Control of Slag Foaming Rate by Sound Wave

Sergey V.Komarov, Mamoru Kuwabara and Masamichi Sano
Sergey V.Komarov is an Associate Professor at the Institute for Advanced
Material Processing, Tohoku University
1,1 Katahira, 2-Chome, Aobaku, Sendai 980-8577, JAPAN
Fax: +81-22-217-5177
Tel: +81-22-217-5177
Mamoru Kuwabara is an Associate Professor and Masamichi Sano is a Professor at the
Department of Material Processing Engineering, Nagoya University
Furo-cho, Chikusa-ku, Nagoya, 464-8603, JAPAN
Fax: +81-52-789-4644
Tel: +81-52-789-4642

Abstract

The present work was undertaken with the aim of studying the effects of sound frequency, sound intensity and viscosity of slag on the slag foaming rate and the steady-state foam height. The experiments were carried out by using two slag systems: $BaO-B_2O_3$ and $CaO-SiO_2-FeO$. The slags were melted at temperature 1223 or 1273 K ($BaO-B_2O_3$ slags$_)$ and 1573 K ($CaO-SiO_2-FeO$). The mechanism of acoustic defoaming was investigated by using water-glycerin solutions at room temperatures. The low frequency sound waves (< 1.3 kHz) are found to be more effective in the slag foaming suppression than high frequency waves (1.3~12 kHz). The steady-state foam height is abruptly decreased when the sound pressure reaches a threshold value which depends on the sound frequency and the liquid viscosity. The results can be explained in terms of enhancing the rates of liquid drainage and film rupture induced by sound.

INTRODUCTION

Many industrial processes are accompanied with foam formation which exerts an adverse effect on the process performance. In metallurgical processes, many chemical reactions proceed at high temperatures in the liquid metal and slag. When the reactions are attended with a gas bubble evolution, it can result in the slag foaming. Examples of the processes are the bath smelting reduction, the preliminary dephosphorization of liquid iron, the converter process [1,2].

It has been known that the foam formation can be suppressed by applying a sound field. This method was used for controlling fast-growing industrial foams [3]. The ultrasound waves allowed the foam to be quickly destroyed in the filling operation of cans [4]. However, works concerning the sound defoaming are very few and the mechanism of the foam suppression is not clear yet. This is especially true for the slag defoaming studies on which are absent at all. The goal of the present work is to study a possibility of the suppression of slag foam exposed to a sound wave under high temperature conditions. To clarify the mechanism of the sound defoaming, the low temperature experiments have been also conducted.

EXPERIMENTAL AND MEASUREMENT PROCEDURE

High temperature experiment

Figure 1 is a schematic of the experimental equipment. The BaO-B_2O_3 slag (1) was melted in an alumina crucible (2) (I.D.40 mm, height 150 mm) at two temperatures, 1223 and 1273K. A SiC resistance furnace with a 10 cm isothermal zone was employed. To produce the slag foam, Ar gas was injected into the slag through an L-shaped submerged steel nozzle (3) (O.D. 3 mm) with three holes drilled at the top of the elbow part of the nozzle in such a way to discharge the gas upwards. Since chemical reactivity and melting point of FeO-containing slag are higher than those of the BaO-B_2O_3 slags, the CaO-SiO_2-FeO slag was melted at temperature 1573K in a crucible made of stainless steel (I.D. 55 mm, height 170 mm). The CaO-SiO_2-FeO slag was premelted by using a resistance furnace under a controlled atmosphere. A small amount of P_2O_5 (1~2% in weight) was added to the melted slag before starting measurements to increase the foam stability. Ar gas was injected into the melt through a bottom nozzle (O.D. 2 mm) fixed at the crucible center.

The Ar gas flow rate was ranged from 15 to 120 Ncm^3/min. The weight of the slags was determined in such a way that the slag height was 4 cm after melting in the crucible. The composition and the physical properties of the slags used in the experiment are presented in Table I.

A sound wave produced by a powerful loudspeaker (4) was propagated to the foamed slag surface through gas atmosphere of the working space consisting of an L-shaped water-cooled adapter (5) (stainless steel, 102 mm I.D.) and an alumina pipe (6) (40 mm I.D.). The loudspeaker (max. electrical input power 50 W) was fixed at the top part of the L-shaped adapter. The sound frequency and the speaker voltage were varied in the ranges of 0 ~ 12 kHz and 0 ~ 10 V, respectively.

The slag foaming is described by two parameters: the averaged slag foaming rate, W_f, and the height of steady slag foam, h_s. Both the parameters were measured by detecting the surface position of the slag by two electric probes, one of which is fixed above the slag surface at rest (7,measuring probe), whereas the other one is submerged in the slag (3,L-shaped lance). This method has been used to study the slag foaming phenomena (for example [5]).

To measure the slag foaming rate, W_f, the measuring probe was fixed at a certain distance, h from the slag surface. W_f, was defined as the ratio of the distance,h, to the value t_c - t_b. Moment of contact of the slag surface with the measuring probe, t_c, was detected by closure of

an electrical circuit consisting of a variable resistor (8) a power supply unit (9), the measuring and the submerged probes. t_b is the time at which the gas bubbles start to discharge from the nozzle orifices. It was determined from the time variation of pressure inside the L-shaped nozzle which was different before and after the start of bubble discharge. The measurements were carried out using a pressure transducer (10) connected to the nozzle. The transducer was used also to determine the bubble detachment frequency which was necessary to calculate the mean bubble size. The steady foam height, h_s, was measured after the gas bubbling for 10 min.

The results of the measurements were processed by a programmable data acquisition processor (11) and stored by a PC.

Room temperature experiment

A cylindrical vessel made of acrylic resin (height 1 m, I.D. 0.1 m) was used for the experiments. The vessel was filled with a liquid (about 0.3 l) containing sodium dodecylbenzene sulphonate (SDBS) as a surfactant. Its concentration in the liquid was 2×10^{-3} M/l. The composition and properties of the used liquids are presented in Table I. The vessel was placed inside an acrylic container to provide the control of gas composition and temperature of the working space. For this purpose, preheated nitrogen was blown into the container. The temperature within the container was maintained at $20\pm1.5^{O}C$.

A column of foam was produced by injecting nitrogen through two nozzles (I.D. 1 mm) fixed at the vessel bottom. Total gas flow rate was 800 Ncm^3/min. It was controlled by two mass flow controllers independently for each nozzle. The foam layer was exposed to a sound wave generated by the loudspeaker which is the same as in the high temperature experiments. The loudspeaker was fixed at the container lid.

To measure amplitude of the sound pressure acting upon the liquid bath surface and resonance frequencies, the pressure transducer was used. It was set at the level of the free surface in such a way to counter the loudspeaker. These measurements were made in the absent of foam on the liquid surface. As the foam column increases in height, indications of the pressure transducer made possible determining the fraction of liquid in the foam column. Neglecting the gas density, r_g by comparison with the liquid density, r_l, the relationship between the liquid fraction, a_l, the measured pressure, P_h and the foam height, h can be expressed by Eq.(1).

$$a_l = \frac{P_h}{hgr_l} - \frac{r_g}{r_l}(1)$$

The foam behavior is explained in terms of parameter Σ, which is the ratio of steady foam height, h_s to superficial velocity, U, and equals to the residence time of gas in foam. The superficial velocity is the following function of gas flow rate, Q, temperature, T, liquid fraction in foam, a_l and inner diameter of vessel, d_c.

$$U = \frac{4Q}{pd_c^2}\left(\frac{T}{273}\right)\left(\frac{1}{1-a_l}\right) \qquad (2)$$

Size of bubbles detached from the bottom nozzle was measured by a high speed video camera with the framing rate of 250s^{-1}. The results were necessary to estimate the thickness of foam film and the fraction of liquid in the foam column.

<center>EXPERIMENTAL RESULTS</center>

Change in foam height with time

The time dependences of foam height are presented in Figs.2,3 ($BaO-B_2O_3$ slag foaming) and 4 (glycerin solution foaming). In the high temperature experiment, fitting the results showed that relationship between foam height and time can be described by Eq.(3)

$$h = \frac{h_s}{A + t} \qquad (3)$$

where h_s is the steady foam height, A is the parameter. The fitted curves are shown in Figs.2 and 3 by lines. Measurement of the slag foam height was restricted by 6 cm because of limitation in isothermal zone mentioned above. When the foam height exceeds 6 cm, h_s was determined from Eq.(3) by the fitting procedure. The results are shown by broken lines.

The results presented in Figs.3,4 reveal that the steady foam height decreases when the foam is exposed to sound wave. The decrease in h_s is especially significant for water-glycerin foam (Fig.4, curve 4).

Two phenomena were observed under the sound application in the low temperature experiments. First, a huge number of small droplets were detached from the foam surface. A part of them flew away from the surface and adhered on the inner surface of the vessel. Second, a strong cavitation occurred inside the foam layer under certain experimental conditions. Both the phenomena were pronounced more for the water foam than for the water-glycerin ones. The results of the observations are presented in Table II by marks D (droplet detachment) and C (cavitation).

