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Studies in mass transfer in a pulsed bubble column

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Abstract

Experimental work conducted establishes the influence of pulsations on mass transfer. Effects of amplitudes and frequencies of pulsations at three liquid bed heights on the rate of mass transfer are analysed. Pulsations above the frequencies 200 c/s show a maximum forty per cent improvement in the mass transfer rate. The vibrational acceleration, provided to the system, has no effect on the absorption rate. The earlier work reported in the literature on this subject is discussed briefly.

Key words: Pulsed bubble column, mass transfer, amplitude, frequency, bed height, vibrational acceleration.

1. Introduction

When a mass of liquid is subjected to oscillate with an up and down motion, a small bubble present in the liquid will move down under certain conditions against the

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buoyance forces. At high vibrational intensities, gas bubbles migrate alternately from top of the column to the bottom and then return to the top. The overall effect is violent and rapid mixing of the gas takes place with the liquid and suspended solids, if present. This phenomenon provides a good method to contact gas-liquid-solid systems. This technique could be used to promote difficult gas absorption either in the presence or absence of suspended catalysts, or to clean or extract solids to produce emulsions. It is a well-established fact that the application of sonic vibrations to the bubble bed gas absorbers results in very remarkable improvement in mass transfer rates.

2. Literature survey

Buchanan *et al*[1] give a detailed description of various processes encountered in a liquid column when subjected to vibrations at various frequencies. They studied the phenomena of cyclic migration of bubbles, in vibrating liquid columns. They performed experiments with varying liquid columns 5 to 15 cm in diameter and 15 to 100 cm high which were vibrated in the amplitude range 0·05 to 0·1 cm and frequencies 1,200 to 2,900 c/s. It was found that there is a certain critical frequency called critical frequency, below which the cyclic bubble migration will not occur. If all other variables are kept constant, this critical frequency is a fixed reproducible quantity. They used the theory of Bjerknes[2] to calculate the downward Bjerknes force on gas bubbles in a column, vibrated at frequencies much lower than the resonant pulsation frequency for individual bubbles. Their calculations predict the minimum frequency required for the cyclic migration to occur. Lighthill[3] was able to show that at the above critical frequency, the oscillations behave like ordinary shear waves whereas below the frequency a quasi-steady-state condition exists in the laminar boundary layer.

Houghton[4] introduced a hydrodynamic model, based on a nonlinear Langevin equation, to demonstrate that it is theoretically possible to arrest the directional motion of particles by applying a sinusoidal velocity to the continuous phase in which they are suspended. The nonlinear equation developed by Houghton[4] gives a general behaviour of free particles in sinusoidal velocity field. His analysis shows that a linear drag law, in which the frictional forces is directly proportional to the relative particle-fluid velocity (Stokes Law), does not result in a stable particle motion. Baird[5,6] reported measurements and theory concerning the stationary, resonant single bubbles and bubble dispersions which are formed in a vertically vibrating liquid column at frequencies 40–1050 c/s using viscous liquids. Viscous damping played an important role in his experiments. The work of Jameson and Davidson[7,8] is concerned with the behaviour of a small spherical gas bubble in a column which vibrates with a simple harmonic motion along the vertical axis under the conditions such that the bubble undergoes no net displacement in the liquid. Their theory for the motion of a single bubble is based on the assumption of potential flow within the liquid around the bubbles. The most important deduction in their work is that they found out the frequency necessary to stabilize the bubble which is similar to that derived by Buchanan *et al*[1]. The motion of particles in a vibrating liquid was also considered by Andrade[9].

