

THE INFLUENCE OF FEEDING RATES AND ROTOR-SHAFT SPEEDS ON RESIDENCE TIMES OF TEA LEAF WITHIN ROTORVANES

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Experimental evidence has been obtained to indicate that the mean residence time of leaf within a Rotorvane barrel is inversely proportional to rotor shaft speed when the ratio of the rate of feed to the rotor shaft speed is kept constant. The quantity of leaf held within the barrel under conditions of dynamic equilibrium is shown to be a function of the rotor shaft speed, the combination of rotor-vanes and end plates fitted to the machine, and of feeding rates.

Mathematical expressions are derived linking these factors and on the basis of these expressions, the influence of feeding rate and rotor shaft speed on Rotorvane rolling of tea leaves is discussed. A method of determining residence times of leaf is indicated. Results of a previous investigation which showed that dhoor outturns, grade outturns and made tea characteristics are independent of rotor shaft speed provided that the ratio of the rate of feed to the rotor shaft speed is kept constant, are discussed on the basis of this theory.

Those conversant with the process of orthodox tea manufacture are familiar with the concept of optimum withered and rolled leaf charges and also with factors that influence these optima.

Experimental evidence has been obtained (De Silva 1965; Kirtisinghe 1967) to show that dhoor outturns, grade outturns and made tea characteristics are independent of rotor shaft speed, if the rate of feed of withered leaf is proportional to the speed of the rotor shaft. In this paper theoretical relationships are derived in support of these experimental findings which stress the importance of regulating feed rates to obtain the best results from Rotorvaning.

Theory

When a Rotorvane is fed, the quantity of leaf discharged (output) would initially be less than that of its intake (input). After a few minutes of operation when dynamic equilibrium has been established between input and output, the quantity of leaf held within the barrel is taken to be a measure of the pressure developed within. In Rotorvanes that are of the same size and having the same fittings, this pressure would in turn regulate dhoor and grade outturns, the temperature rise in transit through the barrel and made tea characteristics.

It has been shown experimentally that the mean residence time of leaf within the barrel of the Rotorvane is inversely proportional to the rotor shaft speed for constant values of the relative feeding rate. Relative feeding rate is defined as the ratio of the absolute intake to the rotor shaft speed; calculated on the 'fps units of measurement can be expressed in terms of the Rotorvane intake in pounds per revolution of the rotor shaft (De Silva 1965). Rotorvanes of the same size and having the same combinations of vanes and end plates are considered similar and to have the same constant of proportionality.

On the basis of the experimental evidence it can be shown that :

$$M = \frac{It_2}{3600} = \frac{K}{3600} \frac{(1)}{3} = \frac{K}{60} \phi = \frac{St}{60} \phi$$

Nomenclature used has been explained in Appendix I. Appendix II gives the derivations of the mathematical expressions and includes the statistical analysis of the experimental results, which has led to the formulation of the theory presented in this paper.

MATERIALS AND METHODS

A marker material which travels in a manner similar to that of preconditioned leaf was employed to determine mean residence times. In order to test the behaviour of the marker material, a preliminary investigation was carried out with aluminium foil particles moulded into shapes such as spheres, flat squares and rectangles and of two different weights corresponding to each shape. After dynamic equilibrium was established, 100 particles of the marker was fed at a given time along with the preconditioned leaf and collected in receptacles held at the discharge end at 5— or 10—second intervals. In this manner the times of transit of almost all the tracer particles fed into the machine were determined. On occasion, however, one or two particles could not be traced and the experimental error caused by the loss of these particles was ignored in the statistical analysis. The number of tracer particles and the mass of leaf in each receptacle were determined. It was found that the mean residence times of these tracer particles and its standard deviation were the same for the different shapes and weights of these particles. It was concluded, therefore, that these aluminium particles behaved in a manner analogous to the tea leaf being fed into the Rotorvane.

The experiments proper were conducted with hand-moulded spheres made from aluminium foil of 0.025 mm thickness and of 4 sq. in. area. As in the preliminary experiment, 100 particles were fed simultaneously into the Rotorvane barrel along with leaf preconditioned for 10 minutes under very light pressure.

