as it is.

The effect of blockage in the circulation tube described above is thought to occur in the model ladle unit as well and accounts for the mixing times increasing with greater gas injection rates after the minimum mixing time has been reached. Both systems are characterised by a narrow cross-section in which the bubble column rises and the effect is not found in the simple ladle systems described in the previous section due to the much larger cross-sectional area of the ladle. The implications of the results presented in this section are that water model work underestimates the quantity of gas injection required to achieve minimum homogenisation times in steelmaking processes by a factor between 3 and 5, when using the power per unit mass criterion.

Further work which would identify a more general relationship between water model and plant results is proposed in the discussion section of this paper.

SURFACE DISTURBANCE

Surface disturbance and splashing became an important issue when the need to inject powder was coupled with a desire to use relatively tight fitting extraction hoods to collect fume and preserve an inert atmosphere above the ladle. In such circumstances, the injection rate of gas is necessarily high to transport the powder but excessive

splashing is likely to damage the extraction hood or cause it to become attached to the ladle top making removal of the ladle after injection difficult. The work to be described was carried out to determine whether a change to a lance design with a number of ports was likely to reduce the splashing problem. It was known from observation of models that splashing was related to the size of the bubbles reaching the liquid surface, and since the size of bubbles at detachment from an injection point was given by the expression;

$$V_B = 1.5\ Q^{1.2}\ g^{-0.6} \quad (2)$$

It followed that persistence of the influence of detachment conditions to the surface would result in reduced splashing with a multi-port lance (because the gas flowrate per port was smaller). However work by Sano and Mori[12] had suggested that break up and coalescence of bubbles took place so vigorously that the influence of detachment conditions would vanish a short distance above the injection point, (they suggested 100 mm), and that thereafter the spectrum of bubble sizes would depend only on the proportion of gas in the bubble plume and on liquid properties.

It was thought that the work could be carried out satisfactorily in a physical model using water as the working fluid provided care was taken with the simulation of penetration of the gas into the liquid. The equipment to be used is shown in Figure 13, and has been described elsewhere in detail[7]. Splashes were detected by allowing them to make contact with a perforated plate when an electrical circuit was made; in this way the number of splashes reaching a given height in a given time period was detected by counting peaks on records of the type shown in Figure 14. Since comparison between lance types was the aim it was not thought that exact duplication of plant conditions was too important, but model flow rates were selected to duplicate realistic plant conditions by relating bubble diameters at detachment in the same way as the general scale, i.e., 1/10. In this way, the model flow rates of 3.55 Nl/min and 10.65 Nl/min were taken to simulate values of 540 Nl/min and 1600 Nl/min.

However, great attention was paid to the penetration of the gas into the liquid on the model and plant, because it is much easier to achieve substantial penetration in water than in liquid metal. There was concern that a 4-port lance of the type shown in Figure 15 might achieve substantial horizontal dispersion of gas in a water model which would be unrealistic in a plant context. To guard against this the penetration

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* V_B is bubble volume (m^3)

Q is gas flow rate through a port (m^3/s)

g is the gravitational constant (m/s^2)

unrealistic in a plant context. To guard against this, the penetration to be expected was calculated using the formula[13];

$$L/d_o = 10.7\ [\rho_g V^2/(\rho_L-\rho_g)\ g\ d_o]^{0.46}\ [\rho_g/\rho_L]^{0.35}\ *$$

For the larger plant flow rate (1600 l/min) the calculated penetration from each of 4 ports of diameter 10 mm was 19.9 mm which in the context of a lance of diameter 170 mm was negligible, but for the corresponding model situation the penetration was 9.4 mm which in the context of a lance of diameter 17 mm was not negligible. Accordingly it was decided to distort the model 4-port lance by increasing the diameter of each port to 2mm thereby reducing penetration to 3.8 mm which was regarded as acceptable. However when experiments began with the model 4-port lance it was immediately clear that bubbling through all 4 ports did not occur. At first it was thought that this might be a function of a badly made lance with ports at different levels but this possibility was eliminated and consideration was then given to the surface tension forces which could resist the initiation of bubbling through any port. Comparison of values of the modified Weber number which is the ratio of the inertial force exerted by the gas to the surface tension force resisting that flow gave values of 6.97 for the plant situation and 0.65 for the model. This certainly explained the model observation and though not ruling out similar effects in the plant situation, indicated that they were much less likely. Unfortunately, the only remedy would have been to increase the gas inertia by reducing port size but this of course would have increased penetration.