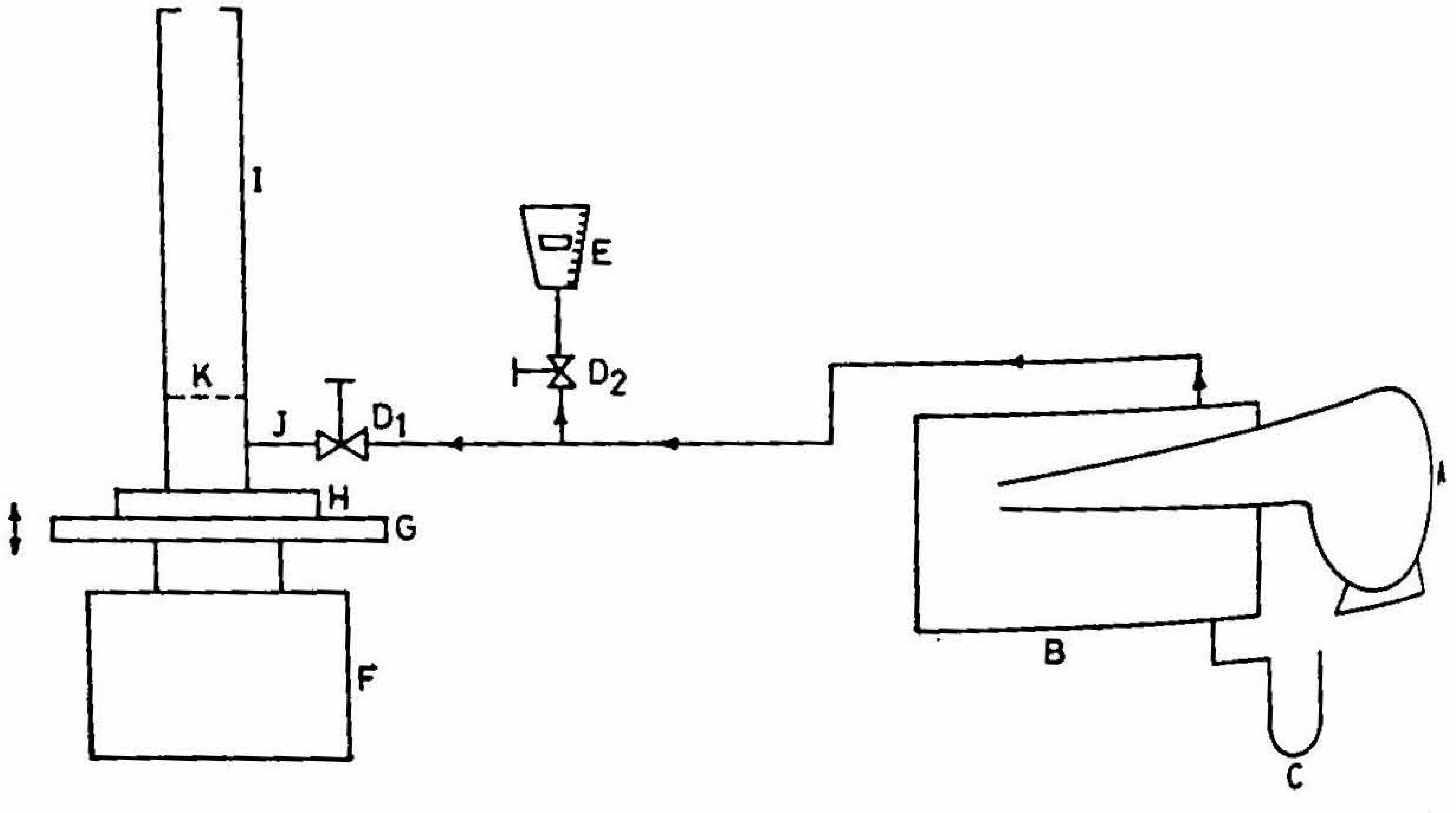
Harbum and Houghton[10,11] give extensive information on absorption rates as a function of frequency, bed height, temperature and sonic power. They analysed the mechanism by which sonic vibrations, in the frequency range 20–2000 c/s and at a total pressure 0·093 atm., influence mass transfer in terms of bed density and bubble size. They found that the rate of absorption of CO_2 in water can be increased by as much as 50% when certain vibrational frequencies are used to excite the bubble bed. Note has not been taken of the possible variation of porosity with position in the bed, but only the overall average porosity was measured. The greatest effect is at about 75 c/s. The fact that the absorption rate shows peaks at certain frequencies together with a relatively small amount of power introduced into the liquid (less than 4W, at all frequencies) indicates that the phenomena are due to resonance effects. In most cases, the peaks in absorption rate occur when the power input to the liquid decreases or is relatively constant. In their experiments they inferred that the maximum power that could be utilised is always less than 4 W, while in the frequency range 70–2000 c/s it is less than 1 W. The K_La values vary linearly with total power supplied to the liquid in the range 0-1 W. Certain frequencies especially in the low sonic range (20-2000 c/s) were particularly effective to enhance K_La values. The vibrations greatly increased the interfacial area 'a' while slightly decreasing the film coefficient 'k_La'. The peak values of k_La observed in their work at various frequencies do not correspond exclusively to the peaks in amplitude or power, and hence may be attributed to 'resonance effects' associated with the frequency alone. Resonance effects are also indicated by the fact that the amplitude of forcing vibration is somewhat dependent upon whether bubbles are present in liquid or not. These effects are more pronounced at the smallest bed heights. It was observed that with decreased bed height, K_La increases, but, however, occurs at a higher frequency. Buchanan *et al*[12] also conducted similar studies as those of Harbaum and Houghton[10,11] using the absorption of oxygen in aqueous solutions of sodium sulfite. The work of Bretsznajder and Pasiuk[13] resembles the studies of Harbaum and Houghton. Their work shows that the greatest concentration absorbed in the period of bubbling of CO_2 column in water is associated with absorption on the free surface of the water in the column. The maximum specific absorptions on that surface are a result of resonance of the liquid filling the column. The resonances are accompanied by energetic disintegration of the upper layer of the liquid and the capture of the gas bubbles from the space above the liquid. Their results are in good agreement with those of Harbaum and Houghton[10,11].

Absorption of oxygen in solution of sodium sulfite is not only an extremely important industrial process but also forms an excellent system for carrying out an experimental investigation for studying the effects of various parameters that influence dissolution of limitedly soluble gases in a pulsed bubble column[14-16]. The rate of dissolution of oxygen ramains more or less unaffected by even large changes in the concentration of sodium sulfite solution[14–16]. In the present investigation it is intended to use a batch experimental set-up for studying the effects of amplitude, frequency, and bed height on the absorption of oxygen in the aqueous solution of sodium sulfite.

