11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

DAMPING OF STANDING WAVES IN CYLINDRICAL VESSELS

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ABSTRACT

The emergence of intensive bath smelting techniques in the metallurgical industry has resulted in an increase in gas volumes being injected into the reaction vessel. Such intensive gas injection has exacerbated the problems of slopping and splashing. There is a need to prevent slopping and splashing but conventional mechanical devices used for their prevention are neither easy to use nor cost effective. In the laboratory, a layer of lighter viscous oil on water was used to simulate the presence of a viscous layer over the melt and to investigated how a viscous layer can help prevent slopping. The results show that a 0.01 m oil layer can reduce the gas flow rates at which slopping occurs and also create an agitated free surface which may interfere destructively with standing waves. The work suggests that the viscous layer can help damp out slopping.

NOMENCLATURE

g	gravitational constant, 9.807 m·s^{-2}.
h	depth of liquid, m.
k	experimental constant in equation.
Q	gas flow rate, m^{3}s^{-1}.
R	radius of circular tank, m.
V_B	bubble rise velocity, m·s^{-1}.
V_{slip}	bubble slip velocity, m·s^{-1}.
δ	logarithmic decrement of standing wave amplitude.
σ	wave frequency, s^{-1}.
ν	kinematic viscosity, m^{2}s^{-1}.

INTRODUCTION

Gas injection into liquid melts is increasing in importance in the metallurgical industry with the emergence of new intensive bath smelting techniques. These techniques require an increase in the mass flux of gas into the bath volume resulting in an increase in bath slopping and splashing. As a consequence, the subject of slop damping and splash reduction in metallurgical vessels has recently been of great interest to the industry.

The problems in the industry are manifold. First, the melts are often highly corrosive, and refractory materials have a finite life-time. The mechanical damping devices used in propellant or tanker slosh prevention are not suitable as the devices wear out in only a matter of hours. Second, the properties of melts are wide ranging in viscosity, density and temperature, resulting in very complex fluid flow behaviour. Third, any attempt to use devices that are protected, e.g. by cooling, involves additional capital, running and maintenance costs. Thus the use of mechanical means for slop damping is neither easy nor cost effective in the metallurgical industry. In industry it is known that quite high gas flow rates can be used without any slopping occurring which can be attributed to the damping effect of the viscous nature of many metallurgical melts. Most metallurgical reactors contain a layer of viscous slag floating above either a complex metallic compound or the metal inself. This study aims to investigate how a viscous layer can be used to reduce slopping.

BACKGROUND

It is a well known proverb that the presence of a thin layer of oil has a calming effect on troubled waters. However, little study has been done in the area of slop damping when the upper layer of viscous fluid is of substantial thickness. Early work in this area was initiated by the existence of a fresh water layer upon a denser and more viscous saline layer in Artic waters. Harrison (1908a, b) looked at the effect of viscosity on waves of finite amplitude and found that the period was not affected to a first approximation. The modulus of decay was found to depend on $\nu^{-1/2}$ where ν is the kinematic viscosity.

A large body of work has been carried out on the sloshing of liquid propellants in rockets and space vehicles. Solutions have been obtained for a large number of tank geometries by solving the Laplace equation and incorporating forced and damping effects using Fourier series. Solutions for arbitrary tank motions can be obtained from harmonic solutions using Fourier series or Fourier integral techniques.

The calculation of surface-wave damping in a viscous liquid confined by solids walls has been carried out by Ursell (1952), Case and Parkinson (1957), Keulegan (1959), Miles (1967), Mei and Liu (1973) and many others. It is common to assume that the motion is essentially irrotational except near the boundaries, where viscous boundary layers of thickness order $(\nu/\sigma)^{\frac{1}{2}}$ (the Stokes boundary layer thickness) are formed, where σ is the wave frequency. Energy dissipation is found to take place in (a) the boundary layers near the solid walls, (b) the boundary layer near the free surface, and (c) the essentially inviscid core. The contributions have been showed by Ursell (1952) to be proportional to $\nu^{\frac{1}{2}}$, $\nu^{\frac{3}{2}}$ and ν, respectively. The damping rate is found by balancing the net rate of energy dissipation with the decay of wave energy. Mei and Liu (1973) found that substantial energy transfer occurs in the neighbourhood of the free-surface meniscus whereby energy is transferred from the wave to the side-wall boundary layer. They also obtained the rate of attenuation and frequency shift due to viscosity.