Residence times of these aluminium foil particles were determined at six different rates of leaf throughput, corresponding to each of four different speeds of the rotor shaft (16, 25.5, 36 and 50 rpm). These throughputs were calculated from the quantities of leaf collected in the receptacles held at the discharge end of the Rotorvane, sampled at 5-second intervals.

An 8-in. series-B Rotorvane fitted with eight forward pitched vanes and one reverse pitched vane placed centrally was used in these experiments. An Iris end plate in the minimum pressure position (fully open) was attached to the discharge end.

RESULTS

Table 1 gives the mean residence times, the standard deviations of distribution of residence times and the standard errors of mean residence at rotor shaft speeds of 16, 25.5, 36 and 50 rpm respectively, corresponding to six different throughputs at each speed. Histograms showing frequency distribution of residence times of particles introduced simultaneously corresponding to each of these shaft speeds are illustrated by Figures 1-4.

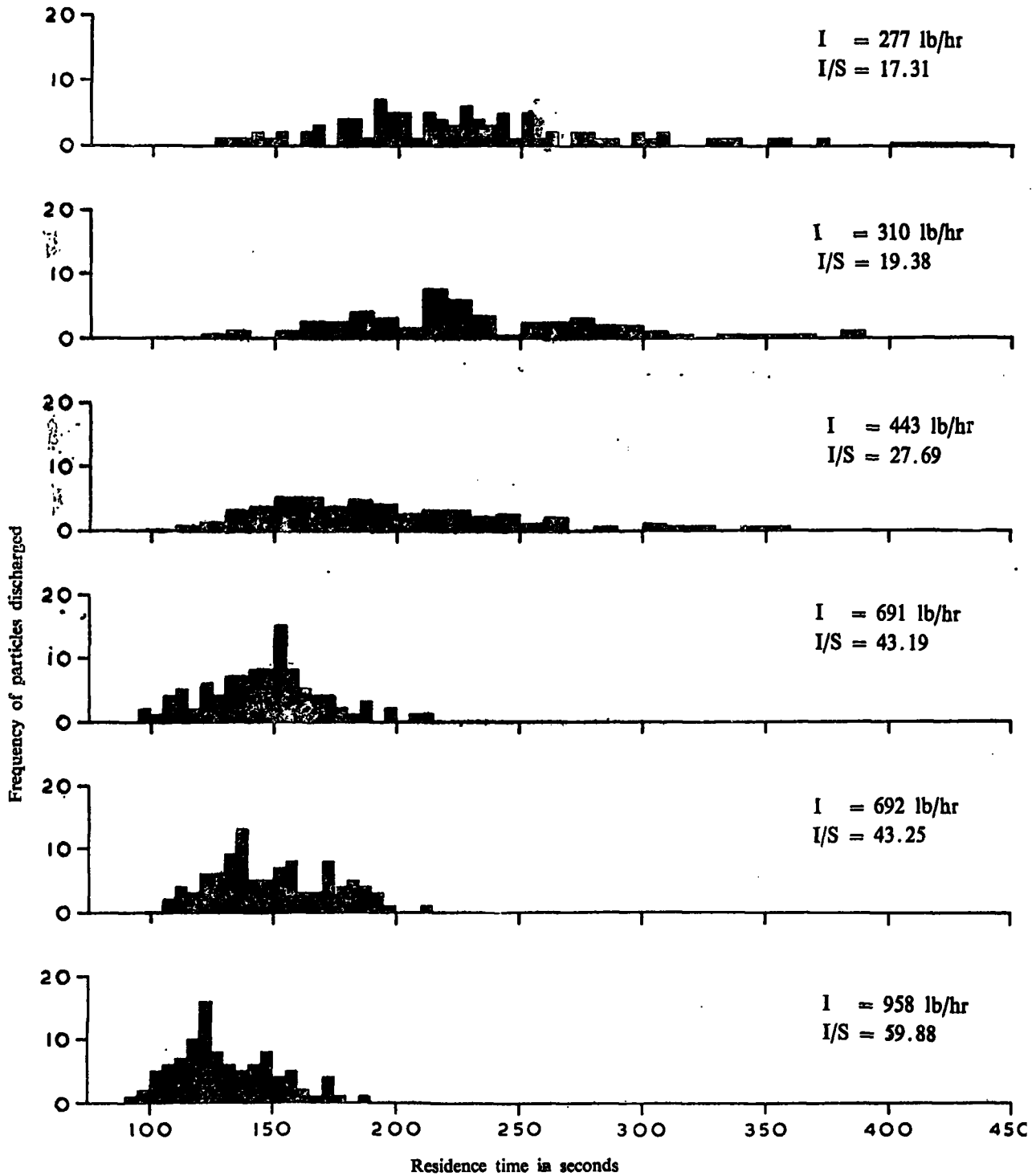


FIGURE 1 — Frequency distributions of residence times of particles introduced simultaneously into a Rotorvane operated at a rotor shaft speed of 16 rpm and fed at six different rates

