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STANDING WAVE FORMATION IN PEIRCE-SMITH CONVERTERS

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ABSTRACT

The periods of the transverse standing waves occurring in the Peirce-Smith converter geometry as a function of bath depth were solved using linear wave theory by formulating an integral equation of the second kind. The eigenvalues of the integral equation gave the wave periods which were calculated for the first four wave modes. They include the complete range of eigenvalues for the first two symmetric standing waves which have not been reported in the literature. Experimental results from a water model agreed with the theoretical predictions over a wide range of bath depths. Data from a Peirce-Smith copper converter were in reasonable agreement with the theory. The occurrence of a standing wave was found to be determined by the bath depth, tuyere submergence and tuyere angle. The results showed that it is possible to obtain regions in the bath depth and tuyere angle/tuyere submergence plots where no standing waves were found and spitting was minimal.

INTRODUCTION

The Peirce-Smith (P-S) converter has been an integral part of many copper and nickel converting operations for eight decades since its use in 1905 at the Baltimore Copper Company. In the P-S converter, air is injected horizontally through a bank of tuyeres into a circular cylinder laid on its side. Few studies have been carried out to investigate the fluid dynamics of the P-S converter and the causes of slopping in such a geometry. Kootz and Gille (1948) observed that slopping of liquid resulting from gas injection depended on the depth of liquid (bath depth) and the submergence of the tuyeres. Richards et al. (1986) studied the formation of standing waves in a water model of a copper converter on a 0.25 scale. They found that the standing wave generated had a constant amplitude of 0.1 m measured at the breast and it was independent of bath depth and tuyere submergence. They extended their water model analysis to a copper converter and concluded that the air flow rate into the converter was limited by the development of a standing wave which generated splash.

THEORY

In the P-S converter geometry, standing waves can be formed in either the transverse or the longitudinal direction. However, only the transverse standing waves are of interest as the longitudinal standing waves are not supported by a constant horizontal force produced by the gas injection. The transverse standing waves are either asymmetric or symmetric as shown in figure 1.

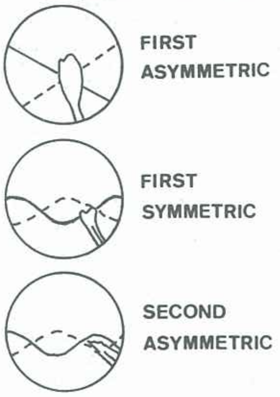

Figure 1: The first three modes of transverse standing waves in the P-S converter

There are no know analytical solutions to the period of the standing waves in a circular canal geometry. Rayleigh (1899) considered the case of a half full circular canal using an approximate energy solution for the fundamental frequency. Budiansky (1960) obtained the wave form and period for the first three asymmetric modes using the method of source and sink. However, his mathematical formulation lacked generality and cannot be easily applied to other geometrical shapes. Davis (1965, 1969) solved the first six modes for the case of a half full circular canal to five significant values, but application of his method to other bath depths is difficult. Chang and Wu (1972) presented a two-dimensional form of the generalised three-dimensional form of Siekmann and Chang (1970) for the fundamental standing wave frequency in an arbitrary shaped container. Chang and Wu showed that the problem can be reduced by using the density of the single layer logarithmic potential $\mu(s)$, to give an integral equation.

The adjoint equation shown below is solved for the eigenvalues, α.

$$\nu(s) = \frac{1}{\pi}\int_{d\Omega} \frac{\partial}{\partial n_1^*} \log \frac{1}{r(s,s_1)}\nu(s_1)ds_1 + \frac{\alpha}{\pi}\int_{d\Omega} H(s_1)\log \frac{1}{r(s;s_1)}\nu(s_1)ds_1 \qquad (1)$$

TABLE I: Data on the Peirce-Smith converter

Diameter	3.96 m
Air pressure	80 - 84 kPag
Air flow rate	12 - 13 Nm^3s^{-1}
Converter fill	1/3 by volume (h/D=0.407)
Slop period	2 s
Standard deviation	0.3 s
Refractory thickness	0.5 m