3. Experimental set-up

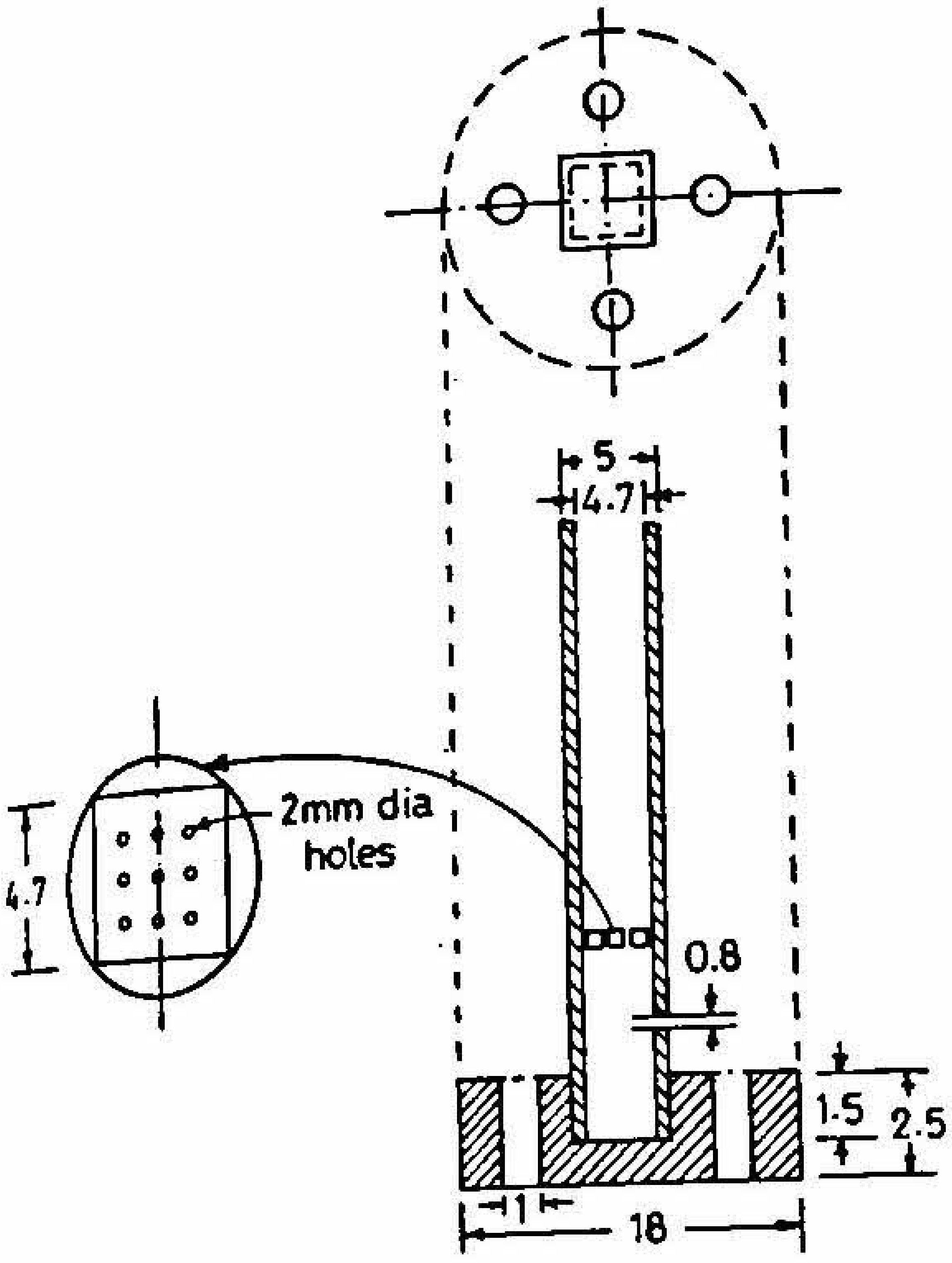
The schematic diagram of the experimental set-up used in the present investigation is shown in fig. 1. A square section column is chosen since it offers some advantages over cylindrical columns such as better space utilization and eliminates lens effect for any photographic study[17]. A square perspex column (fig. 2) is mounted on an 18·5 cm diameter and 2·5 cm thick circular disc (H). This disc is mounted on a vertically vibrating platform (G), Type VP-4 (fig. 3), which vibrates electrodynamically in the frequency range 1–2000 c/s. The specifications of this vibrator are indicated in Table I.

The column is provided with an air inlet (J) of 0·75 cm dia situated at 2·5 cm from the base. A portable wolf air blower (A) is used for constant supply of air. In order to have stable air supply the blower is connected to an air stabilizer (B) through which air is drawn. Air is introduced centrally into the column through a 0·3-cm thick, 0·2-cm diameter perforated bubble plate (K). Globe valves (D_1, D_2) are employed



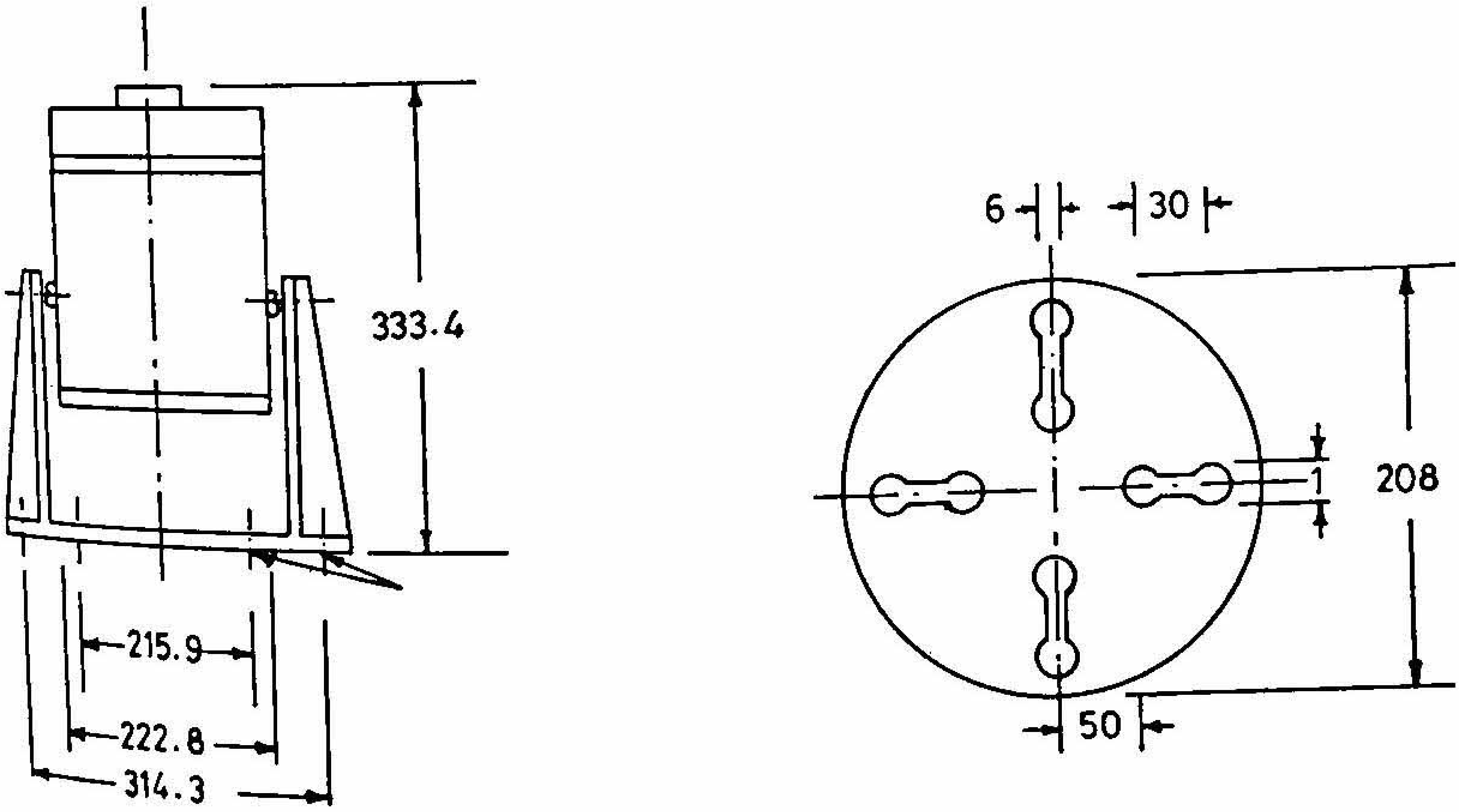
A	Blower	E	Rotameter	I	Perspex column
B	Stabilizer drum	F	Vibrator	J	Air inlet
C	Monometer	G	Vibrating platform	K	Perforated plate
D_1, D_2	Valve	H	Base of column		

FIG. 1. Experimental set-up.