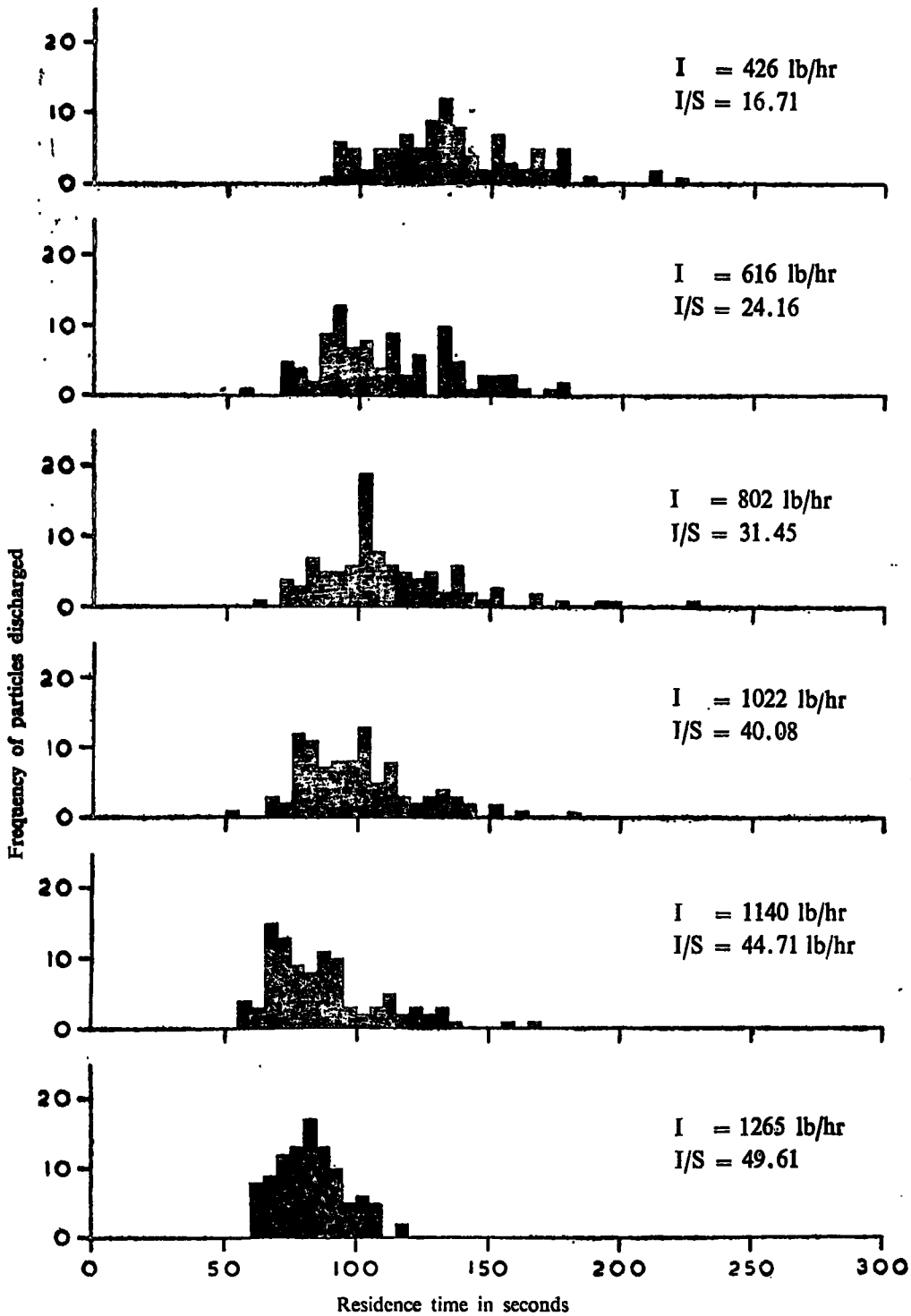


FIGURE 2 — Frequency distributions of residence times of particles introduced simultaneously into a Rotorvane operated at a rotor shaft speed of 25.5 rpm and fed at six different rates

