ENCLOSURE (B) 2

ENTRAINMENT AND PLATE EFFICIENCY OF BUBBLE-CAP RECTIFYING COLUMNS

by

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LIST OF TABLES
AND ILLUSTRATIONS

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I. INTRODUCTION

A. History of Project

There have been many investigations of the plate efficiency of bubble-cap fractionating towers, but the information on allowable vapor velocity is still incomplete. Even today, large scale commercial towers are operating with relatively low vapor velocities. After review of the information on this subject, it was concluded that the main factors controlling the vapor velocity are entrainment and pressure drop across the bubble plate.

In recent years, the importance of entrainment as a factor in determining the allowable vapor velocity has come to be more fully recognized. Sherwood and Jenny reported experimental data for the water-air system, and pointed out that the entrainment for this system is substantially negligible until vapor velocity of 1.2 meters per second is reached. This conclusion cannot be directly applied to a petroleum system since, the physical and chemical propebties of water, steam, and air are quite different from those of petroleum. Particularly, the specific gravity of water is greater than that of petroleum, and, on the other hand, the specific gravity of oil vapor is greater than that of air or steam. In consequence, the suspending velocities of oil particles are higher than for water particles. Experimental data are needed on entrainment during actual distillation. The work presented here represents an effort to clear these points with a view to raising the capacity of bubble towers.

B. Key Research Personnel Working on the Project

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Chem. Eng. Sub. Lieut. H. KINGO

Chem. Eng. Sub. Lieut. I. KANISE

II. DETAILED DESCRIPTION

A. Description of Apparatus

The apparatus used in this work is shown in Figure 1(B)2. This shows the apparatus used for the fundamental experiments, and for these experiments two columns were used. One is a small laboratory column with three single-cap plates. In designing this column, much case was taken to provide more severe conditions for entrainment than ordinarily exist in actual columns.

On the basis of data on the dimensions of commercial towers in this country and information on structual factors affecting entrainment reported by previous investigators, a plate spacing of 25 centimeters (minimum size for petroleum fractionator), and a slot area per plate section of about 4% were adopted for the small laboratory column. Liquid submergence (distance between top of slot and liquid level), is variable up to a maximum of 2.5 centimeters. Another semi-commercial column was devised to simulate an actual column as closely as possible. This could be attached to the same still-put and condenser. Sufficient heating and condensing surface were provided to permit running at high vapor velocities. Most previous investigators adopted only two plates, and calculated the entrainment from the analysis of liquid on the upper plate, and liquid drops which were carried away from the upper plate by vapor into the condenser were neglected. In our apparatus, however, all entrainment from the middle plate was caught by the upper plate, and entrainment data were corrected for the same. Only data with good material balances were utilized in correlations. In order to withdraw a definite volume of sample quickly, a special calibrated sampling pipette was provided on each plate. A sight glass, hand hole, and level gauge were also provided on each plate. Due to the nature of this investigation, downflow pipes were not installed.

The columns, still hot, and vapor lines were insulated with asbestos covering.

B. Test Procedures

In order to find the characteristic properties of the apparatus with regard to previous investigations, entrainment and pressure drop were determined for the water-steam system. At first, to preheat the column, water was added to the still-pot from the feed tank, and brought to boiling by heating with steam.

The vapor flowed up the column, condensed on the wall, and accumulated on each plate. When the temperature of the top of column reached 100°C, the heating steam valve was closed, and the condensed water on each plate was withdrawn quickly through the three-way-cock of the level gauge. Next, a definite volume (1000cc) of 0.1 N NaOH solution was introduced on the lower plate and same volumes of distilled water were introduced on the middle and upper plates. These liquids also had been preheated to their boiling points (a successful test demanded much care in preparation). Then the still was carefully heated until the vapor velocity reached the desired value. When a steady state was obtained, liquid samples were withdrawn from each plate simultaneously through sampling pipettes, and after maintaining the steady state for a definite time, samples were again withdrawn as before. The content of NaOH on each plate was determined by titration with standard sulphuric acid, and a NaOH material balance was calculated.