Dimensions are in cm

Fig. 2. Details of perspex column.



(a) VIBRATOR

(b) VIBRATING PLATE

Dimensions are in mm

Fig. 3. Details of vibrator.

Table I
Specifications of the vibrator

Vector force	11 kg
Frequency range	1·5–10,000 c/s
Table diameter	6·8 cm
Moving system weight	0·43 kg
Stroke	1 cm
Method of cooling	Natural

Table II
Range of parameters studied

Parameter	Range
Frequency	0–2000 Hz
Amplitude	0–0·75 cm
Bed height	5–15 cm

to control the air flow rate which is measured by a rotameter (E). The range of parameters studied at the constant air flow rate, in the present investigation, are given in Table II.

4. Procedure

The air blower was first started and the air flow rate was set to the required rate. The vibrator was then switched at the predetermined frequency and amplitude. Freshly prepared sodium sulfite solution of concentration 0·02 M, mixed with copper sulfate catalyst of 10^{-6}M concentration, was quickly introduced into the column mounted on the vibrator, and the stop watch was simultaneously started. During the experimental work, the temperature of the bed and the expansion attained by the bed were noted. The vibrations and the air flow were both arrested at the end of the required contact time.

Two samples were collected, one initially and the other at the end of experiment. The sample from the column was siphoned out into a conical flask keeping the collection end under the layer of liquid paraffin oil to prevent further oxidation of solution by the atmospheric oxygen. The unoxidized sulfite content was determined by the iodometric method. All the experiments were carried out at 36° C, at constant air flow rate of 1875 cc/min and for a contact time of 5 minutes, varying the amplitude, frequency and bed height.

5. Results and discussion

5.1 *Effect of amplitude*

The experimental results on the effect of amplitude of pulsations on the mass transfer rate are presented in Table III and are graphically represented in figs. 4 and 5. For the curve A in fig. 4, corresponding to frequencies 5 c/s and 10 c/s, there is an initial increase in mass transfer rate with increase in amplitude from 0·125 to 0·25 cm

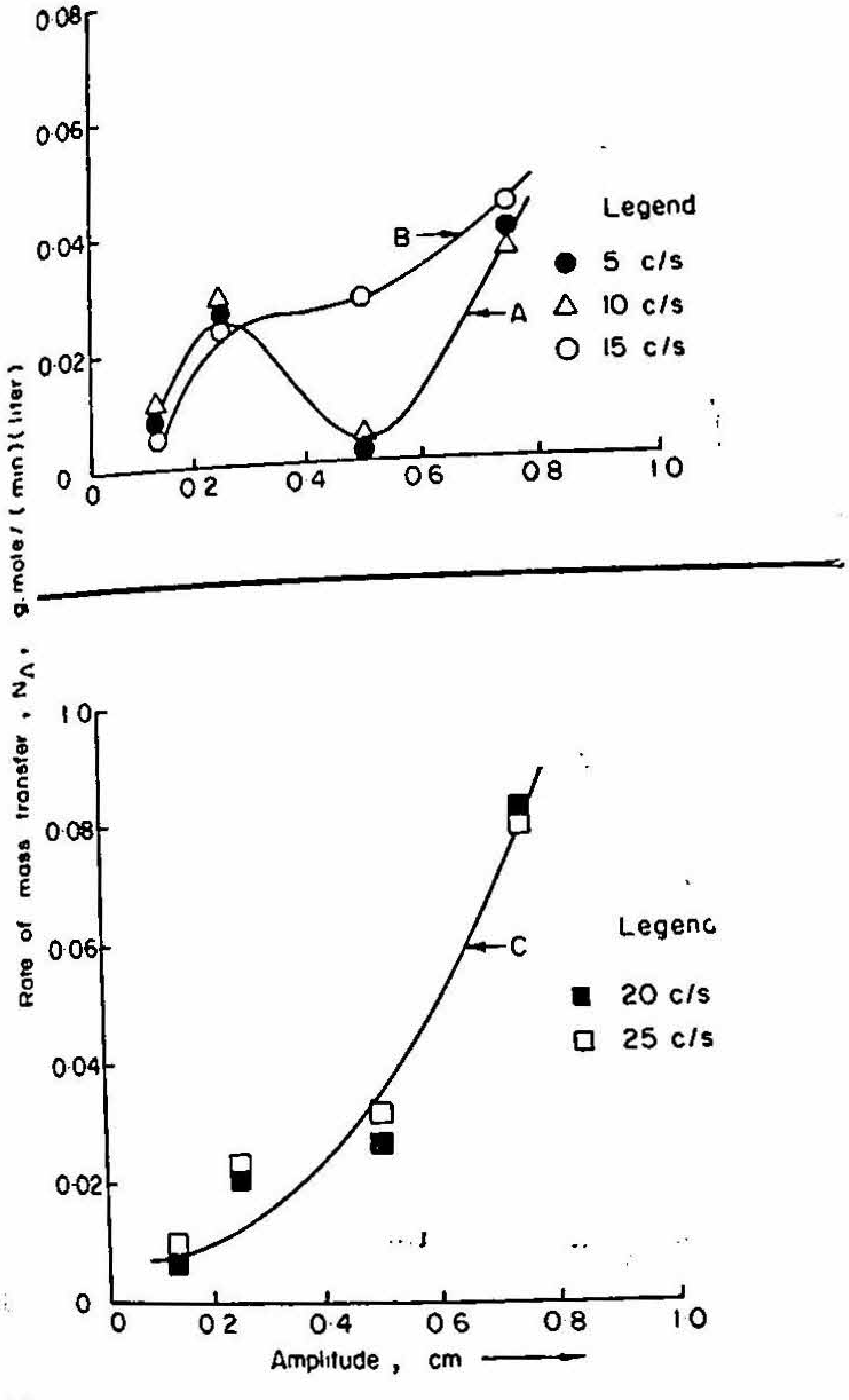


FIG. 4. Effect of amplitude on mass transfer rate at a bed height of 9·0 cm.

and a sudden decrease is noticed with a further increase of the amplitude to 0·5 cm. But a gradual enhancement in mass transfer rate is observed with further increase in the amplitude. When the frequencies of vibrations are in 15–25 c/s range, a steady enhancement in mass transfer rate is noticed (Curves B and C in fig. 4) for all the amplitudes studied.