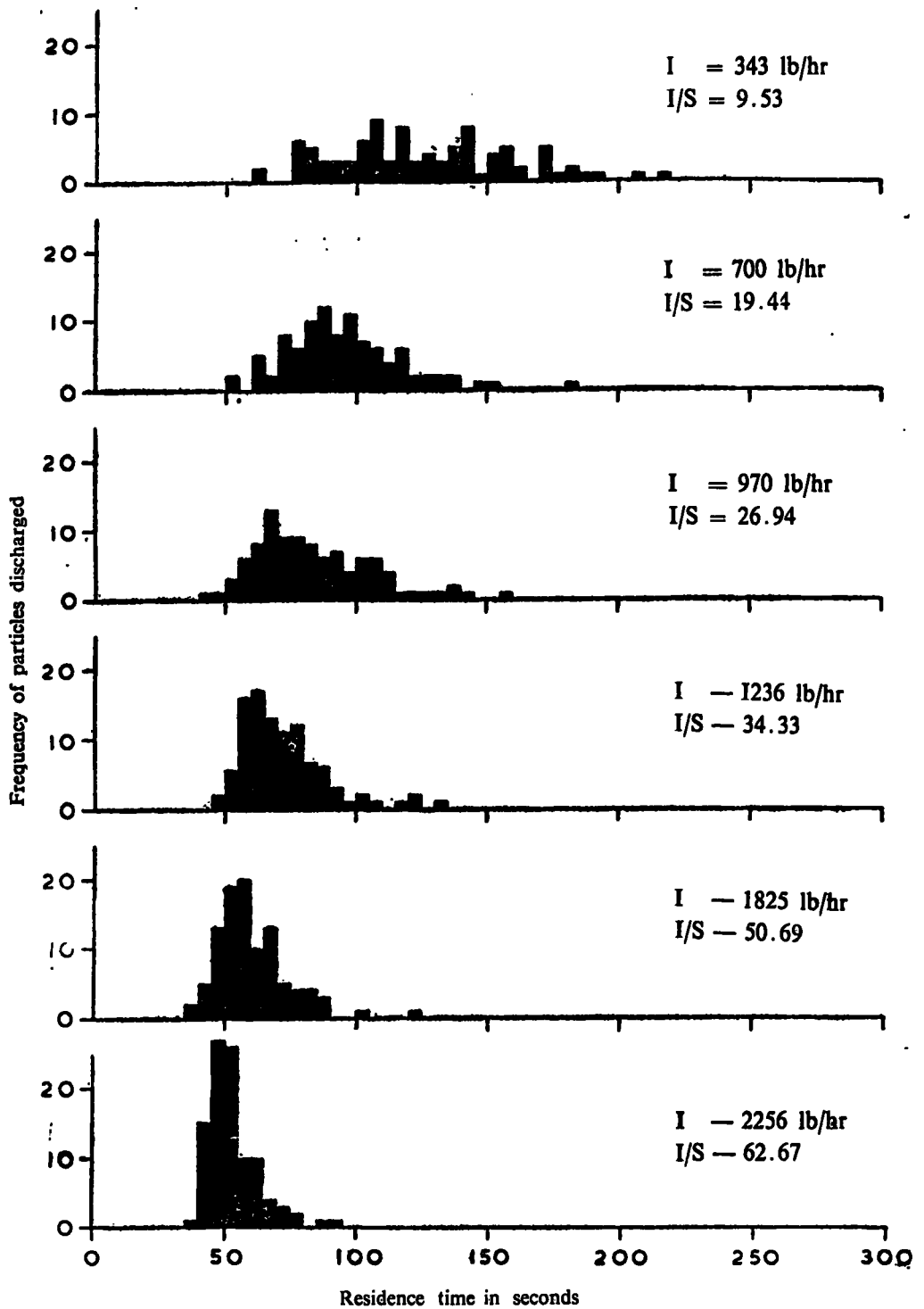


FIGURE 3 — Frequency distributions of residence times of particles introduced simultaneously into a Rotorvane operated at a rotor shaft speed of 36 rpm and fed at six different rates