Effects of frequency and viscosity on foam behavior

Figures 5 and 6 are typical plottings showing the effect of sound frequency on relative slag foaming rate W_f/W_{f0} (W_{f0} is the foaming rate in the absence of sound wave). According to the results, the relative foaming rate increases and decreases as the sound frequency is changed. The variation in W_f/W_{f0} ranges from 0.1 to 1.4 and occurs at irregular frequency intervals.

Table II presents the residence time of gas bubble in water and water-glycerin foams depending on sound frequency. In the low frequency range (50~1300 Hz), the measurements were conducted at the resonance frequencies only. The frequencies were found by previous measurements.

On the whole, the largest defoaming effect is observed under low frequencies (< 1000 Hz) in both the high and low temperature experiments. In this range, the higher is the liquid viscosity, the larger is the defoaming effect of sound (Table II). The high temperature results confirm this tendency (Fig.3). In addition, there is a tendency for decrease in W_f/W_{f0} (slag A) and Σ(water-glycerin solutions) at frequency of 10 kHz as compared with no sound condition.

DISCUSSION

Evaluating the thickness of foam film

It is known that a foam layer consists of three elements: gas bubble, thin film and interconnecting channels named as the Plateau borders containing the main amount of the liquid [6]. A photograph of the top surface of a foam column, shown in Fig.7, gives an idea of the foam elements. The film on the top surface of the foam is subjected to the action of the sound pressure primarily. Depending on the film thickness and physical properties of liquid and gas, the wave can be reflected from the surface and/or propagates inside the foam layer.

Garrett [7] showed that the height of a foam in steady state, h_s, depends on the foam film thickness, d at the top surface as

$$\frac{h_s}{r_b} = \frac{2.625(\boldsymbol{\mu}_l U r_b)^{\frac{5}{4}}}{(\boldsymbol{\rho}_l g)^{\frac{1}{4}} \boldsymbol{\sigma} \boldsymbol{\delta}^{\frac{7}{4}}} (4)$$

where $\boldsymbol{\mu}$, $\boldsymbol{\rho}_l$ and $\boldsymbol{\sigma}$ are the viscosity, the density and the surface tension of liquid, U is the gas superficial velocity (Eq.(2)). Thus, measuring the bubble radius, r_b and the steady foam height, h_s, one can evaluate $\boldsymbol{\delta}$. On some rearrangement, Eq. (4) can be rewritten as

$$\boldsymbol{\delta} = 1.74 \frac{(\boldsymbol{\mu}_l U)^{\frac{5}{7}} r_b^{\frac{9}{7}}}{(\boldsymbol{\rho}_l g)^{\frac{1}{7}} (\boldsymbol{\sigma} h_s)^{\frac{4}{7}}} \qquad (5)$$

Figure 8 is a plot of the gas bubble radius against the gas flow rate for BaO-B$_2$O$_3$ slags. The relationships are practically linear. According to the calculated results, the film thickness equals to 29.0, 14.3 and 8.1 μm for the slag A (T = 1273K, Q = 60 Ncm^3/min), the water-glycerin solutions with the glycerin concentration 90 and 85%, respectively on the assumption that the liquid fraction in foam $\boldsymbol{\alpha}_l \ll 1$.

Reflection of sound wave from the foam film

When the wave is incident upon the surface normally, the reflection coefficient, R can be expressed by the following equation [8]

$$R = \frac{\left(\dfrac{\boldsymbol{\rho}_g c_g}{\boldsymbol{\rho}_l c_l} - \dfrac{\boldsymbol{\rho}_l c_l}{\boldsymbol{\rho}_g c_g}\right)^2}{4\cot^2 \dfrac{2\boldsymbol{\pi}\boldsymbol{\delta}}{\boldsymbol{\lambda}_l} + \left(\dfrac{\boldsymbol{\rho}_g c_g}{\boldsymbol{\rho}_l c_l} + \dfrac{\boldsymbol{\rho}_l c_l}{\boldsymbol{\rho}_g c_g}\right)^2} \qquad (6)$$

where $\boldsymbol{\lambda}_l$ is the length of sound wave in liquid, $\boldsymbol{\rho}_g$, $\boldsymbol{\rho}_l$, c_g and c_l are the densities and sound velocities in gas and liquid, respectively. The coefficients calculated from Eq.(6) are shown in Fig. 9 as a function of frequency. The velocities of sound in water and gases (N$_2$ at 293 K and Ar at 1273 K) were taken from the literature [9]. Since the data on the sound velocities in the water-glycerin solutions and melted slags are absent in the literature, they were assumed to equal to those in water and the Pyrex glass, respectively [9].

Mechanism of the sound defoaming

Figure 9 reveals that the reflection coefficients of sound wave incident upon the foam surface are very small in the frequency ranges where the large defoaming effect was found. These ranges are indicated in Fig.9 by vertical lines with arrows. Thus, the incident wave is transferred inside the foam layer causing physical phenomena, which can affect both the liquid drainage and the film rupture.

There is a large difference between sound propagation in a foam and that in air. The difference is related with the action of sound wave on the bubbles and the Plateau borders. This causes oscillations of the foam bubbles. As a result, the liquid is forced to flow from the foam films into the Plateau borders and then drains down to the liquid bath. According to the model proposed by Vafina, et al.[10,11], a sound wave propagating through a foam layer can accelerate the liquid drainage when the following condition is valid

$$\boldsymbol{\omega} < 2\boldsymbol{\nu}_l / S \qquad (7)$$

where $\boldsymbol{\omega}$ ($=2\boldsymbol{\pi}f$) is the angular frequency of sound wave, $\boldsymbol{\nu}$ is the kinematic viscosity of liquid, S is the cross sectional area of the Plateau border adjoining to the bubble. Relation (7)

gives a critical frequency f^*. If the sound frequency exceeds this value, the effect of sound on the liquid drainage is expected to be insignificant. The area S can be calculated from Eq.(8) under the assumption that S is much smaller than square of the bubble radius, r_b [12].

$$S = 0.186 \rho r_b^2 \left(\frac{a_l}{1 - a_l} \right) \qquad (8)$$

where a_l is the fraction of liquid in foam.

The measurement results showed that the fraction of liquid in foam decreases sharply with the foam height (Fig.10). In the case of 85% water-glycerin solution, the liquid fraction is ranged from 0.025 to 0.003 as the foam height varies between 2 and 13 cm. Considering 1- a_l is nearly 1, f^* can be given:

$$f^* = \frac{5.38 \eta_l}{\rho^2 r_b^2 a_l} \qquad (9)$$

Assuming that the liquid fractions in foam for all liquids used in the experiments are varied through the same range, one can estimate the critical frequencies for both the largest (0.025) and the smallest (0.003) fractions of liquid. The results are presented in Table III. It should be noted that experimentally estimated a_l corresponds to the averaged value. However, the liquid fraction in foam decreases with distance from the surface of liquid bath. Therefore, f^* can be probably larger than that predicted by Eq.(9), at least in the upper part of the foam.

Thus, the frequency range in which the sound wave enhances the liquid drainage, should be increased with the liquid viscosity when the other parameters are kept constant. The experimental results presented in Table 2 and Fig.11 conform to this prediction. Figure11 shows Σ as a function of sound pressure exerted on the liquid surface. It can be seen that the residence time of gas is steeply decreased when the sound pressure reaches a critical value. This value decreases as the sound frequency decreases and the liquid viscosity increases. Although the results of the high temperature experiments do not support such sharp decrease in foam height with sound pressure, Fig.12 demonstrates that there is an evident tendency for a significant decrease in the relative foaming rate as the loudspeaker input voltage increases on frequencies 220 and 400 Hz. However, no dependence was found between W_f/W_{f0} and f at f = 1000 Hz. The reason is that the frequencies of 220 and 400 Hz are possibly close to resonance frequencies and provide a comparatively large level of the sound pressure, while the frequency of 1000 Hz is not.

Another expected effect resulting from the forced bubble oscillations is an increase in the rate of film rupture. It is assumed that this causes the intense droplet formation mentioned above. Furthermore, the droplet formation rate can be expected to increase as the foam film becomes thinner with decreasing the liquid viscosity. Since the film rupture takes place only at the top surface of foam layer, the contribution of the enhanced rupture to sound defoaming is smaller as compared with that of the accelerated liquid drainage. This explains in particularly why the defoaming effect of sound was smaller for low viscous water foam than for water-glycerin foams having large viscosities. The viscosity of water and f^* are too small in order to gain any significant defoaming due to an enhancement in the liquid drainage. The height of the water foam is reduced as a result of the strong film rupture induced by sound wave.