EFFECT OF TUYERE SUBMERGENCE AND BATH DEPTH ON WAVE FORMATION

One hundred and ten runs were carried out where the gas flow rate was varied to see what free surface phenomena occurred over a gas flow rate range between Ma = 0 to 1. This allowed the identification of the regions where standing waves occurred in the tuyere submergence and bath depth plots. Figure 4a shows the regions where no standing wave and substantial splashing-shearing of bath liquid (labelled A) and first asymmetric wave (labelled B) were found. The tuyere submergence isobaths shown in figure 4 are dependent on the tuyere angle as the tuyeres are set into the wall of the model. Theoretically, the maximum tuyere angle possible is 90°, but the water model is limited to 27.5° by the supports required to keep the model in position. Figure 4a shows that the presence or absence of standing waves is a strong function of the tuyere submergence. For tuyere submergences of 0 to 40 mm, no standing waves are formed. A minimum tuyere submergence of 60 mm is required for the formation of the first asymmetric standing wave. The maximum bath depth at which experiments could be carried out was limited by the amount of the standing wave spilling out of the converter mouth. For the water model, the maximum bath depth was h/2a=0.65.

For tuyere submergences below 20 mm, two phenomena occurred, both of which were detrimental to a converter process. The first phenomena is the channelling of gas where the gas stream velocity was high enough to shear through the liquid. The channelling of gas diminished considerably as the tuyere angle became more negative but even at large negative angles, the plume lifted itself from the water interface fairly close to the wall and the gas plume did not penetrate downwards to a large extent. The second phenomena is the splashing and spitting of liquid and it was magnified by high gas flow rates and positive tuyere angles.

A minimum tuyere submergence of 60 mm is required for the first asymmetric standing wave to occur. Above a bath depth of h/2a=0.5, two changes occur. The region of no standing wave increases from 40 mm for h/2a = 0.5 to 60 mm for h/2a=0.6. The region where the first asymmetric standing wave begins increases from 60 mm for h/2a = 0.55 to 80 mm for h/2a=0.6. Between regions A and B, there is a region of tuyere submergence of 40 to 60mm where splashing was not severe and no first asymmetric standing waves were formed. In the operation of a P-S converter, it could be possible to conduct gas injection at these tuyere submergences which would ensure that wave formation and splashing were minimised.

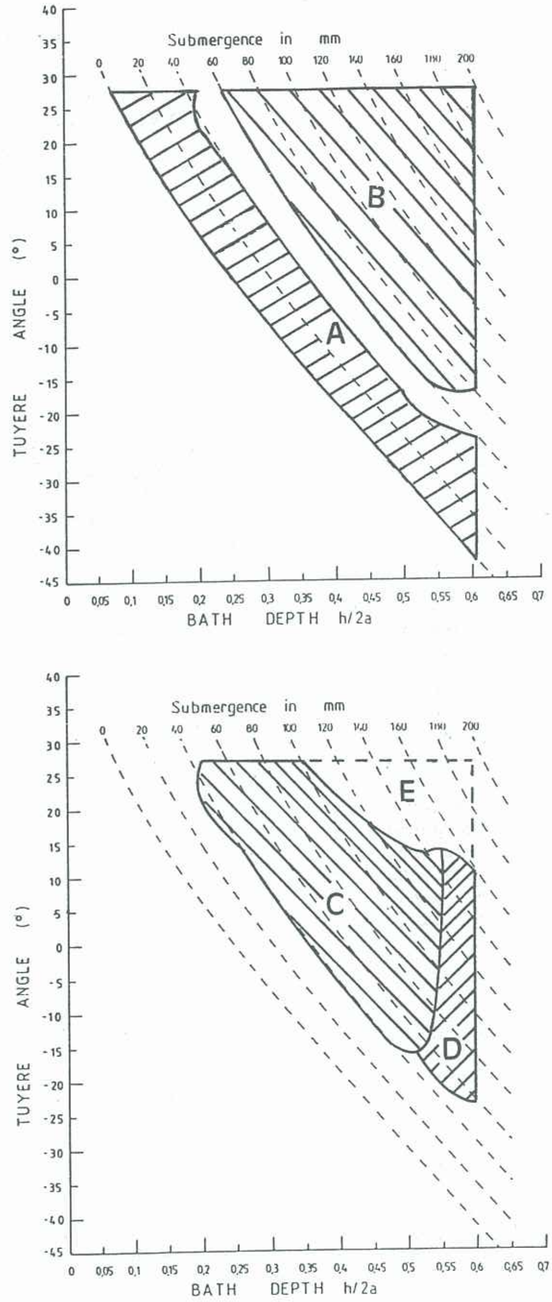

Figure 4: Effect of the tuyere angle/ tuyere submergence and bath depth on the presence or absence of standing waves in the water model of a P-S converter. A - spitting; B - first asymmetric standing wave; C - first symmetric standing wave; D - half first symmetric standing wave; E - no first symmetric standing wave.