Accordingly, it was decided to carry out the tests using mercury as the working fluid. Matching of the modified Weber number with the specified flow rates required a port diameter of 0.43 mm, and a lance was manufactured with 4 ports of diameter 0.45 (the nearest drill size available); the predicted penetration in mercury with this port diameter and a gas injection rate of 10.65 Nl/min was 2.9 mm, an acceptable value (in water with this lance the predicted penetration is 26.7 mm). The results for the 1-port and 4-port lances operated in mercury are shown in Figure 16 and as can be seen, splashing has been unaffected by the change in lance design thus confirming the predictions of the work due to Sano and Mori. Figure 17 shows the results obtained when the same two lances were operated in water and, as can be seen, splashing has been substantially reduced by the 4-port lance. This is thought to be a

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* L is penetration (m)

d_o is nozzle diameter (m)

ρ_g is gas density (kg/m^3)

ρ_L is liquid density (kg/m^3)

V is gas velocity at the port (m/s)

misleading result since the reduction is due to wide dispersion of the gas bubbles rather than the reduction in their size at detachment. This assumption is confirmed by Figure 18 where dispersion in the mercury model was increased by increasing the lance diameter to 51 mm (510 mm on the plant scale); as can be seen the 4-port lance of this diameter has a clear advantage.

Apart from being an example of the limitations of a water model applied to a homogenisation process, the work described in this section of the paper is also somewhat paradoxically an example of the usefulness of such a model operated in parallel with the mercury based model, since the effects discussed could actually be observed in the water model.

DISCUSSION OF THE RESULTS PRESENTED

The purpose of the paper has been to give an indication of the problems which arise when large volumes of liquid metal require homogenisation and of the methods which are adopted to find answers to these problems. It is perhaps relevant to emphasise that although this paper has concentrated on the injection of gas into steel ladles, i.e., the configuration of Figure 2, gas is actually injected into liquid metal at almost every stage of the steelmaking route. It is thus important to understand the effects of this gas and to be able to simulate these effects in configurations very different from that of Figure 2.

It has been demonstrated that the commonly used approach to homogenisation problems, based on a physical model containing water and the power per unit mass criterion is inadequate to deal with liquid metals.

Because of the convenience of using water for flow measurements, observations and mixing tests, and the inconvenience of using a liquid such as mercury for such work, there is obvious reluctance to accept that the inadequacy cannot be circumvented. It is thought that there are two possible explanations for the modelling problem. The less likely is that the energy made available in liquid metal, in large part as a result of the thermal expansion of the gas, has been over - estimated. The assumptions made are susceptible to test using the cooled gas technique and this should be done if only for purposes of elimination. A more likely explanation is that the effect termed run back, when it occurs in vertical pipe, two-phase flows, occurs also in the bubble cone in a gas stirred ladle. The density dependence of this phenomenon would result in a larger fraction of the energy (per unit mass) made available by gas injection being dissipated as turbulence within the bubble cone and a smaller fraction accelerating the flow of liquid towards the surface in liquid metal than in water. Since this flow towards the surface is responsible for bulk circulation in the ladle, the consequence for overall homogenisation is clear. There is no simple method of obtaining the information required to confirm that this explanation is correct and, more importantly, to obtain empirical scaling factors which will allow the continued use of water for the modelling of liquid metal flows in cases where gas injection takes place. However, a program of work involving velocity measurement in mercury, water and organic liquids of intermediate densities has been