The increase in mass transfer with the increase in amplitude above the frequencies 15 c/s is understandable because more energy is imparted to the system for creation of ample turbulence in the liquid phase thus creating larger interfacial area for mass transfer. Also, better bubble size distribution is observed, visually, throughout the

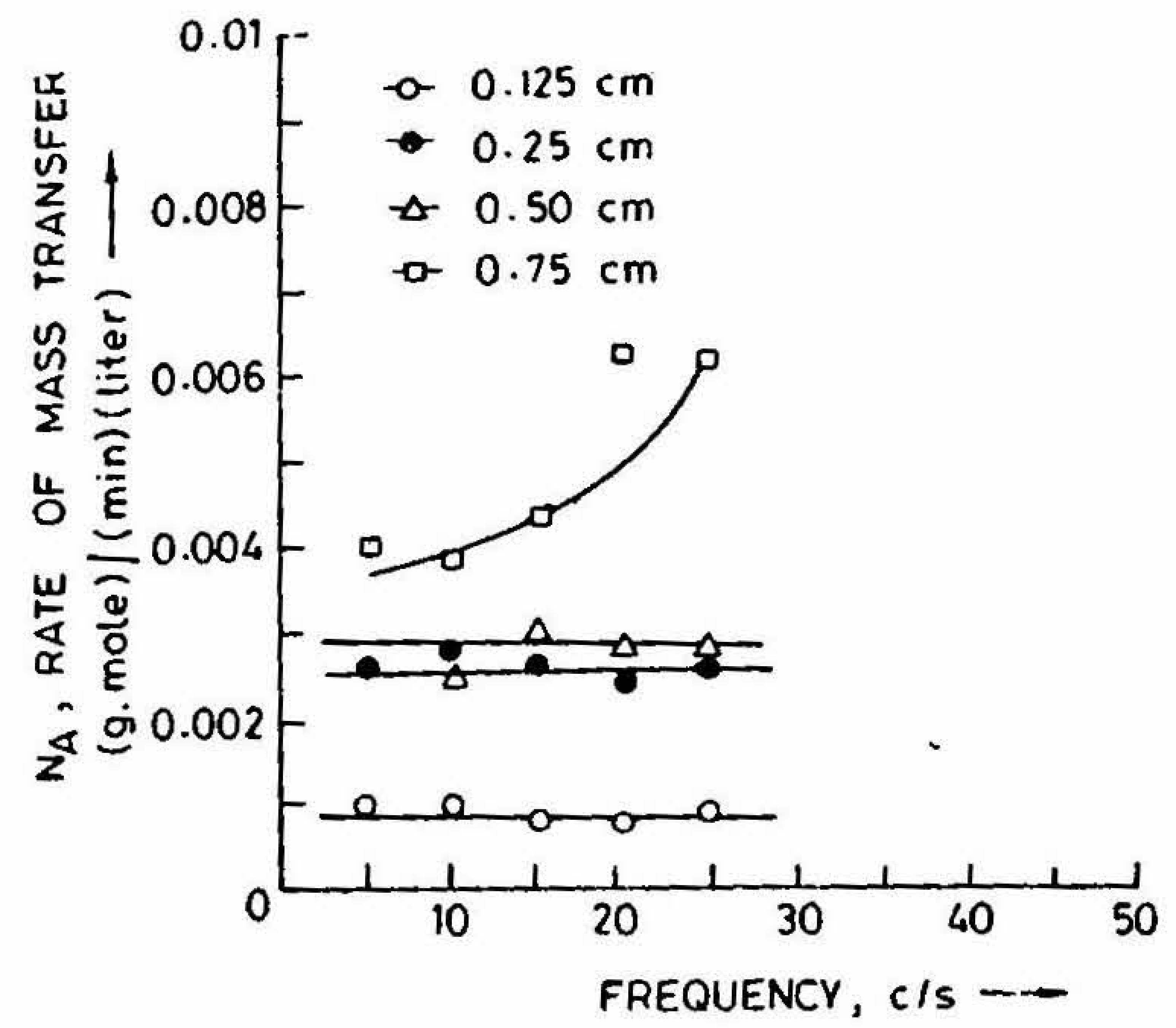


FIG. 5. Effect of frequency on mass transfer rate at a bed height of 9·0 cm.

column at all the amplitudes in the frequency range 15–25 c/s. At 0·75 cm amplitude, the phenomena of froathing and excessive splashing of solution are also observed.

It is quite difficult with the present data to explain systematically the mechanism of absorption in this amplitude range, unless an extensive study on the determination of interfacial area and hold up is conducted. However, there could be two possibilities for the uneven behaviour of rate of mass transfer within the amplitude range 0·125–0·5 cm. Firstly, dripping of liquid from the perforations of the gas distributor, secondly the bubbles coalesced to form larger bubbles thus forming stationary slugs which continuously issued out smaller bubbles. Due to these factors there was a net decrease in the interfacial area. Both these factors might have contributed to lower the mass transfer rate within the amplitude range 0·125 to 0·5 cm. At higher amplitudes, say 0·75 cm, no such slug formation was observed and agitation became more vigorous and effective. Due to these reasons, a sharp increase in mass transfer rate was observed.

5.2 *Effect of frequency*

It can be observed from figs. 4 and 5 that variation of frequency of pulsation has hardly any effect on mass transfer rate for lower amplitude values (0·125 to 0·5 cm) but an increase in mass transfer rate can be observed with increasing frequency of pulsation by increasing the amplitude to 0·75 cm. This is understandable since at constant amplitude a higher frequency of pulsation means higher power input into the system.