The data were utilized only when the reduction of NaOH on the lower plate agreed well with the increase on the middle and upper plates. Entrainment was calculated by the same method as described by Holbrook and Baker or Sherwood and Jenny. Vapor velocity through the column was calculated from the flowmeter reading and the volume of condensate.

The next determinations were made on a narrow cut aviation gasoline-gasoline vapor system, and finally on the toluol-toluol vapor system.

Inspections on these substances are given in Table I(B)2. In the table, it is seen that the properties of the water-air system and hot water-steam system are similar and the gasoline-gasoline vapor system and toluol-toluol vapor system are also similar. For the hydrocarbon systems, analyses were made as follows. A definite volume of dyed solution was fed on the lower plate and the same volume of distilled water was fed on the middle and upper plates. To the liquid on the lower plate was added a definite volume of non-volatile dye, and the concentration of dye on the middle and upper plate caused by entrainment during the process was estimated from the color determined with a colorimeter.

To investigate other variables effecting plate efficiency, and to determine over all plate efficiencies, a larger continuous rectification pilot plant column was constructed. Experimental work was done with this column on the methanol-water system and benzol-toluol system, but since the apparatus lacked an automatic controller, steady state could not be reached and satisfactory material balances were not obtained. Consequently, these data were discarded and it was planned to modify the apparatus. This could not be realized, however, because of circumstances caused by the war.

C. Experimental Results

1. Entrainment. The experimental data are shown graphically in Figure 2(B)2 and are compared with data reported by previous investigators. It is seen that the data for the hot water-steam system correlate well with the water-air data of Sherwood and Jenny obtained on a single-cap laboratory column with column diameter of 25 centimeters and variable plate spacing ranging from 31 to 61.5 centimeters If Sherwood and Jenny's data are extrapolated to a plate spacing of 25 centimeters, they ccnincide with the author's. This is to be expected, since the internal structures of both columns are similar, as well as the physical and chemical properties for both systems. By this comparison, the characteristics of the test apparatus, and confidence in the experimental procedure, were established.

Investigation of the hydrocarbon systems were made on the same apparatus. At first, a narrow cut fraction of aviation gasoline, 110°C-130°C was used. However, the investigation of this complex mixture was unsuccessful because the moles of vaporization and condensation at each plate were not equal, resulting in flooding. Therefore, it was decided to investigate the toluol-toluol vapor system, which has properties similar to the aviation gasoline fraction, as shown in Table I(B)2. As a result of this investigation, entrainment for the toluol-toluol vapor system was found to be unexpectedly low as compared with the water-steam system.

2. Pressure Drop. The pressure drop data are shown in Figure 3(B)2 in which the pressure drop across one plate in millimeteters of mercury is plotted against vapor velocity through the column. On the basis of Figure 3(B)2 it is calculated that a vapor velocity of 1.0 meter per second can be safely used in a commercial petroleum column (atmospheric pressure) without exceeding the flooding point.

3. Discussion of Results. With regard to the fact that the entrainment ratio for the toluol-toluol vapor system is unexpectedly low, the authors explain this as follows:

> If the data are plotted against linear velocity, the curves for both systems fall more closely together than when plotted against mass velocity. However even when plotted against linear velocity, entrainment for the hydrocarbon system is far lower than the water-steam system. In reviewing the factors affecting entrainment, especially surface tension and densities of liquid and vapor (refer to Table I(B)2) the effect of surface tension appears to be more controlling than density difference between liquid and vapor, and the smaller the surface tension, the smaller the entrainment ratio. When it is considered that mercury, which has a high surface tension, is easily scattered into fine particles, whereas ships at sea often pump oil (with low surface tension) to calm the waves, it can be appreciated that the phenomenon of entrainment is much affected by the tendency to form liquid particles. Most fractionating columns have been designed by the equation of Souder and Brown, but in this equation the effect of surface tension is not considered as a direct variable.