Finally, the sound defoaming found in the high frequency range (slag A and water-glycerin (85%) solution at 10 kHz) can be explained by a reflection of sound wave from the foam surface. The alternating pressure, exerted upon the surface during the reflection, can excite a capillary wave on the surface leading to a fast rupture of the film. To examine this assumption, additional experiments require.

The rates of all the three phenomena, namely the liquid drainage, the film rupture during the

bubble oscillation and capillary wave propagation must be governed by the level of sound pressure in the working space. Under given acoustic power of sound generator and distance between the generator and the liquid bath, the sound pressure is strongly dependent on frequency and increases significantly when the latter equals to a resonance value. In support of this interpretation, we measured the relative slag foaming rate depending on the sound frequency varied through a small range. The results, presented in Fig.13, indicates that there is a strong relationship between W_f/W_{f0} and f. This explains the variation in relative foaming rate with frequency presented in Figs.5 and 6.

CONCLUSION

The results of high and low temperature experiments showed that the sound waves allow the slag foaming to suppress. The defoaming effect of sound depends on the sound frequency, pressure and the liquid viscosity. On the whole, the sound waves of low frequency (90~1300 Hz) are more effective for suppressing the slag foaming than high frequency waves (1300~ 12000 Hz). There are frequencies at which the sound defoaming effect is especially large. Under the given conditions, they were 200, 350 and 10000 Hz for the BaO-B_2O_3 slags, and 400 Hz for the CaO-SiO_2-FeO slag. This can be explained by resonance phenomena.

According to the results of the room temperature experiments, foam height is abruptly decreased when the sound pressure reaches a threshold value. This value becomes smaller as the sound frequency decreases and the liquid viscosity increases. Generally, the defoaming effect of sound increases with liquid viscosity.

In the low frequency range, the experimental results can be explained by enhancing the rates of liquid drainage from the foam film and the film rupture resulting from the foam bubble oscillations induced by sound. When the foam surface is exposed by a high frequency sound, the wave is reflected from the surface. It is assumed that the alternating pressure, exerted upon the surface, can excite a capillary wave on the surface leading to a fast rupture of the film.

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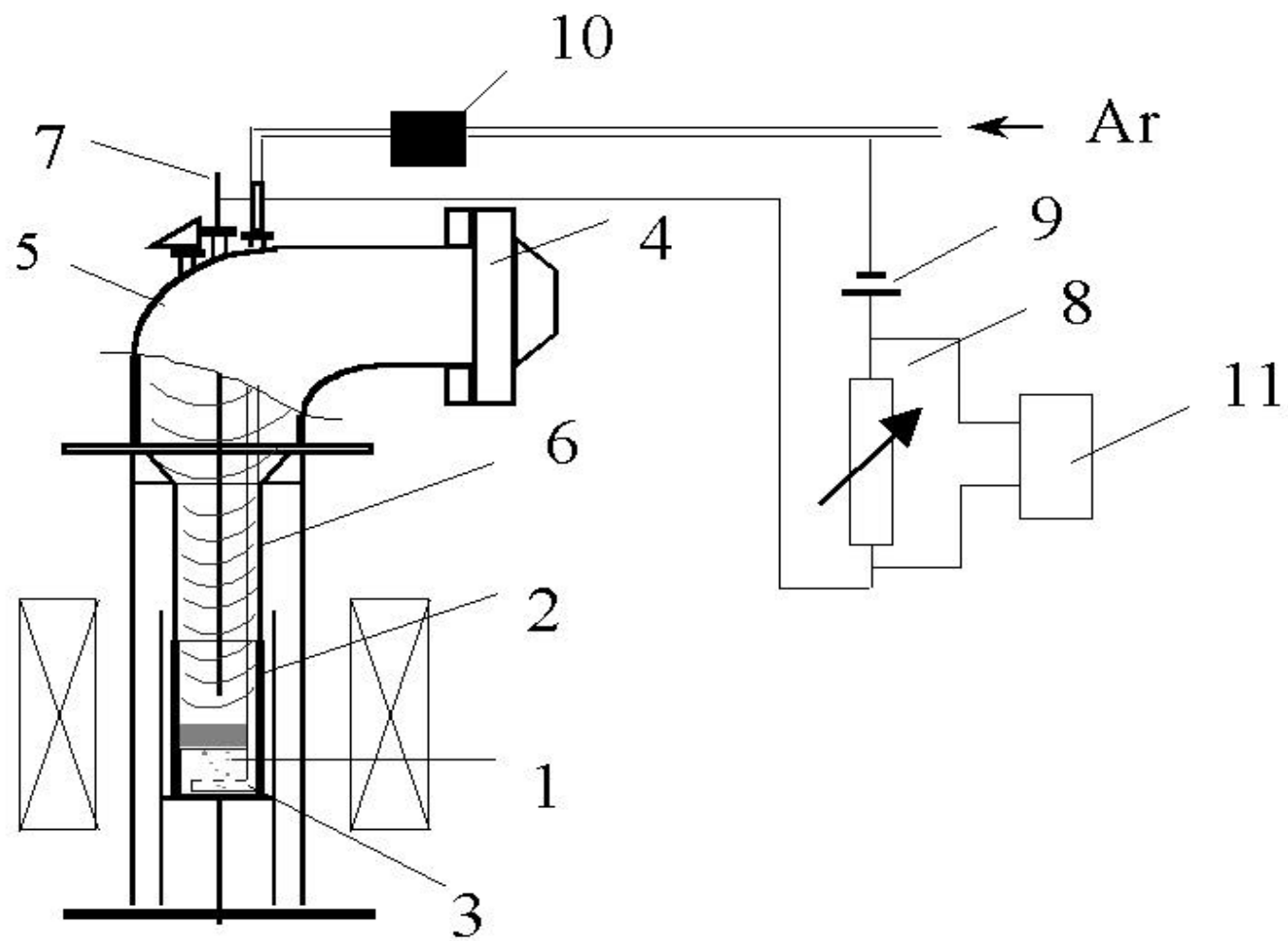12. Bhakta A.R., Khilar K.C., Langmuir, vol.7,1991,1No.8, p.827
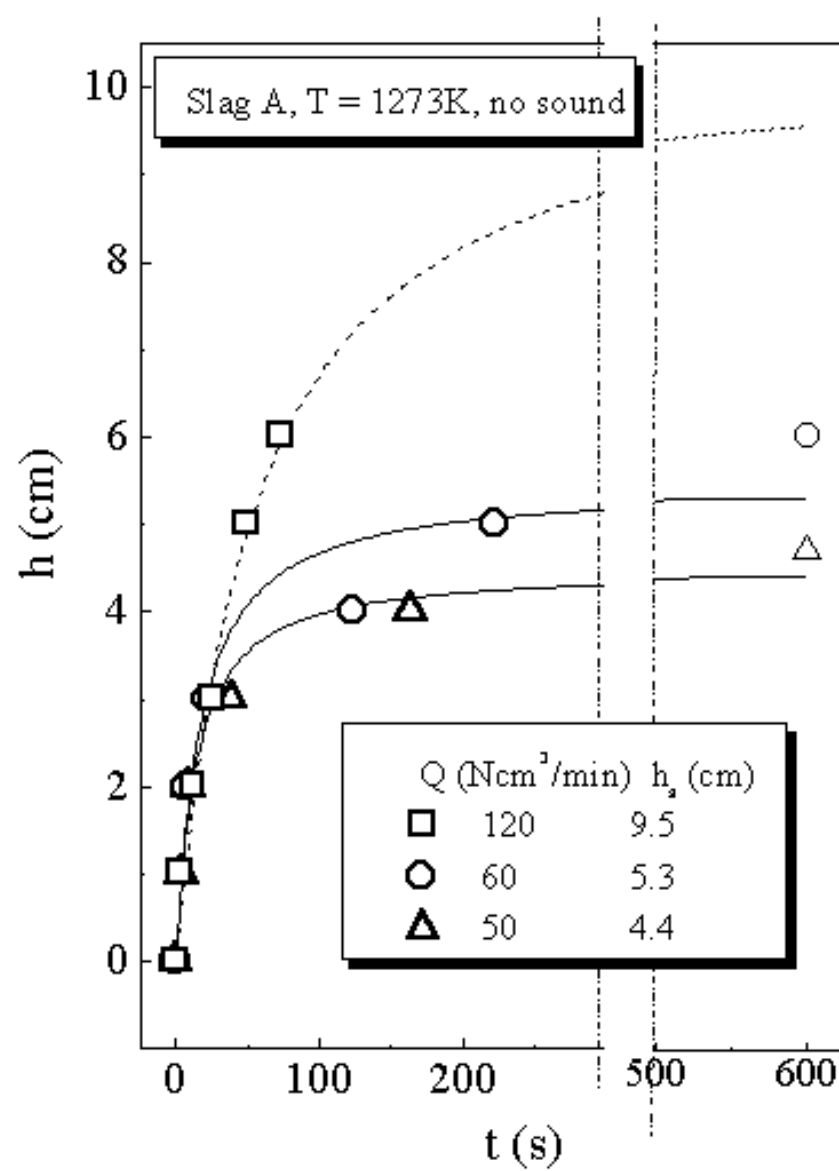
Figure 1 : Experimental set-up
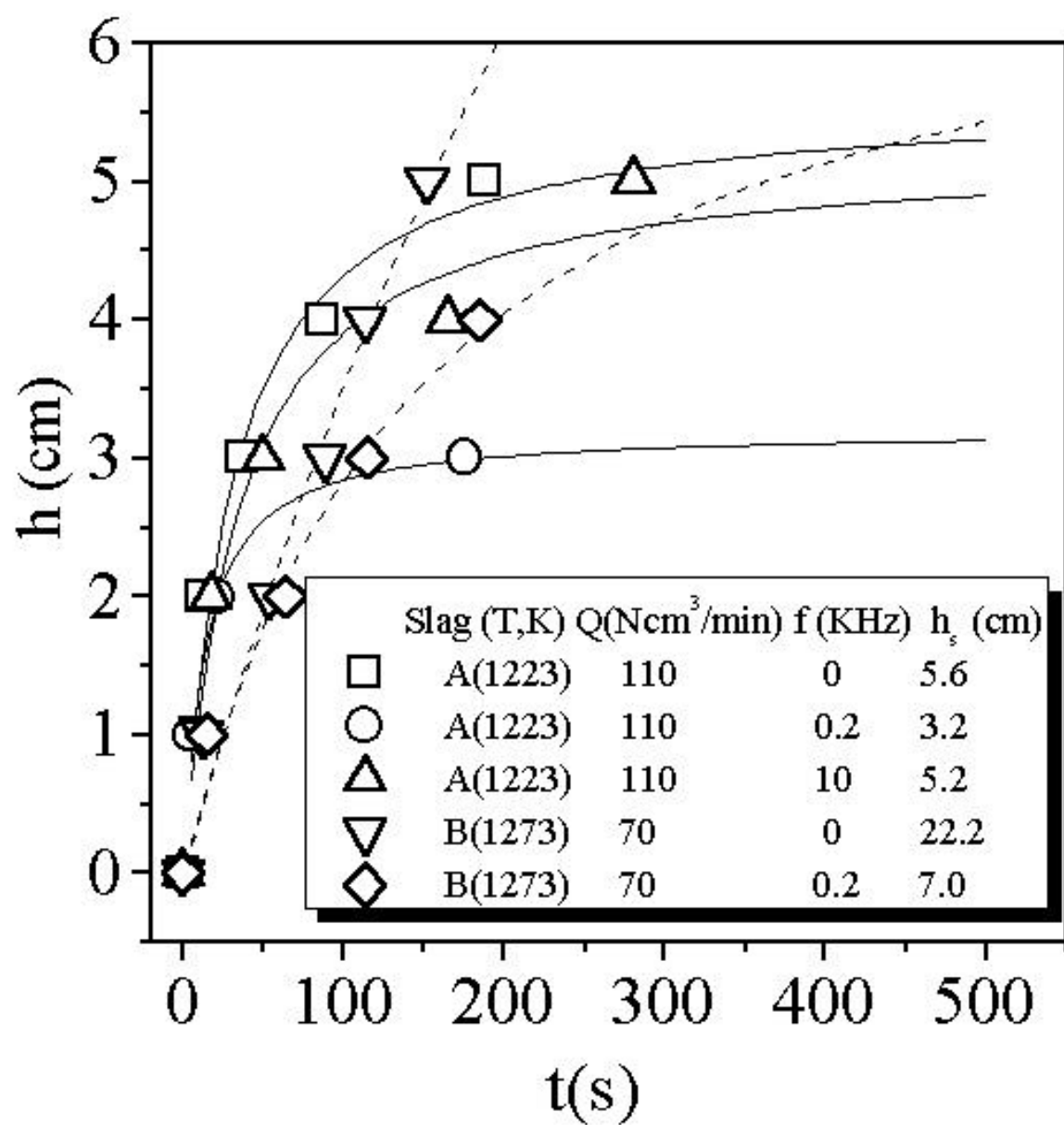
Figure 2 : Change in foam height with time.