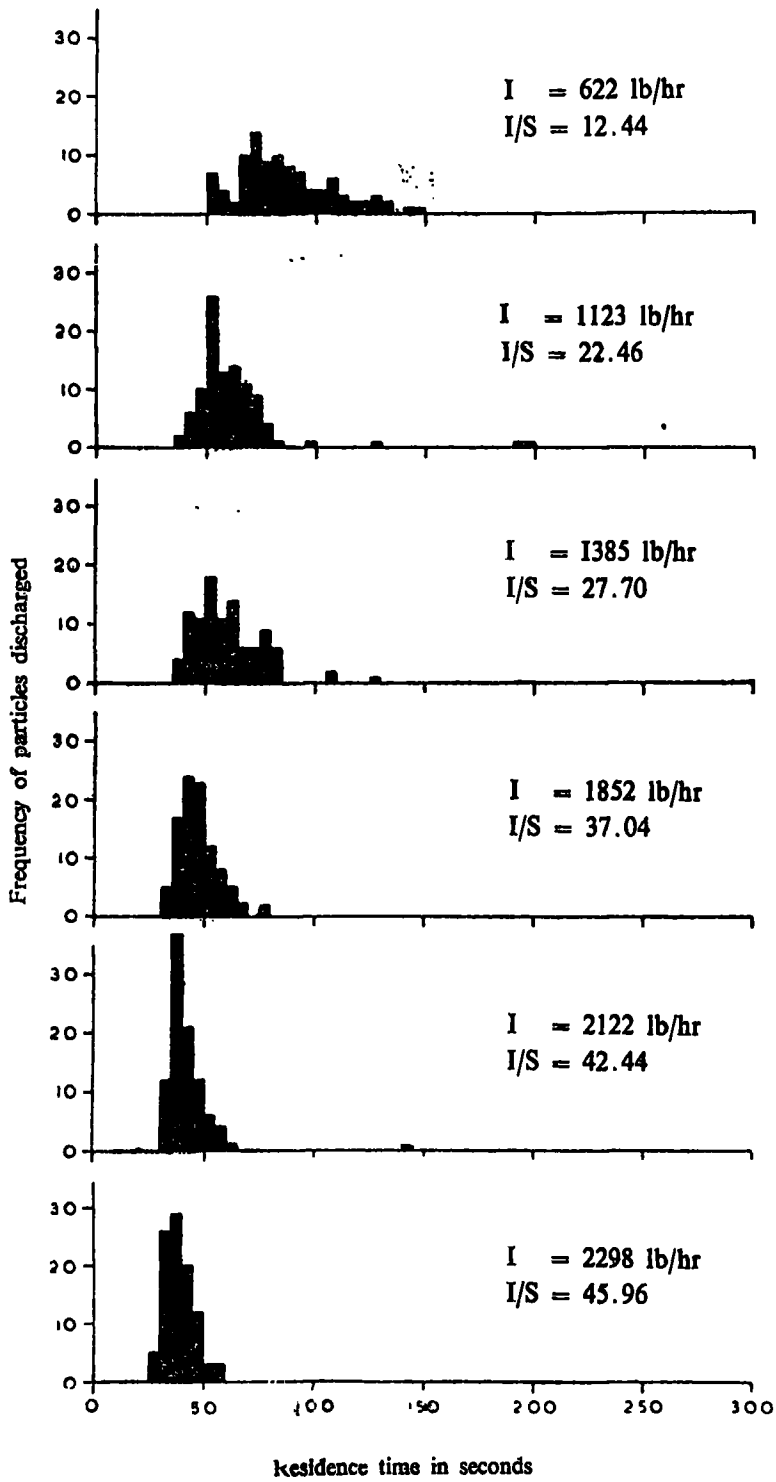


FIGURE 4 — Frequency distributions of residence times of particles introduced simultaneously into a Rotorvane operated at a rotor shaft speed of 50 rpm and fed at six different rates