The solution of this integral equation has been outlined by Liow and Gray (1989) where the periods have been approximated using Chebyshev approximation with the bath depth as the variable. The dimensionless eigenvalue, α, is given by

$$\alpha = (2\pi/T)^2 a/g. \qquad (2)$$

from which the period of the standing wave (T) can be calculated given α and a. The theoretical values of α are graphed in figure 2.

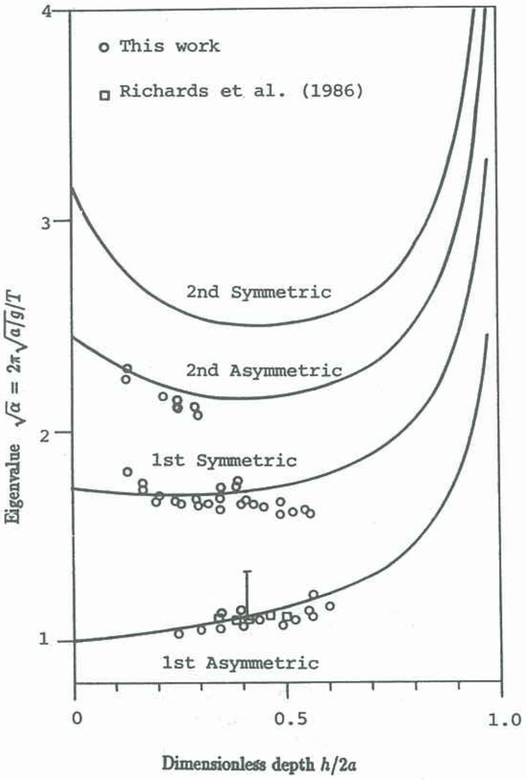

Figure 2: Comparsion of the theoretical and experimental eigenvalues of the standing waves in a P-S converter geometry. The I bar represents the result for the industrial P-S converter with its standard deviation.

EXPERIMENTAL

The water model was a perspex slice model of a P-S converter of 0.375 m diameter and 0.149 m thick. Three replaceable brass tuyeres of 3 mm internal diameter were fitted flush with the circular wall to simulate the operation of the converter. A schematic diagram of the apparatus is shown in figure 3. It was not possible to orientate the tuyere angle (to the horizontal) independently of the tuyere submergence as the tuyeres were built into the cylinder side. Varying the tuyere submergence led to a change in the angle at which the gas was injected into the bath for a fixed volume of liquid. A bank of rotameters measured the gas flow rate into the tuyeres. The gas flow was split by a distributor so that the inlet gas to the model was spread across the length of the converter.

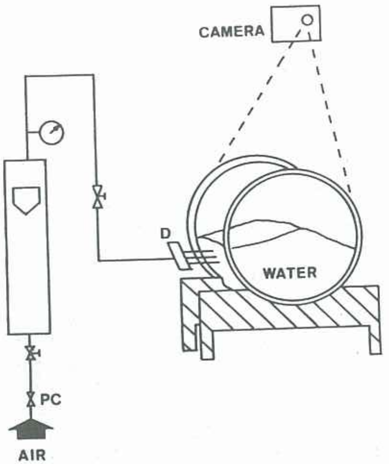

Figure 3: Schematic diagram of the experimental apparatus. PC - pressure controller, D - distributor.

The model liquid was tap water. The compressed air was approximately 70% saturated with water vapour. The standing waves generated were filmed at 20 frames per second with a 16 mm HyCam camera. The wave period obtained from the film were checked with chart recorder readings of the change in pressure in a tube closed at one end and partially submerged into the liquid. It was found that the wave periods could be reliably obtained from the chart recorder readings with the repeatibility to within ±1%.

RESULTS

The period of the standing wave as a function of bath depth is shown in figure 2. For h/D≥0.56, the slopping of water made it difficult to obtain the standing wave period. The water tended to spill out of the opening at the top of the water model. The range of results obtained is useful as in practice, P-S converters are not normally operated more than half full. The results suggest that slopping will pose a problem in plant operation when standing waves are formed in a P-S converter than is more than half full. The eigenvalues calculated for the experimental results agree well with the theoretical prediction shown in figure 2. The results of Richards et al. (1986) have been included and they agree with our theory.