Slag (T,K)	Q(Ncm³/min)	f (KHz)	h_s (cm)
A(1223)	110	0	5.6
A(1223)	110	0.2	3.2
A(1223)	110	10	5.2
B(1273)	70	0	22.2
B(1273)	70	0.2	7.0

Figure 3 : Change in foam height witn time.

	Gl(%)	f (Hz)	P_s (Pa)
1	85	0	0
2	90	0	0
3	85	289	2130
4	85	289	2460
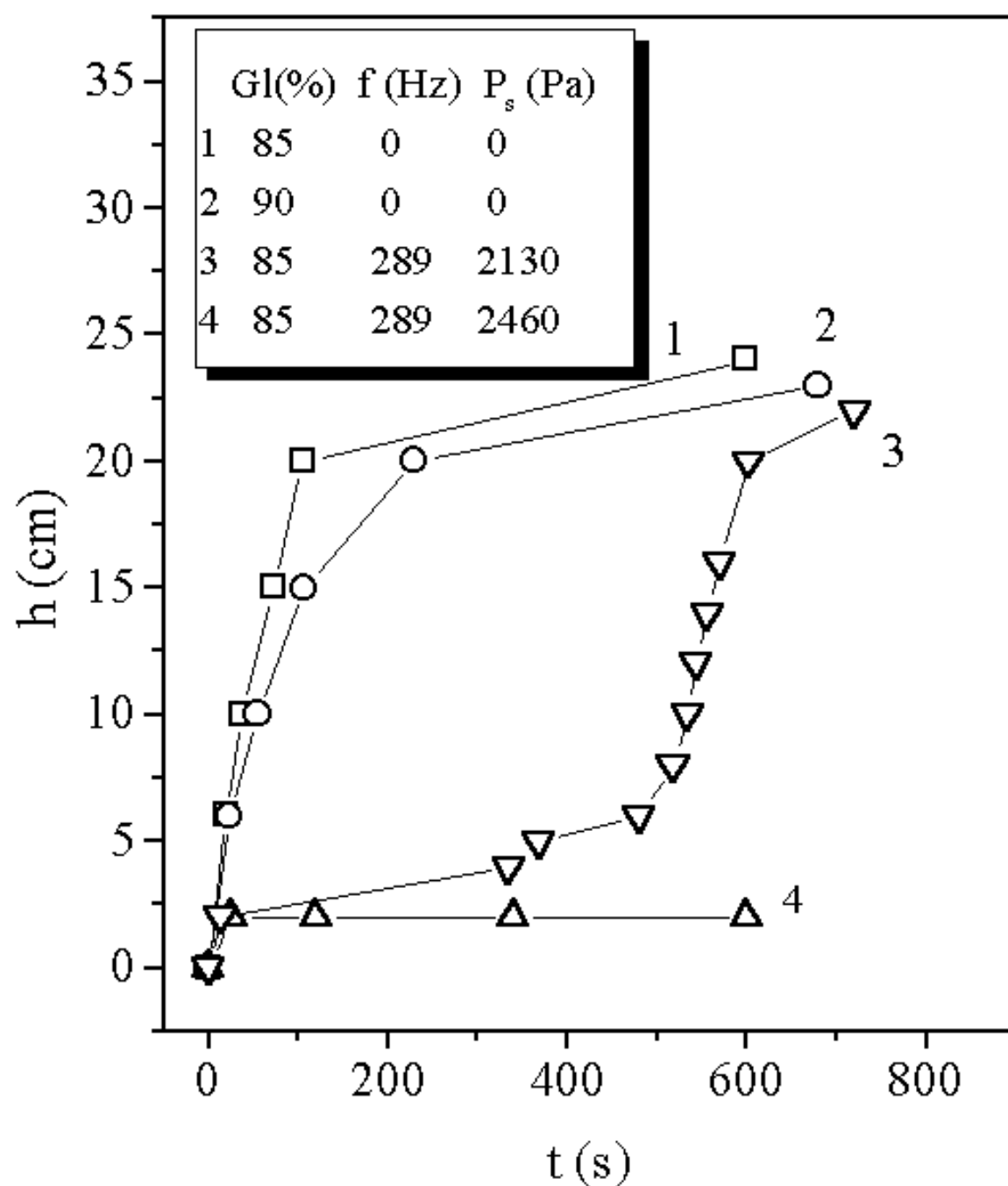
Figure 4 : Change in foam height with time.
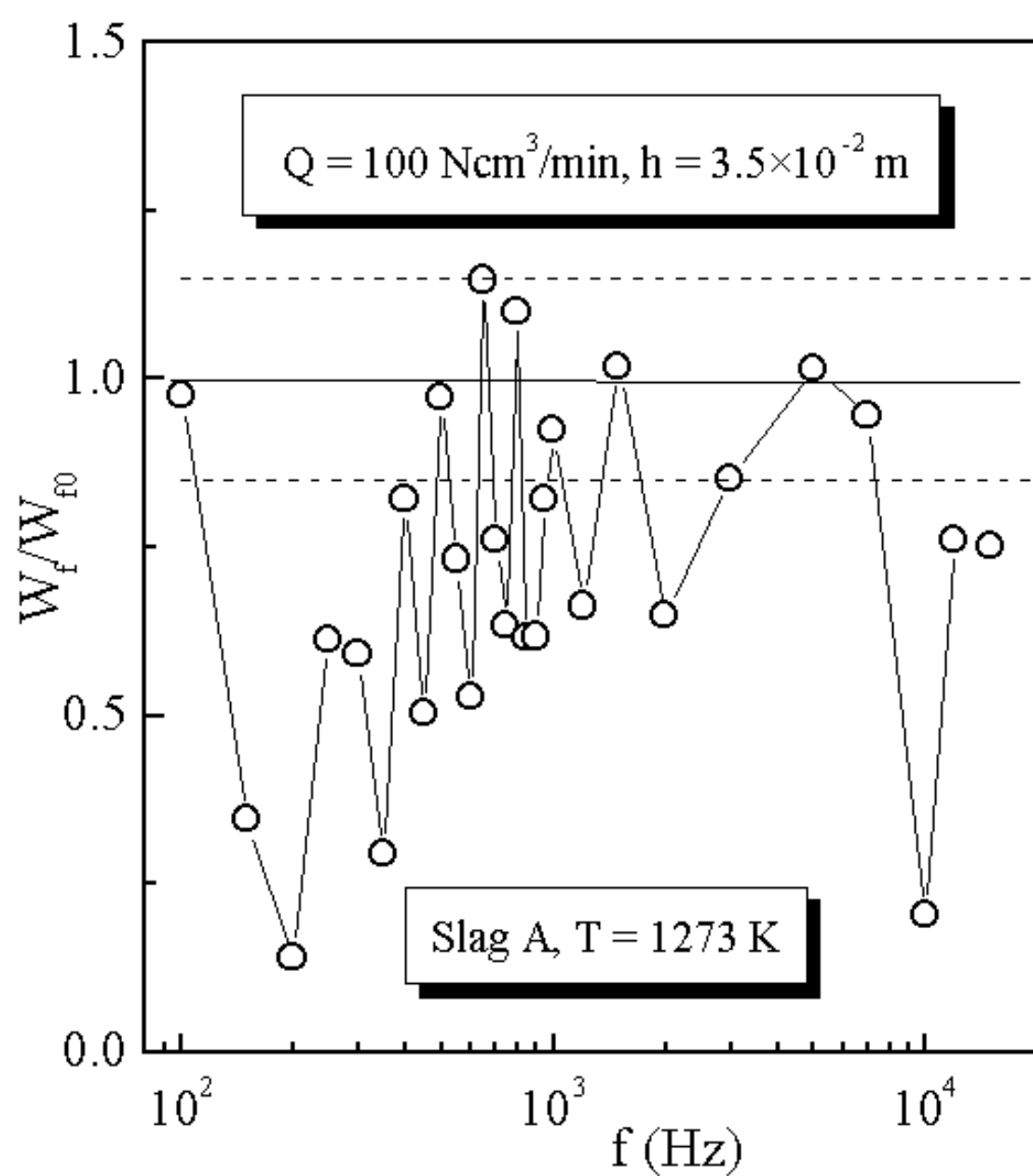