The use of baffles to prevent slopping has been studied by Miles (1958) and Silverman and Abramson (1966). Linear damping is introduced into the dynamic analysis through the resonance terms of the equations governing a mechanical model representation of the liquid forces and moments. This model assumes that the behaviour of the liquid oscillating in its fundamental mode is analogous to the behaviour of a linear, viscously damped, single degree-of-freedom system. The main difficulty with the method is in trying to predict the amount of damping present in a given tank configuration. The mechanical means of damping by the use of baffles, moveable or floating devices, expulsion bags and diagrams have been studied (Silverman and Abramson 1966). The effectiveness of rigid-type baffles depends largely upon the location of the baffles with respect to the liquid free surface and on the baffle geometry. In viscous damping, the significant variables are liquid height, liquid kinematic viscosity and tank size.

If there is no energy input into a system that is oscillating, then the successive decrease in oscillation of the wave results from energy dissipation. This damping is defined as the logarithmic decrement δ in the amplitude of a standing wave, where

$$\delta = \ln \left| \frac{\text{Maximum amplitude of any oscillation}}{\text{Maximum amplitude one cycle later}} \right| .$$

For a circular cylindrical tank of radius R, the damping coefficient (Silverman and Abramson 1966) may be expressed by

$$\delta = 4.98 \nu^{1/2} R^{-3/4} g^{-1/4} \times$$
$$\times \left[1 + \frac{0.318}{\sinh\left(1.84\frac{h}{R}\right)} \left(\frac{1-\frac{h}{R}}{\cosh\left(1.84\frac{h}{R}\right)} + 1 \right) \right].$$

For $h/R > 1.0$, the square bracketed term in the above equation reduces to 1.

EXPERIMENTAL APPARATUS

The apparatus (Parker and Rodgers 1990), shown in Figure 1, consists of an upright cylindrical vessel of perspex, diameter of 0.245 m, mounted in a square stainless steel tank equipped with two perspex viewing windows. The square tank was filled with water to minimise optical distortion. The windows were marked at 2 cm intervals to assist in the reading of the amplitude. A brass lance of 0.3 cm internal diameter was submerged into the cylindrical vessel to inject air at the central position. The depth of the lance submergence could be varied.

A pressure transducer connected to a pipe with one end opened and submerged in the bath allowed a large number of wave periods to be recorded with a chart recorder and averaged. A 0.01 m thick layer of Newtonian white paraffin oil (Shell Ondina 15) was placed on the water surface. Its dynamic viscosity was 0.03471 Pa.s (0.3471 poise) measured over a range of shear rates on a Weissenberg rheogoniometer and its density was 849.7 ± 0.9 kg/m^3 at 20°C. The experiments were carried out at an average room temperature of about 20°C. The gas flow rate was varied between 1 to 20×10^{-4} m^3/s, the depth of water from 0.015 to 0.35 m, and the depth of lance submergence from 0.05 to 0.25 m.

RESULTS

The cylindrical vessel gives rise to radial, transverse and rotational standing waves. The radial waves do not contribute to slopping. The transverse waves give rise to slopping but for gas injected vessels, two transverse waves at right angles combine to form a rotating wave which circulates around the bath with the same period as the transverse wave. The rotating wave is the dominant wave that is observed and often leads to slopping and splashing at high gas flow rates.