Table III

Effect of amplitudes on the mass transfer rate for various constant frequencies

Frequency (c/s)	5	10	15	20	25
Amplitude (c)	N	N_A	N_A	N_A	N_A
0·125	0·0098	0·00952	0·00732	0·00697	0·0083
0·250	0·02552	0·02710	0·02530	0·02255	0·0241
0·500	0·00061	0·002402	0·0287	0·0269	0·0269
0·750	0·0391	0·03690	0·0424	0·062	0·061

The results of experiments on the studies of the effect of frequency of pulsation in a higher range (200–2000 c/s) on mass transfer are presented in Table IV. A typical plot of frequency *vs* mass transfer rates for 5 cm bed height is shown in fig. 6. There seems to be no definite trend of the curve in any of the similar plots. However, the oscillating nature of the effect of frequency on mass transfer rate of sodium sulfite is clearly noticeable in the curve. This sort of experimental investigation would need a large amount of data with a very small variation in the frequency in order to obtain the exact oscillating nature of these curves. Since it was not possible to obtain such a large data, as would be required for the prediction of the true nature of the curve, a few readings obtained have been joined by straight broken lines. These broken lines by no means suggest the absence of a sharp peak existing between any two points. The curve shows that whenever pulsations are introduced to the bubble bed, there is always an enhancement in the mass transfer rate, whatever may be the frequency of pulsation. The dark line parallel to the abscessa in the plot represents oxygen absorption in the case of unpulsed bubble bed which is always lower than the minimum mass transfer rate of pulsed column. The peaks in the plots represent the occurrence of the phenomena of resonance at the particular frequencies for which the amplitude is determined by the amount of thrust provided to the liquid into the column, which was kept constant for all the experimental readings represented in the curves. The nature of these curves shows that the resonance frequency, at which peak mass transfer rate is obtained, is not only a function of amplitude of pulsation but also of the bed height. For example, at the bed height of 12 cm and frequency 1800 c/s, the datum point lies at the trough of the curve, whereas at the same frequency but at a lower bed height (5 cm) the point lies on the crest of the curve.

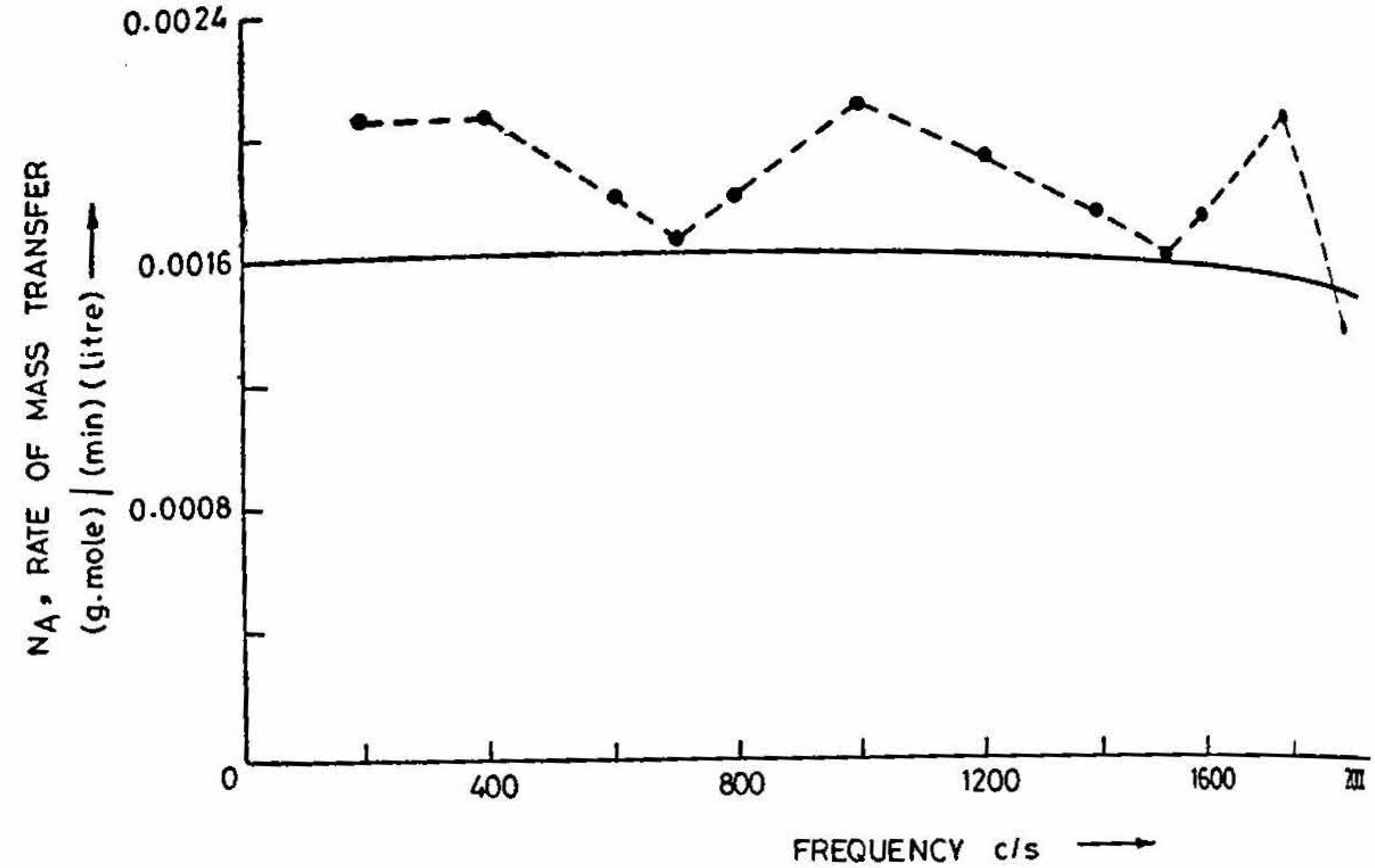


FIG. 6. Frequency *vs* mass transfer rate at a bed height of 5·0 cm (thick line is for the unpulsed system).