Figure 5 : Relative foaming rate plotted against
sound frequency.
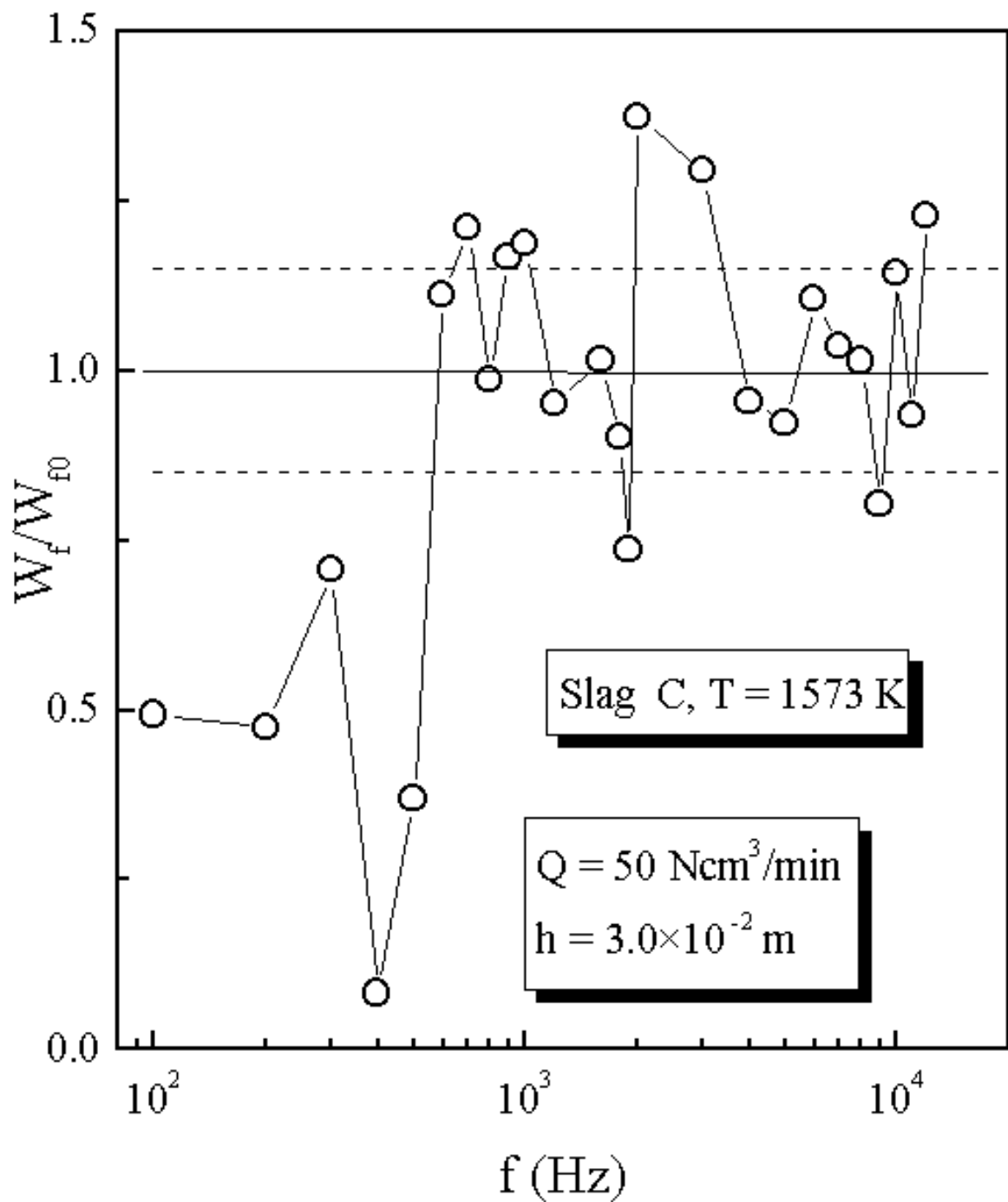
Figure 6 : Relative foaming rate plotted against
sound frequency.
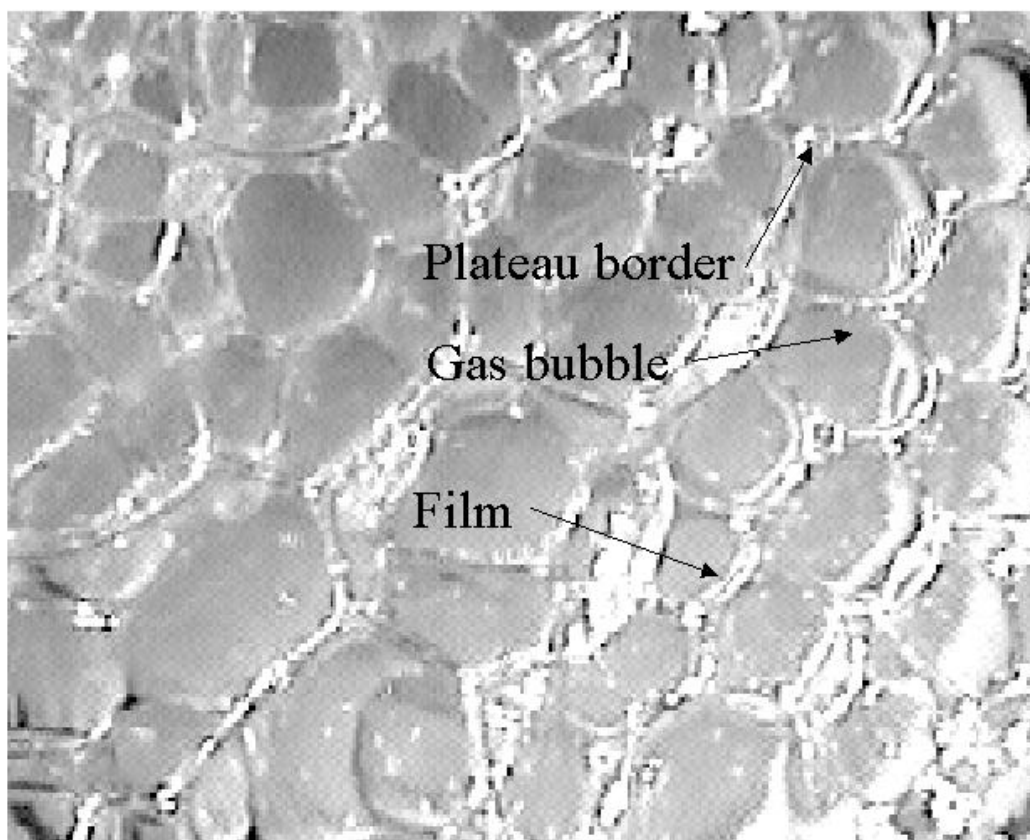
Figure 7 : Foam structure
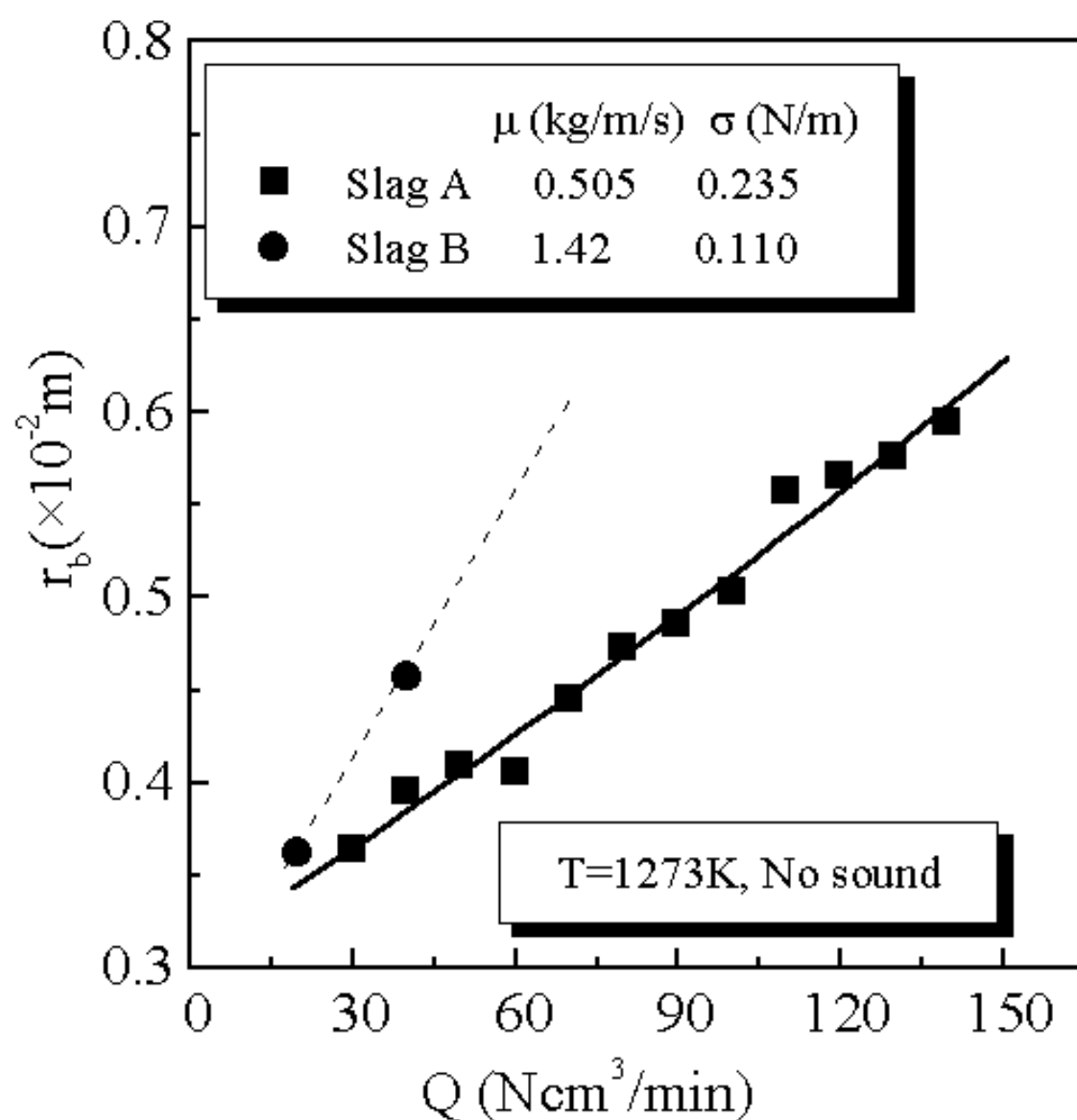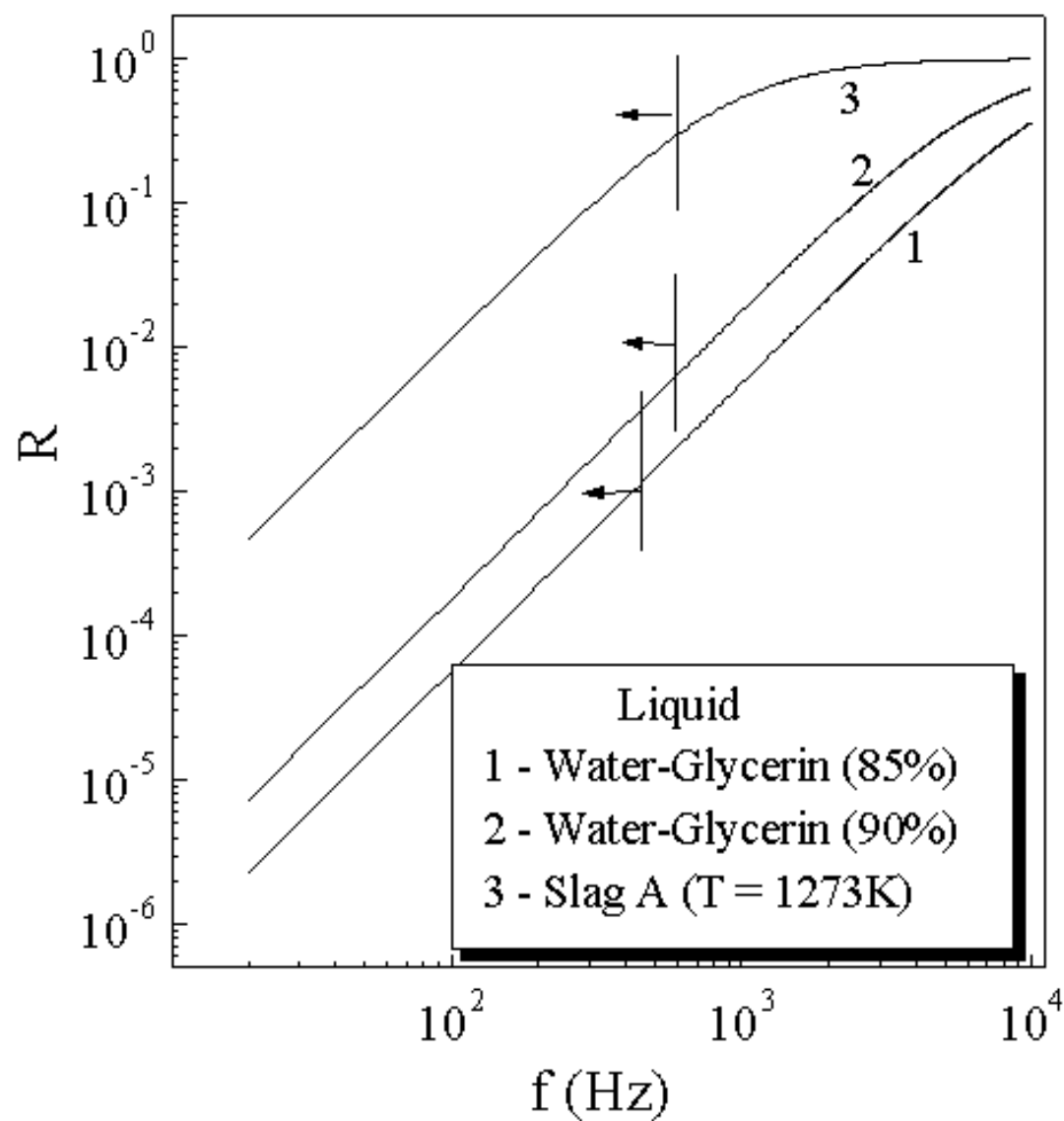
Figure 8 : Effect of gas flow rate on bubble radius.