Reference case for the formation of rotating waves

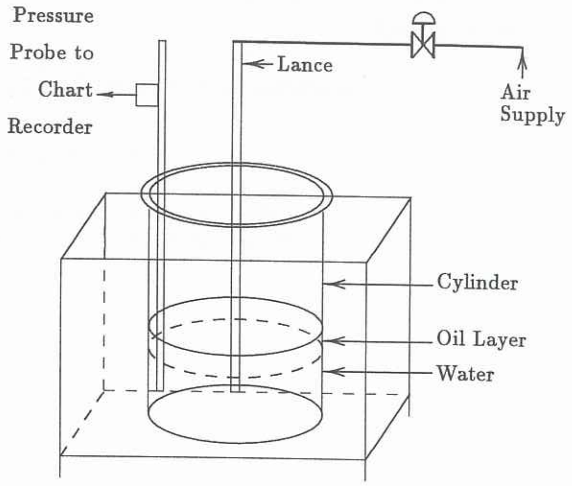

Figure 1: Experimental apparatus

Figure 2 shows that for a bath depth of 0.35 m and a given lance submergence, the rotating waves appear between a lower gas flow limit and an upper gas flow limit. The deep water assumption was valid ($h/R > 1$) and the calculated period of the fundamental wave mode of 0.517 seconds agreed to within ±3% of the measured value. The region where rotating waves occur forms an envelope in the gas flow rate and lance submergence plot.

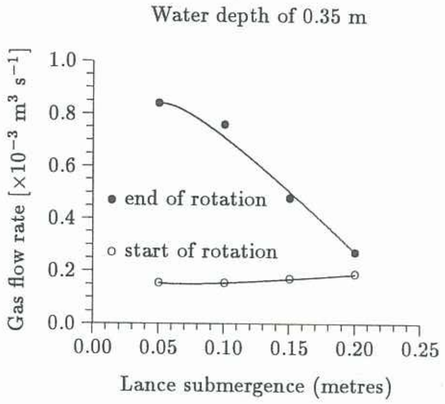

Figure 2: Regime of the rotating wave in a water bath

The existence of a lower and an upper limit to the air flow rate producing the rotating waves indicates that the gas plume must resonate and enhance the rotating wave. Schwarz (1990) suggests that the mechanism for the resonance-like phenomena occurs when the bubble travel time is half the wave period (defined as the critical time). The bubble plume velocity in the spherical cap region is correlated (Sahai and Guthrie 1982) by

$$V_B = V_{slip} + \frac{kQ^{1/3}h^{1/4}}{R^{1/3}} .$$

At low lance submergence, it is possible that the bubbles may not have even reached the terminal velocity of travel. The above correlation shows that the bubble velocity is a weak function of Q and h. The slip velocity will probably vary little with changes in Q and h since the liquid velocity will be increased in the same direction as the rising bubble. Schwarz (1990) showed that for a given gas flow rate, there is a range of travel times around the critical time where some kind of reinforcement of the slop is encountered but the amplitude is smaller than the amplitude for the critical time slop. This range of travel time is reflected in the existence of a gas flow rate range for each lance submergence where rotating waves occur. As the lance submergence increases, the distance for the bubble to travel increases. The corridor of suitable physical values for reinforcement of the slop is decreased and is reflected by the rapid fall in the gas flow rate for the end of the rotating wave.

Effect of oil on the rotating waves

The range of air flow rates giving rise to the rotating wave is substantially reduced when a 0.01m layer of oil is placed on the surface of the bath as shown Figure 3. The data point for the end of the rotating wave at a lance submergence of 0.2 m gave a very high gas flow rate which needs to be investigated further.

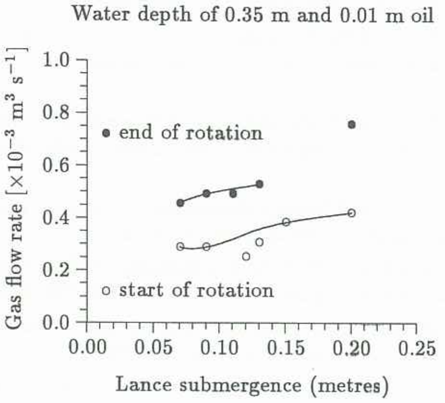

Figure 3: Regime of the rotating wave with oil layer

Observations showed that the oil layer initially impeded the rise of gas bubbles to the top surface at low gas flow rates. As the gas flow rate was increased, the central plume rose to push the oil layer out radially with some degree of mixing. With high gas flow rates, the immiscible oil formed an emulsion with the water. The oil layer moved to the outer perimeter of the water bath. This effectively formed a flexible circular baffle at the outer perimeter with the gas plume in the inner perimeter. This circular baffle formation may be responsible for the damping that occurs but it may not be as efficient as a fixed baffle since it rotates with the fluid.