PEIRCE-SMITH CONVERTER DATA

In order to test the validity of the theoretical analysis, the period of the standing wave in a P-S copper converter was measured during the start of the copper blow by visual observation through the mouth. The dimensions of the converter and the measured results are given in table I. For a converter with a liquid depth of h/D=0.41, the eigenvalue is 1.2 for the first asymmetric standing wave. The calculated standing wave period is 2.3 s with a standard deviation of 0.3s. Accurate visual observations are not possible due to the difficult environment existing at the converter mouth. However, the experimental value is distinct from all other modes of the standing wave shown in Figure 2 and shows that the first asymmetric standing wave was observed. The period of the standing wave calculated from the linear wave theory can therefore be applied to the case of slopping with molten liquid in a P-S converter.

Figure 4b shows the region where the first symmetric standing wave occurs. The region is divided into two parts. Region C is where the full first symmetric standing wave occurs; and region D is where the half first symmetric standing occurs. It was found that above $h/2a=0.5$, the energy of the gas was not sufficient to give rise to a complete symmetric standing wave. The standing wave measured in the first half of the model at the air injection side had a period slightly longer than the theoretical prediction. The free surface at the second half of the model had a symmetric standing wave which cyclically formed and degenerated with time. A longitudinal standing wave appeared randomly. The half first symmetric and longitudinal standing waves interacted to form a free surface that was rather more choppy than would have been if a full first symmetric standing wave was formed. However, the amount of splashing was visually observed to be small. There was an upper tuyere submergence limit for the first symmetric standing wave shown by the region marked 'E'. No first symmetric standing waves were found. This upper tuyere submergence limit varied between 100 mm at $h/2a=0.35$ to 150 mm at $h/2a=0.55$. Above the upper tuyere submergence limit, the gas entered the bulk liquid at a point which corresponded to a distance approximately a quarter of the free surface distance from the model wall.

CONCLUSION

The periods of the transverse standing waves occurring in the P-S converter geometry as a function of bath depth were solved using linear wave theory by formulating an integral equation of the second kind. The eigenvalues of the integral equation gave the wave periods which were calculated for the first four wave modes. They include the complete range of eigenvalues for the first symmetric standing waves which has not been reported in the literature. Experimental results have shown that the theory agrees well over a wide range of bath depths for the water model. The experimental data showed that the first and second asymmetric, first symmetric and longitudinal standing waves exists in the water model. The first symmetric standing wave was enhanced by the longitudinal standing wave which showed that the three dimensional geometry of the model was important in governing the existence of a standing wave. In the design of a P-S converter, it would be necessary to take into account the three dimensional shape of the converter to avoid one standing wave enhancing another. Data from a P-S copper converter shows reasonable agreement with theory showing that the theory is applicable for metallic liquids.

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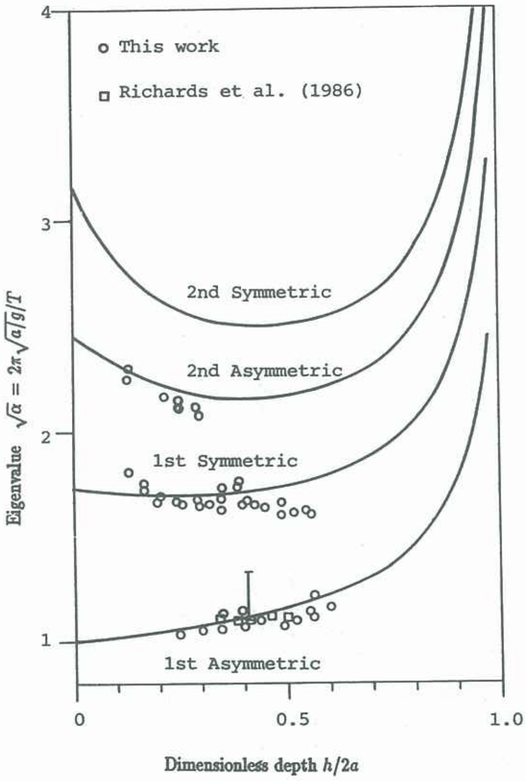

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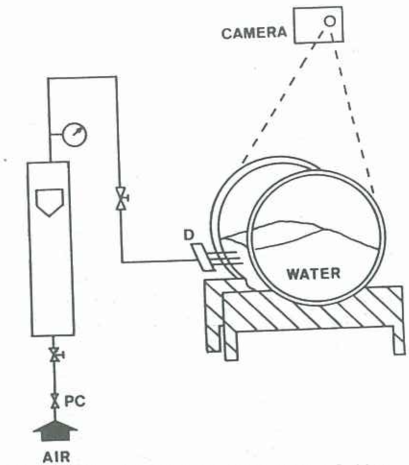

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