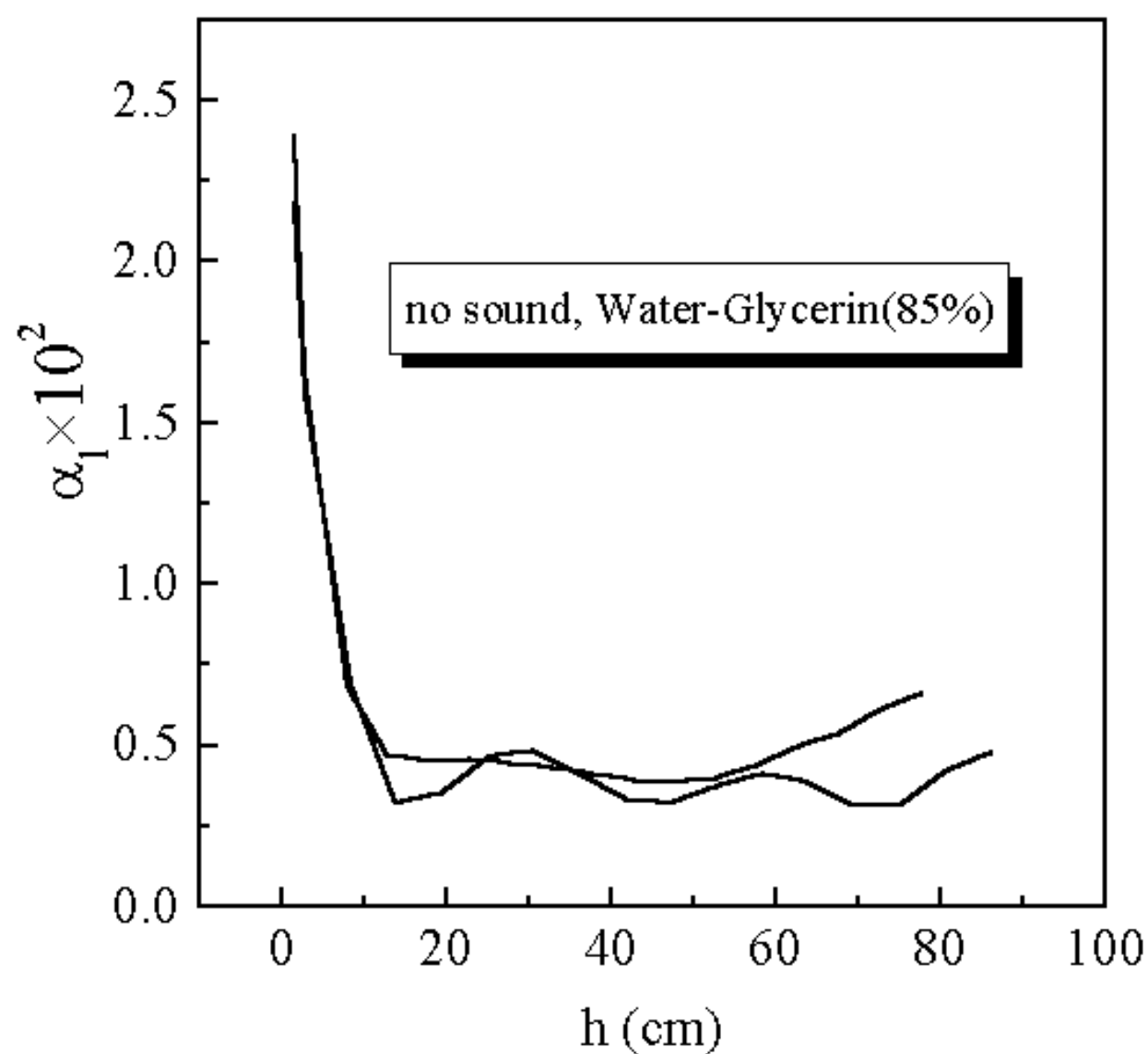Figure 9 : Reflection coefficient plotted against sound frequency.