TABLE 1 — *Distribution of residence times of leaf particles and its dependence on feeding rates, at four rotor shaft speeds*

S Root shaft speed (rpm)	I Intake (lb/hr)	I/S (lb/rev.)	t Mean residence time (sec)	Std deviation of distribution of re- sidence times (sec)	Std error of mean residence time (sec)
16	277	17.3	228	57.2	5.78
	310	19.4	232	53.3	5.33
	443	27.7	197	50.9	5.11
	691	43.2	146	23.8	2.38
	692	43.3	150	23.9	2.39
	958	59.9	131	20.5	2.07
25.5	426	16.7	135	28.1	2.82
	616	24.2	111	26.3	2.63
	802	31.5	112	28.5	2.87
	1022	40.1	101	23.0	2.31
	1140	44.7	88	22.4	2.26
	1265	49.6	83	13.2	1.32
36	343	9.5	125	33.6	3.45
	700	19.4	95	22.3	2.25
	970	26.9	84	22.7	2.28
	1236	34.3	72	16.5	1.65
	1825	50.7	60	13.7	1.37
	2256	62.7	53	9.9	0.99
50	622	12.4	86	21.9	2.20
	1123	22.5	62	22.9	2.29
	1385	27.7	60	15.8	1.58
	1852	37.0	47	9.2	0.93
	2122	42.4	44	16.1	1.65
	2298	46.0	39	6.8	0.69

Conclusions

Using the data presented in Table 1 with suitable mathematical transformation it can be shown that :

$$St = K \dots\dots\dots (1)$$

Although this expression has been established only for one combination of vanes and end plates in an 8-in. Rotorvane, it is assumed that the same relationship will hold true for other combinations, differing only in the value of K. On the basis of equation (1), it has been shown in Appendix II that

$$M = \frac{It}{3600} = \frac{K}{3600} \left(\frac{I}{S}\right) = \frac{K}{60} \phi = \frac{St}{60} \phi$$

DISCUSSION

Since $M = \frac{K}{3600} \left(\frac{I}{S}\right) = \frac{K}{60} \phi$, it is evident that at constant ϕ , M is only dependent on K. In other words, if the absolute feeding rate is directly proportional to the rotor shaft speed or if the relative feeding rate in pounds per revolution of the rotor shaft is the same, then the value of M will be dependent only on K which is a constant for all similar rotorvanes. Hence under these conditions and on the basis of the assumption of the theory, the degree of pressure developed inside similar Rotorvane barrels will be independent of the rotor shaft speeds or absolute feeding rates. Thus the dhool outturns, grade outturns and characteristics of made teas produced using similar Rotorvanes should be independent of rotor shaft speeds or absolute feeding rates provided I/S or relative feeding rate (ϕ) is the same for all speeds.

Although it is known that the pressure developed within the barrel increases with increasing values of M , the optimum value of M has yet to be determined. The relationship between M and the other characteristics, such as dhool and grade outturns can also vary. For instance, an increase in M could result in increased dhool outturns and give more colour and strength in the liquor but these improvements could be at the expense of leaf appearance.

The standard deviation of distribution of residence times can be taken as a measure of the circulation of particles within the barrel. A high value for this figure would indicate good circulation, whereas a low value would indicate less mixing. This value would be zero when plug-flow of leaf particles takes place within the barrel. From Figures 1-4 it is evident that for low values of the relative feeding rate I/S , the standard deviations of the distribution times are large and *vice versa*. Circulation is, therefore, influenced by the relative feeding rate and optimum results from Rotorvaning are likely to be found at a figure of I/S , where there is both pressure and circulation.

In Rotorvanes of the same size and having the same combinations of vanes and end plates and fed at the same rate (I), the M values decrease with increase in rotor shaft speed (Appendix II). Under these feed conditions, pressure developed will be a function of the rotor shaft speed and consequently dhool outturns, grade outturns and made tea characteristics will also be governed by the speed of the rotor shaft.