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Souder-Brown's equation for allowable vapor velocity

$$W = C\sqrt{D_2(d_1-d_2)}$$

where W = mass velocity (Kg/m^2 hr)

d_1 = density of liquid (Kg/m^3)

d_2 = density of vapor (Kg/m^3)

C = constant affected by surface tension and plate spacing determined from Figure 1(B)2.

III. CONCLUSION

It is shown by this investigation that, for a hydrocarbon system, entrainment is less than for the water-air system. Sherwood and Jenny pointed out, as the result of their experiments, that efficiency is not substantially reduced by entrainment until an entrainment ratio 0.1 is reached, and that this ratio would not be reached at ordinary vapor velocities in an actual column. As can be seen from Figure 2(B)2, for the small laboratory column an entrainment ratio 0.1 is reached at a vapor velocity of about 1.0 meter per second. In the 40 centimeters semi-commercial column the entrainment ratio is about 0.01 for the same vapor velocity.

In a large scale commercial column with plate spacing of 50 centimeters or over, allowable vapor velocity of 1.2 meters per second, at least, can be safely used from the standpoint of entrainment and pressure drop across the plate.

Bibliography

Sherwood and Jenny: Ind. Eng. Chem. 27 265 (1935)

E. M. Baker: Ind. Eng. Chem. 31 717 (1939)

Holbrook and Baker: Ind. Eng. Chem. 26 1063 (1934)

Souder and Brown: Ind. Eng. Chem. 26 98 (1934)

C. C. Peavy and E.M. Baker: Trans. Amer. Inst. Chem. Eng. 33 315 (1937)

Pyott, Jackson: Ind. Eng. Chem. 26 1068

Ashraf. Cubbage, and Huntington: Ind. Eng. Chem. 26 1068 (1934)

Kirshbaum: "Distillier und Rektifizierteknik" (1940)

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Table I(B)2
PROPERTIES OF DISTILLATION SUBSTANCES

Substance	Molecular weight (gm.)	Specific gravity		Surface tension (dyne/cm)	B.P. (°C)
		liquid	vapor		
92 Octane Av.Gas 110-130°C	ca.100	ca.0.733	0.0027 (100°C)	19.0	125 (50% pt.)
Toluol	92	0.796 (111°C)	0.0029 (111°C)	19.9 (111°C)	111
Water	18	0.985 (100°C)	0.0059 (100°C)	61.5 (100°C)	100
Air	29		0.0013 (room temp.)		

System	Difference of Density between liquid & vapor	Surface Tension (dyne/cm)	Viscosity(c.p.)	
			liquid	vapor
Water-air	0.999	72.1 (25°C)	0.0185 (25°C)	0.895 (25°C)
Water-steam	0.957	61.5 (100°C)	0.013 (100°C)	0.284 (100°C)
92 Octane aviation gasoline	0.730	19.0 (ca.100°C)	0.011-0.020 (100°C)	0.20-0.29 (100°C)
Toluol-Toluol vapor	0.793	19.9 (110°C)	0.025 (110°C)	0.25 (110°C)