Figure 10 : Change in foam liquid fraction with distance from liquid surface.
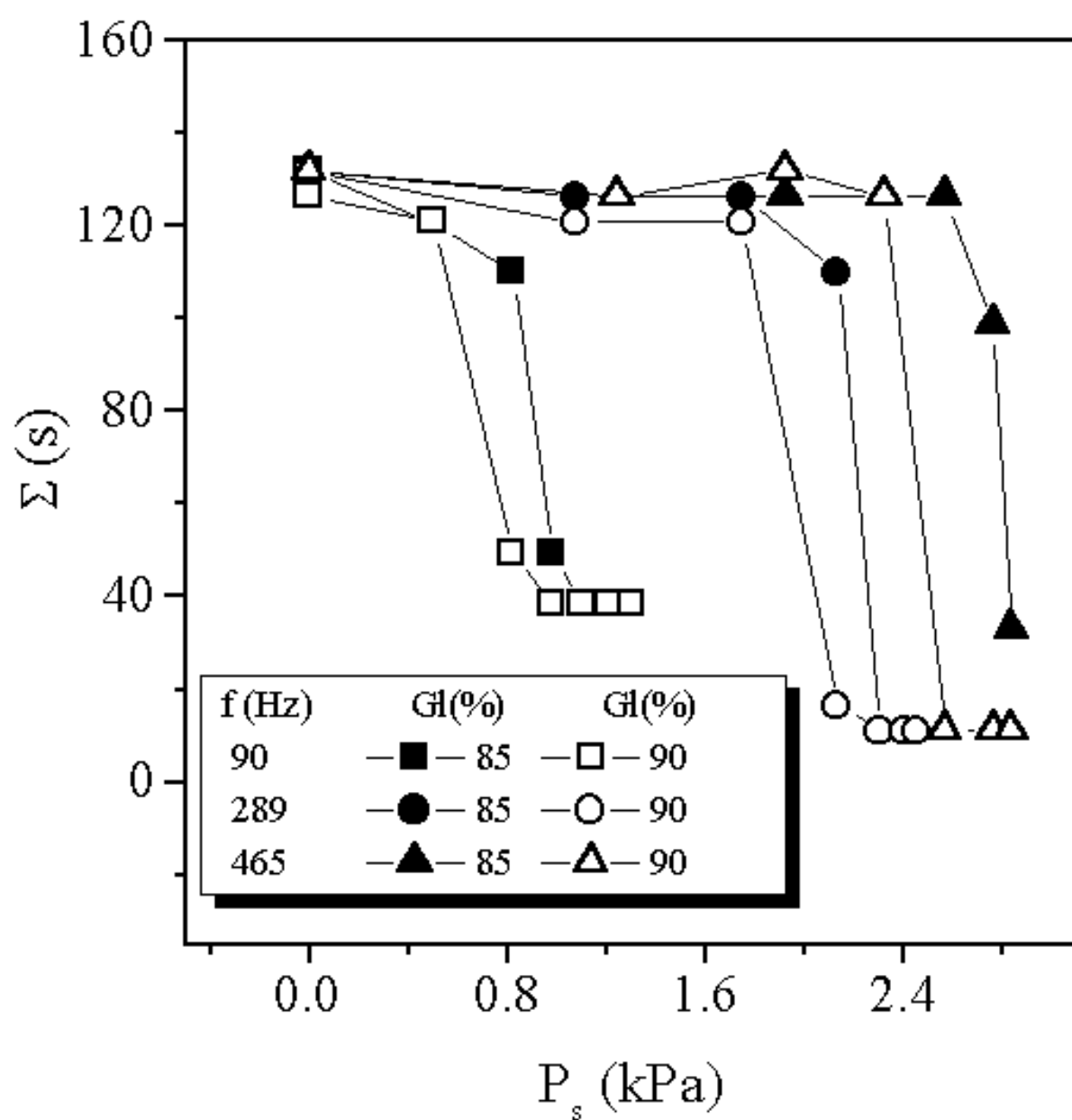
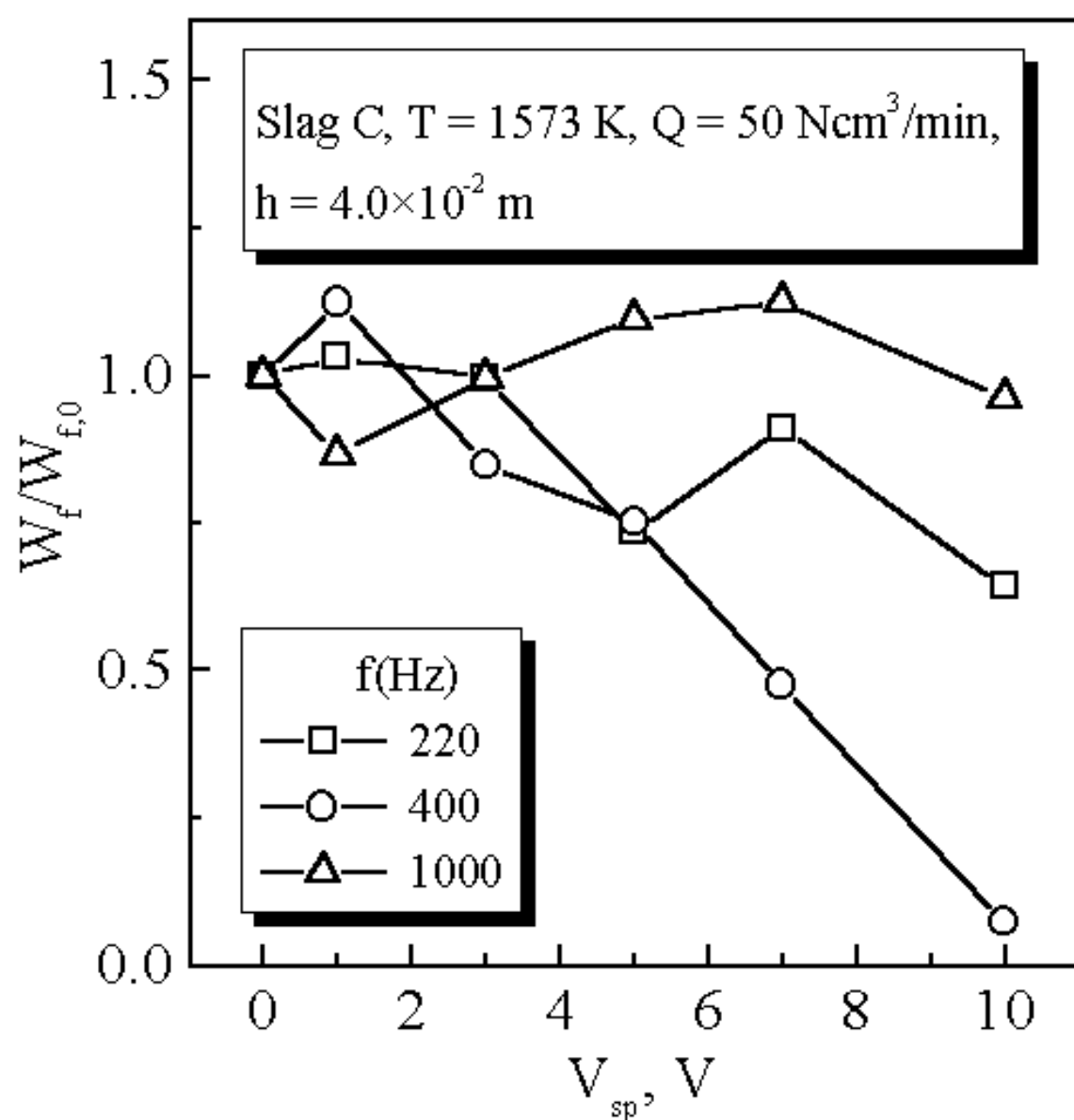Figure 11 : Parameter Σ plotted against sound pressure.