The results of an experiment conducted at the Tea Research Institute of Ceylon (De Silva 1965) provide evidence in favour of the theory postulated in this paper.

According to the theory, it was shown that the dhool outturns, grade outturns and characteristics of made teas produced using similar Rotorvanes to be independent of rotor shaft speeds or absolute feeding rates provided the relative feeding rate (ϕ) is kept constant. In different Rotorvanes having different arrangements of vanes and end plates the effect of rotor shaft speeds and interactions of rotor shaft speeds with other parameters which distinguish one arrangement from another will not be significant with respect to dhool outturns, grade outturns and made tea characteristics. This means that any one given arrangement will perform in a like manner at all speeds for constant ϕ .

In the experiment under discussion (De Silva 1965) four different arrangements of vanes and end plates in an 8-in. Rotorvane operated at three rotor shaft speeds have been investigated. These four arrangements correspond to two combinations of vanes incorporated with Iris end plates having minimum and maximum apertures for the discharge of leaf. The aim had been to conduct the experiment, keeping the value of I/S or relative feeding rate (ϕ) constant throughout the investigation for all four arrangements. In practice however there had been some variation in the mean values of ϕ due to imperfections of the feeding arrangement. Results have revealed that the interactions of rotor shaft speeds with other parameters (*ie* rotor-vane combinations and apertures of the Iris end plates) were not significant for dhool outturns, grade outturns and made tea characteristics in accordance with the theory. The effect of rotor shaft speed has been found to be significant ($P < 0.05$) with respect to dhool outturns, quality, flavour and valuations. These differences have been attributed to differences in ϕ values as would be expected on the basis of this theory. It has also been shown that neither dhool nor grade outturns nor made tea characteristics were significantly different for equal values of ϕ .

SUMMARY

The assumption is made that the quantity of leaf held within the Rotorvane barrel under conditions of dynamic equilibrium is a measure of the pressure developed in rolling; this pressure in turn governs dhool outturns, and made tea character.

Experimental evidence has been obtained to show that mean residence times are inversely proportional to the speed of its rotor shaft for constant ϕ . On the basis of this experimental finding, equations relating the quantity of leaf held within the barrel under conditions of dynamic equilibrium M , to absolute and relative feeding rates, rotor shaft speeds and mean residence times of leaf are derived in Appendix II for all rotorvanes.

These equations are :—

$$M = \frac{It}{3600} = \frac{K}{3600} \left(\frac{I}{S}\right) = \frac{K}{60} \phi = \frac{St}{60} \phi$$

Results of an earlier experiment conducted by the TRI are discussed in terms of this theory.

REFERENCES

- DE SILVA, W. C. A. (1965). Importance of feeding rates in Rotorvane manufacture. *Tea Q.* 36, 151-166.
- KIRTISINGHE, D. (1967). Report of the Technology Division. *Rep. Tea Res. Inst. Ceylon* 1966, 2, 98-105.

APPENDIX I

Nomenclature

- I = Absolute feeding rate (lb/hr)
- K = A constant at constant ϕ , dependent on parameters such as the size of Rotorvanes, vane and end-plate combinations, etc.
- M = Quantity of leaf held inside the barrel under conditions of dynamic equilibrium of input and output (lb)
- S = Rotor shaft speed (rpm)
- t = Mean residence time (seconds)
- ϕ = Relative feeding rate (lb/revolution)

APPENDIX II

Mathematical Analysis

It is evident from Table 1 that the standard errors of mean residence times differ widely at different values of I/S for any rotor shaft speed, and consequently a regression analysis could not be carried out to determine if a relationship existed between the relative feeding rate and mean residence time.

These results were, therefore, transformed to their natural logarithms and the heterogeneity of variances of mean residence times were thereby considerably reduced. Transformed results from Table 1 are presented in Table 2 along with other relevant information.