The rotating wave observed at a particular gas flow rate was not sustained over a period of time. The rotating wave tended to form and disappear and then reform. The surface of the bath was agitated with waves of a random and disrupted nature being present in between the rotating waves. In order to quantify what was happening, the wave periods were recorded over a time period for the range of gas flow rates that the rotating wave did appear. The frequency of occurrence of the wave periods were then graphed. Two sets of experiments on the wave periods were carried out:

i) Variable water depth, 0.015 to 0.35 m with a constant lance submergence of 0.1 m.
ii) Variable lance submergence from 0.05 to 0.30 m with a constant water depth of 0.35 m.

Effect of variable bath depth

The histogram in Figure 4 shows the effect on the wave period distribution with varying bath depth and a constant lance submergence of 0.1 m. There is a wide spread of wave periods. At a bath depth of 18 cm, the wave period is skewed towards values lower than the fundamental wave period of 0.517 seconds indicating that higher wave modes are present. Between bath depths of 20 to 28 cm, the wave periods centre around the fundamental wave period with a sharp central peak. The scatter of wave periods indicate that the fundamental wave period is modified by the presence of viscous damping and other wave modes present in the bath. For the bath depth of 30 cm, the wave periods become more distributed and the central peak is not so prominent.

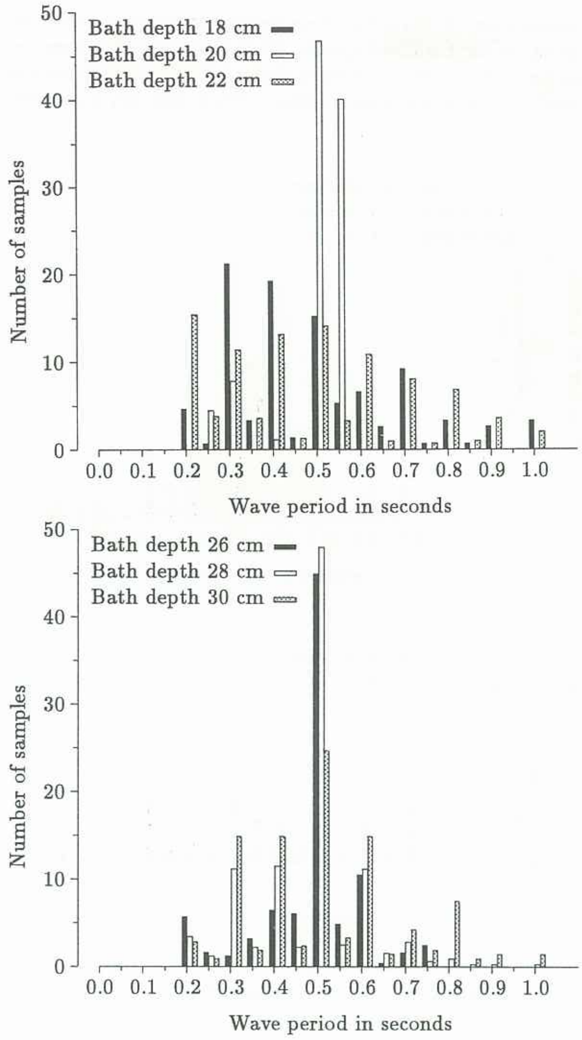

Figure 4: Histogram of wave period for a lance submergence of 10 cm

Effect of variable lance submergence

Figure 5 shows the effect of varying lance submergence with the bath depth constant at 0.35 m. At this bath depth, the wave periods are distributed around the fundamental wave period. As the lance submergence decreases, the wave period distribution spreads more evenly over a wide range resulting in no dominant wave period. This spreading out results in the rotating wave being unable to reinforce itself leading to an agitated free surface being formed instead. The exact mechanism for the formation of a wave spectrum and how it is distributed is not known. There may be similarities with the above phenomenon and the existence of a wave spectrum in oceans.