Table IV
Effect of frequency on the mass transfer rate for various constant bed heights

Bed height (cm) Frequency (c/s)	5·0 N_A	9·0 N_A	12·0 N_A
***	0·001615	0·001715	0·001715
200	0·00206	0·029	0·0084
400	0·00206	...	0·0084
424	...	0·0284	...
600	0·00179	0·0246	0·00865
800	0·00179	0·0286	0·0071
1000	0·00208	0·0472	0·00624
1200	0·00192	0·0472	0·0101
1400	0·001765	0·0496	0·008275
1600	0·001775	...	0·01208
1800	0·00214	0·0410	0·00878
2000	0·001485	0·01598	0·0197

** Values for the unvibrated liquid column.

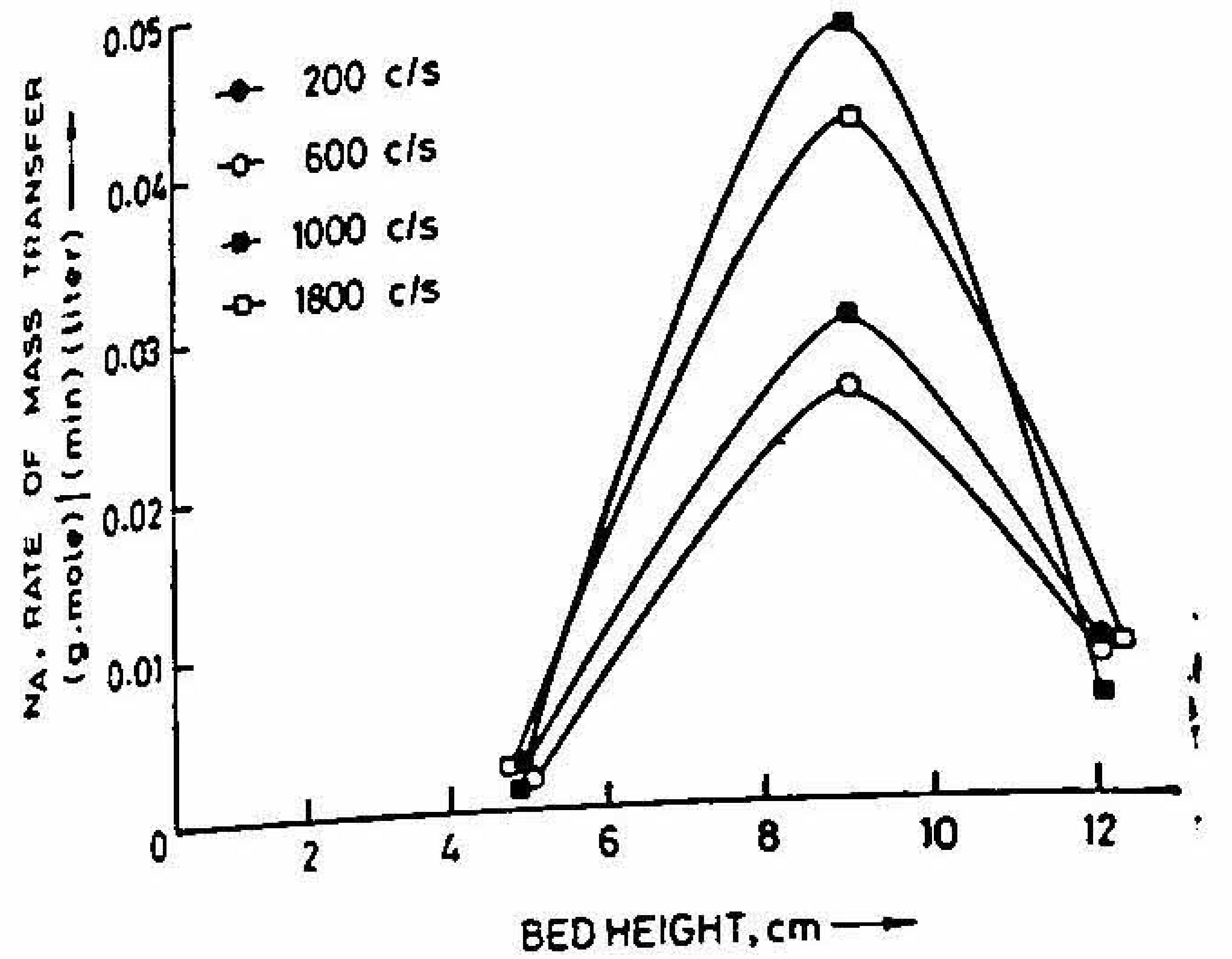


Fig. 7. Effect of bed height on mass transfer rate.

Appearance of froth and a uniform distribution of bubbles were observed at these resonance peaks. However, excessive splashing and vigorous bubble recirculation were also observed at the frequencies 1200 and 1600 c/s and at a bed height of 12 cm. The lower points in the curves were in contrast and accompanied by only a slight expansion of the bed, little froth formation and the presence of large number of tiny bubbles.

5.3 *Effect of bed height*

The results of experiments on the studies of the effect of bed height on mass transfer rate for different constant frequencies are presented in fig. 7. All these curves show an increase in the mass transfer rate with an initial increase in the bed height, reaching the maximum at a bed height of 9 cm. There is a sharp decrease in mass transfer rate with further increase of the bed height. For lower bed heights (say 5 cm) air just shoots out like a jet from the air distributor causing less intimate contact with the liquid. As the bed height is increased (say up to 9 cm), the residence time for bubbles is more under the conditions of intimate contact between the two phases. This causes an improvement in overall mass transfer rate. As the bed height is further increased the partial pressure of oxygen present in the bubble reduces thus reducing the equilibrium concentration of oxygen at the gas-liquid interphase. Another factor that causes reduction in the mass transfer rate is that with further increase in bed height the power availability per unit volume of liquid from the pulsations gets considerably reduced. The range of the bed heights studied in the present work is lower than the ones reported in the literature[10-12] (above 15 cm) and hence it has not been possible to compare the effect of bed height on the mass transfer rate.