ENCLOSURE (B)2

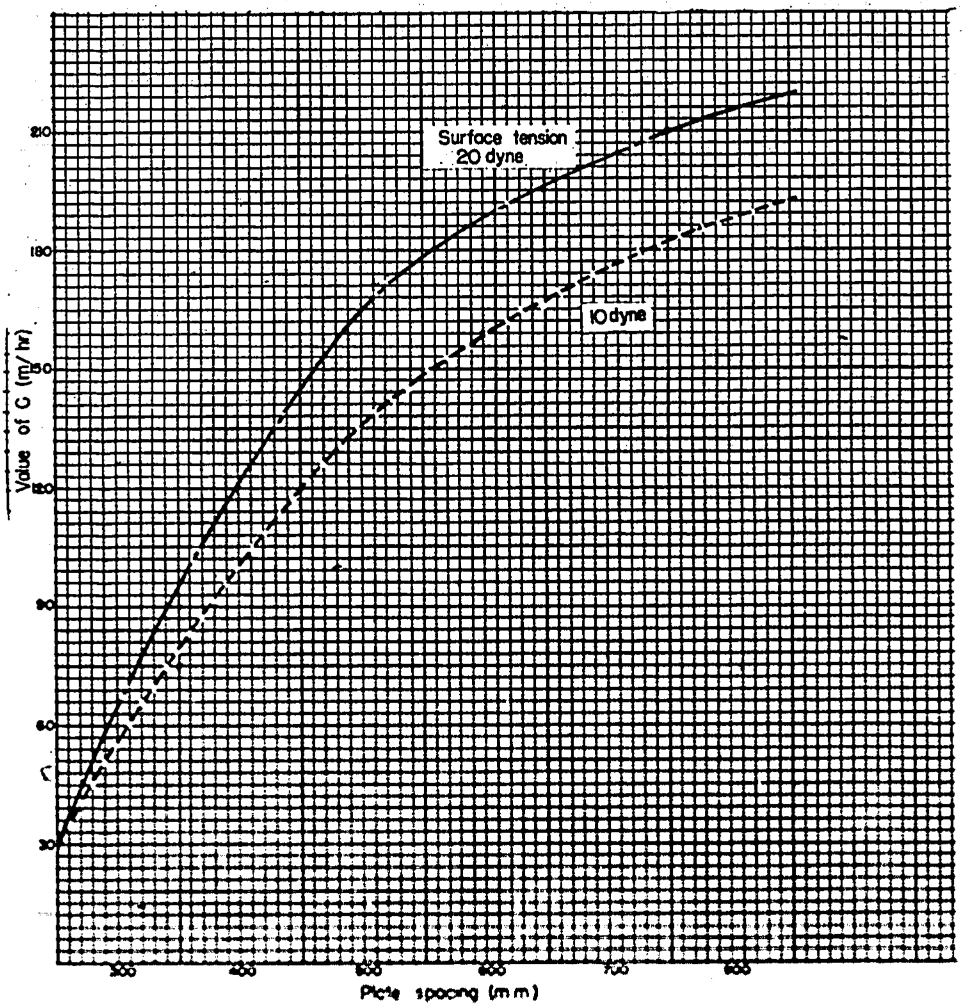

Figure 1 (B)2

CHART FOR DETERMINING CONSTANT

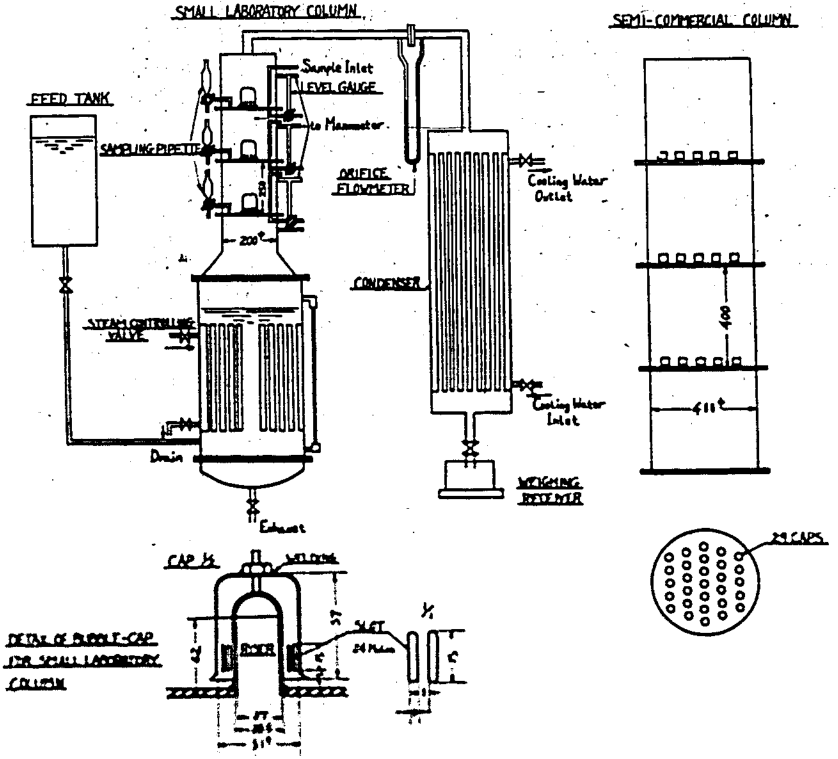

Figure 2 (B)2