DISCUSSION

In the metallurgical industry, there is a tendency to use a height to diameter ratio between 1 and 2 in the design of cylindrical metallurgical vessels. Further experiments (Parker and Rodgers 1990) show that the rotating standing wave preferably forms in this region. Moreover, the lance submergence to diameter ratio regions where the rotating wave is formed is often used for industrial operation. The water modelling results for the 0.35 m bath depth showed that the oil layer does not change the region of lance submergence at which the rotating wave occurs, it only changes the gas flow rates at which the rotating wave occurs. The results suggest that the rotating wave can be avoided either by deep or shallow lance submergences outside the rotating wave envelope as shown in

Figures 1 and 2. However, these regions of operation often result in the formation of splash. For a low lance submergence, the gas will be able to channel through the bath resulting in splash and poor gas-liquid contact. For a deep lance submergence, the increase in compressor costs, coupled with the gas transferring more of its potential energy to the bath will result in greater mixing and gas-liquid contacting and increased splashing.

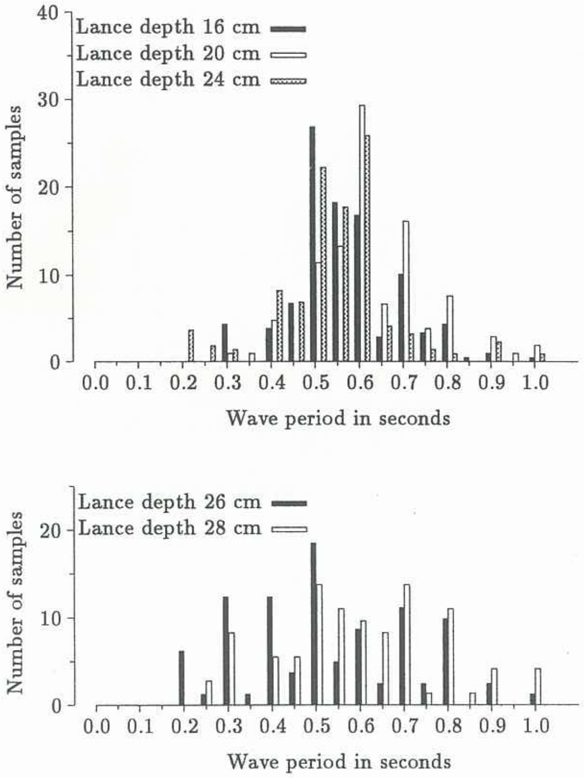

Figure 5: Histogram for wave period for a bath depth of 35 cm

There is a possibility that the presence of a viscous layer can result in a free surface that has a spectrum of wave lengths which can interfere destructively to reduce the formation of rotating waves. Consequently, any force and moments due to wave motion on the supporting structures will be reduced. Moreover, the reduction in the region where the rotating waves can occur increases the possibility of finding a high gas flow rate where splashing may not be so critical as to deter the running of the process. As slag layers in metallurgical vessels tend to be much deeper than those used in the above experiments, it would be necessary to look at viscous oil layers whose thicknesses are comparable to that of the water layer.

CONCLUSION

The presence of a 1 cm layer of oil on the surface of cylindrical water bath was found to have a significant effect in damping out the rotating wave. The rotating waves formed with the layer of oil on the water did not have a dominant fundamental period. Instead a wide spectrum of wave periods was observed. The study indicated that rotating waves will form in the existing metallurgical vessel due to the choice of height to diameter ratios being used. However, the presence of a slag layer may aid in destroying the slop by forming a spectrum of wave periods which interfere destructively, as well as by reducing the region of gas flow rates where the rotating wave is stable.

ACKNOWLEDGMENTS

Research support for Dr. Liow and related developments within the GKW CRC has been provided by the Australian Mineral Industries Research Association Ltd. The authors acknowledge the assistance of Ms. Lisa-Anne Parker and Jennifer Rodgers in the collection and evaluation of data.

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