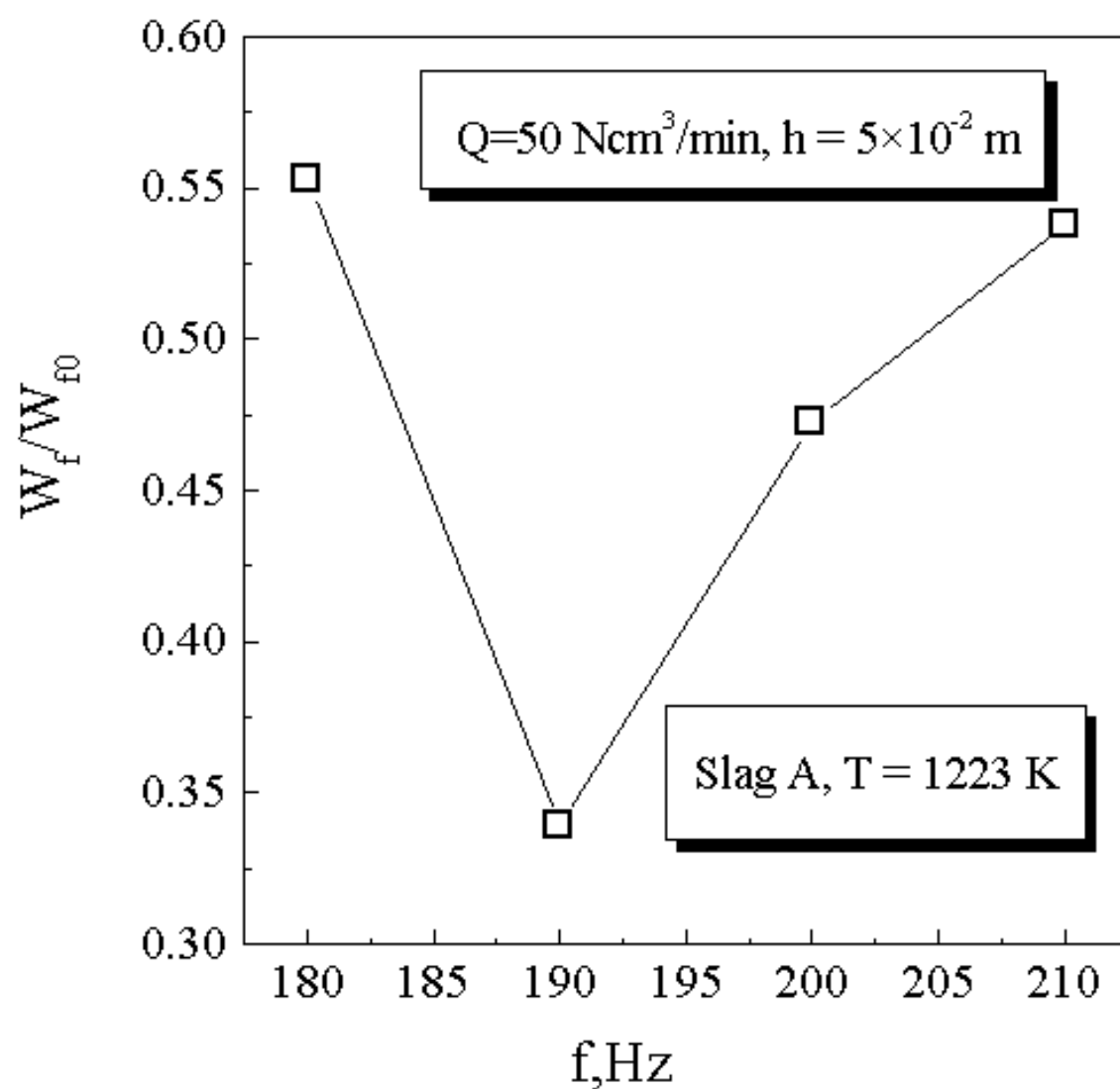Figure 12 : Relative foaming rate plotted against speaker voltage.

Figure 13 : Relative foaming rate plotted against sound frequency.

Table I: Physical properties of liquids

Property / Liquid	Viscosity (Pa·s)	Surface tension (N/m)	Density (kg/m³)
Slag A : 36.3%BaO-63.7%B_2O_3	0.977/0.505	0.239/0.235	3265/3231
Slag B : 17.8%BaO-82.2%B_2O_3	2.584/1.17	N.d./0.116	2454/2432
Slag C : 40%CaO-40%SiO_2-20%FeO	0.73*	0.4*	3400*
Water - SDBS	0.001	0.072	1000
15%Water-85%Glycerin-SDBS	0.102	0.0665	1222
10%Water-90%Glycerin-SDBS	0.225	0.066	1235

N.d. no available data. Temperature 1223 K/1273 K, * - 1573 K

Table II: Gas residence time in foam, Σ depending on sound frequency

N	f (Hz)	P_s (Pa)	Σ (s) Glycerin(85%)	Glycerin(90%)	Water
1	0	0	131.9	126.4	82.4
2	89~90	1303.8	38.5	37.5	44.0 *N*
3	284~287	2455.9	11.0 *N,D*	10.0 *N*	38.5 *N,D*
4	467~474	2833.1	33.0 *N,D*	11.0 *N,D*	38.5 *N,D*
5	653~660	1254.6	140.1	8.2 *N*	38.5 *N,D*
8	1210~1224	1020.9	144.2	109.9	49.5 *N,D*
9	10000	-	76.9	109.9	82.5

Table III: Critical frequencies for various liquids

Liquid	Critical frequency f^*, Hz a_l=0.025	a_l=0.003
Water-glycerin solution (85%)	149	1242
Water-glycerin solution (90%)	324	2700
Slag A (T = 1273 K)	378	3156