DIAGRAM OF DISTILLATION TEST APPARATUS

ENCLOSURE (B)2

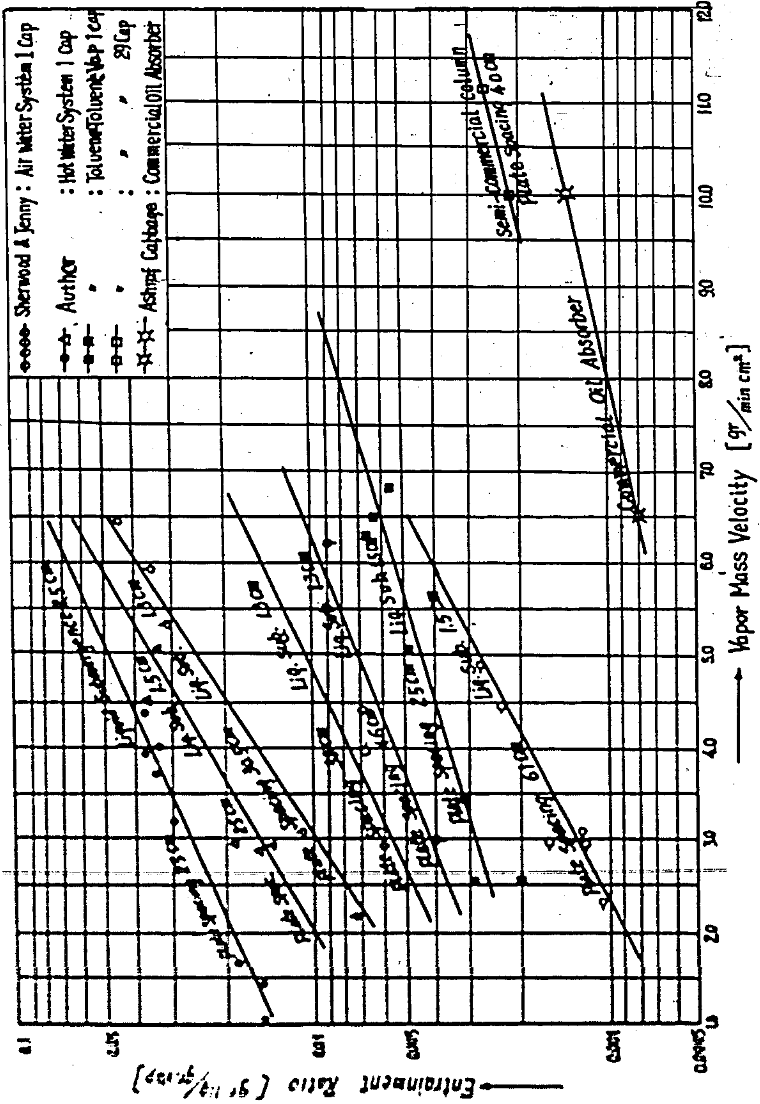

Figure 3 (B)2
ENTRAINMENT vs VAPOR MASS VELOCITY

ENCLOSURE (B)2

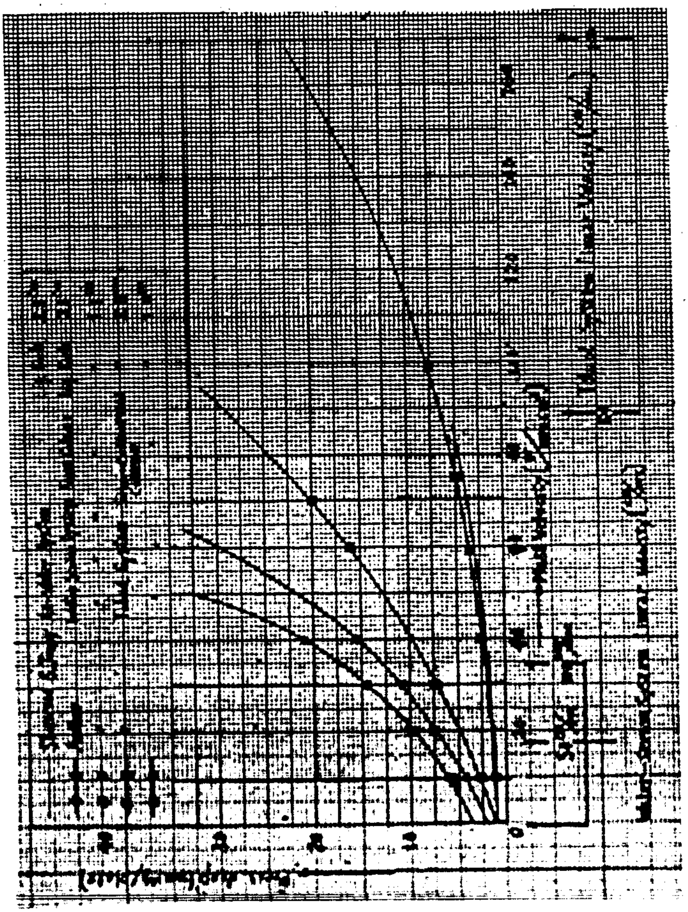