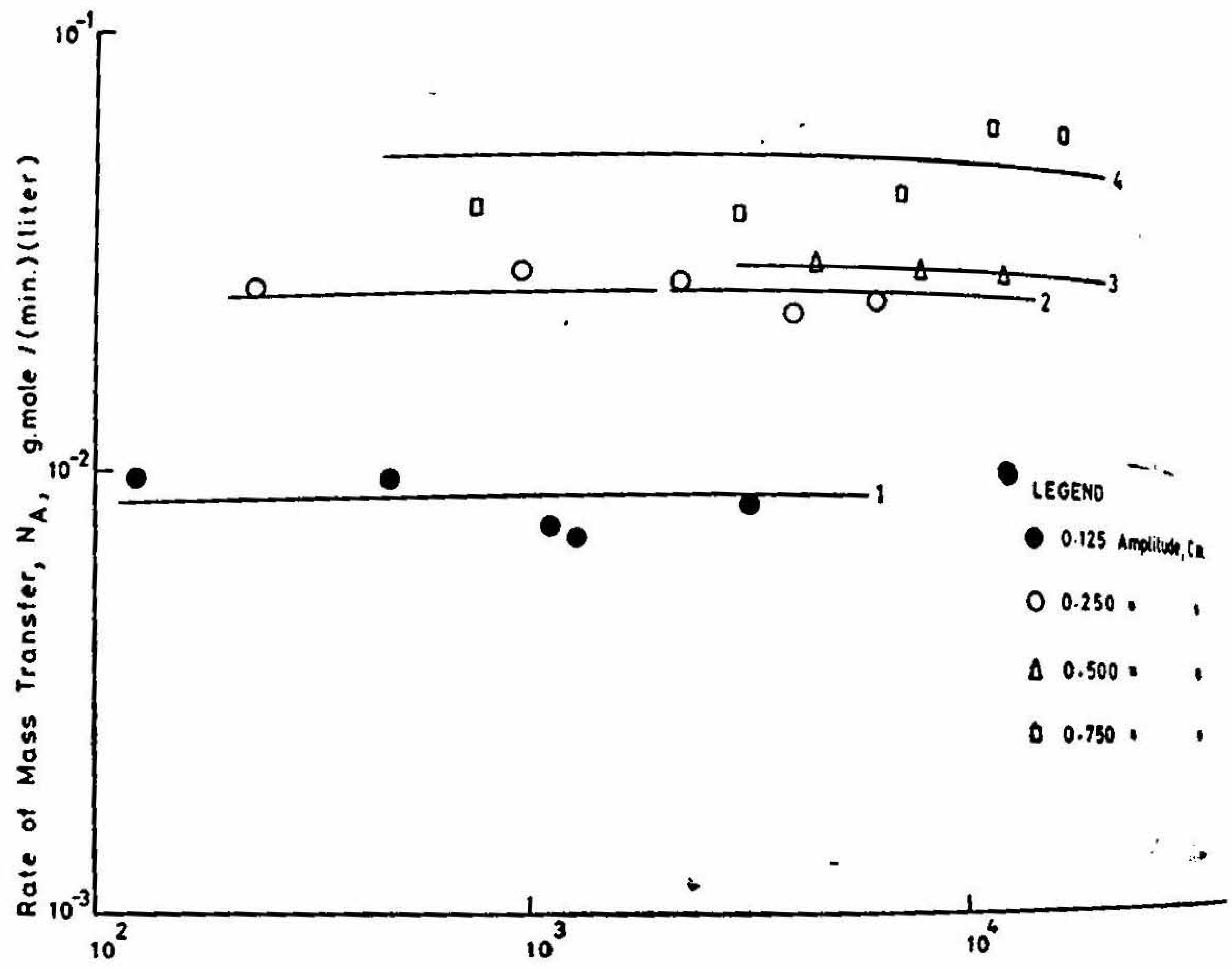


FIG. 8. Vibrational acceleration *vs* rate of mass transfer.

5.4 *The effect of vibrational intensity*

The effect of vibrational acceleration ($\omega^2 A$) on the mass transfer rate is shown in fig. 8. The vibrational acceleration is limited only to the frequency range 5 to 25 c/s and the amplitude range 0·125 to 0·75 cm. The plot shows that the absorption rate is independent of the vibrational acceleration provided to the system. However, the conclusion drawn from fig. 8 is contrary to the work reported by Buchanan *et al*[12] who mention the rate of mass transfer as 1·1 power of ($\omega^2 A$). In their work, the frequency is much higher than that in the present work and the amplitude is below 0·1 cm; also the bed heights are higher than the highest bed height studied in the present work. Although in this investigation the effect of power consumption could not be determined, in concurrence with the conclusion of Buchanan *et al*[12], the authors believe that the power requirements in a well-designed unit will not be excessive. This conclusion is well supported by the work of Harbaum and Houghton[11].

The present work is limited only to one particular system, *viz.*, air-Na_2SO_3 aqueous solution. Although such similar studies[10-13] are available in the literature, the authors feel that the work reported, including the present investigation, are qualitative in the absence of adequate experimental work. So it is necessary to carry out such studies considering several other systems to establish a very generalized effect of pulsations on mass transfer processes.

6. Conclusions

The following conclusions are drawn from the present experimental investigations involving absorption of oxygen in the sodium sulfite solution :

(i) The absorption rate is indeterminant within the frequency range 5–10 c/s and the amplitude below 0·5 cm. However, the amplitudes above 0·5 cm will cause an enhancement in the mass transfer rate.

(ii) For the frequencies between 15–25 c/s, the absorption rate will increase with increase of amplitude.

(iii) For a higher frequency range (above 200 c/s) the phenomena of resonance dominates the system so much that no direct relationship between the rate of mass transfer and the frequency of vibration can be established. Pulsations above the frequencies 200 c/s show a maximum 40% improvement in the mass transfer rate.

(iv) The overall rate of mass transfer increases initially with increase of liquid bed height, reaching the maximum at a bed height of 9 cm, and then decreasing sharply with further increase in the bed height.

(v) Within the ranges of frequencies, amplitudes and bed heights studied, the absorption of oxygen are independent of the vibrational acceleration provided oo the system.

Notation

A Amplitude (cm)

N_A Rate of mass transfer (g. mole/ (mit) (litre)

ω Vibrational frequency (radians/sec)

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