Figure 4 (B)2
VAPOR VELOCITY vs PRESS. DROP

ENCLOSURE (B)2

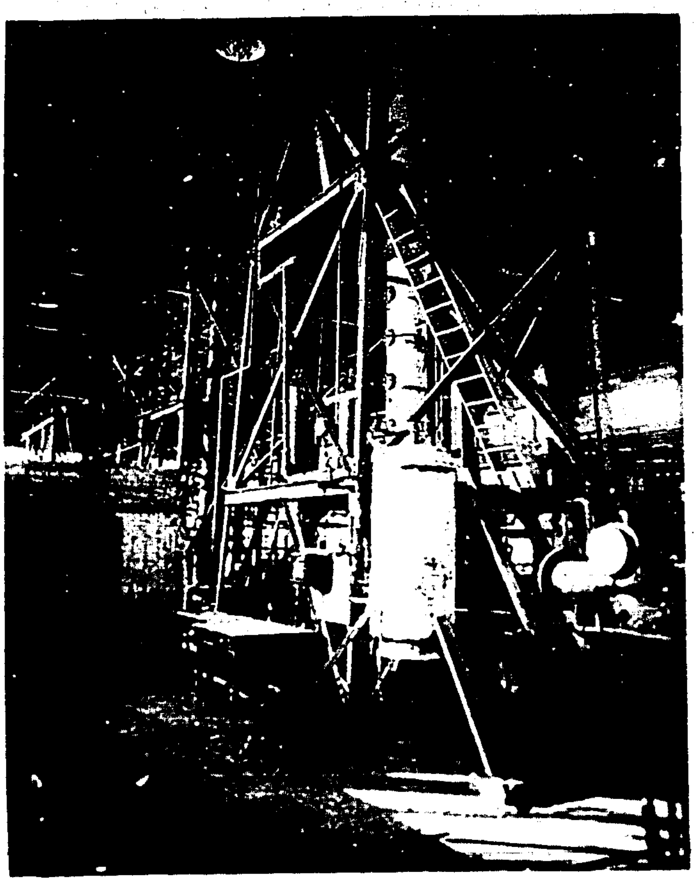

Figure 5 (B)2
DISTILLATION APPARATUS FOR PROCESS ENGINEERING