TABLE 2—Relative feed rates, mean residence times and related quantities transformed to natural logarithms at shaft speeds of 16, 25.5, 36 and 50 rpm

S Rotor shaft speed (rpm)	$1/S=60$ ϕ	$\text{Log}_e \frac{t}{S}$	t Mean residence time (secs)	Mean residence time calculated from distribution of log_e residence times (secs)	Mean log_e (residence times)	Std deviation of distribution log_e residence times	Std error of mean log_e re- sidence times	Log_e St— log_e S — log_e
16	17.31	2.8511	228	221	5.4001	0.0597	0.0060	8.1727
	19.38	2.9644	232	226	5.4191	0.0513	0.0051	8.1917
	27.69	3.3210	197	191	5.2517	0.0592	0.0060	8.0243
	43.19	3.7657	146	144	4.9714	0.0270	0.0027	7.7440
	43.25	3.7671	150	148	4.9985	0.0252	0.0025	7.7711
	59.88	4.0924	131	130	4.8644	0.0235	0.0024	7.6370
25.5	16.71	2.8161	135	132	4.8829	0.0417	0.0042	8.1215
	24.16	3.1847	111	108	4.6854	0.0551	0.0055	7.9240
	31.45	3.4484	112	109	4.6879	0.0557	0.0056	7.9265
	40.08	3.6911	101	99	4.5906	0.0484	0.0049	7.8292
	44.71	3.8002	88	86	4.4491	0.0558	0.0056	7.6877
	49.61	3.9034	83	82	4.4097	0.0245	0.0024	7.6483
36	9.53	2.2542	125	121	4.7922	0.0749	0.0077	8.3757
	19.44	2.9674	95	93	4.5296	0.0520	0.0053	8.1131
	26.94	3.2939	84	81	4.3980	0.0682	0.0069	7.9815
	34.33	3.5361	72	71	4.2560	0.0438	0.0044	7.8395
	50.69	3.9259	60	59	4.0792	0.0441	0.0044	7.6627
	62.67	4.1380	53	53	3.9636	0.0292	0.0029	7.5471
50	12.44	2.5209	86	83	4.4195	0.0624	0.0063	8.3316
	22.46	3.1117	62	60	4.0858	0.0669	0.0067	7.9979
	27.70	3.3215	60	58	4.0653	0.0600	0.0060	7.9774
	37.04	3.6121	47	46	3.8322	0.0351	0.0035	7.7443
	42.44	3.7482	44	42	3.7365	0.0562	0.0058	7.6486
	45.96	3.8278	39	38	3.6484	0.0292	0.0029	7.5605

It is evident from Table 2 that the mean residence times calculated after transformation of distributions into \log_e residence times are not very different from the distribution of residence times given in Table 1. These discrepancies were, therefore, ignored.

Figure 5 gives the plot of $\log_e I/S$ vs $\log_e St$ for rotor shaft speeds of 16, 25.5, 36 and 50 rpm. On carrying out a regression analysis to determine whether a linear relationship existed between values of $\log_e I/S$ and $\log_e St$ for each of the four shaft speeds tested, the correlation coefficients were found to be highly significant ($P < 0.001$). These correlation coefficients and regression equations are given in Table 3.

TABLE 3 — correlation coefficient for six pairs of values and corresponding regression equations

Rotor shaft speed (rpm)	Correlation coefficient	Regression equations			
16	-0.991	$\log St$	+	$.4753 \log I/S$	= 9.5682
25	-0.959	$\log St$	+	$.4045 \log I/S$	= 9.2615
36	-0.997	$\log St$	+	$.4422 \log I/S$	= 9.4024
50	-0.988	$\log St$	+	$.5711 \log I/S$	= 9.7939

A single regression analysis was also carried to determine any linear relationship between pairs of values of $\log_e I/S$ and values of $\log_e St$ corresponding to the four rotor shaft speeds. Once again the correlation coefficient is highly significant ($r = -0.970$). This regression is illustrated in Figure 6. The regression equation obtained was :

$$\log St + .4665 \log I/S = 9.4853 \quad \dots\dots\dots (2)$$

The values of $\log_e St$ estimated using equation (2) were found to be very close to the values of $\log_e St$ estimated using regression equations given in Table 6 and the small differences between estimates by these two methods were found to be statistically non-significant (Chi Square test). Equation (2) can, therefore, be used to estimate values of $\log_e St$ for varying rotor shaft speeds and feeding rates.

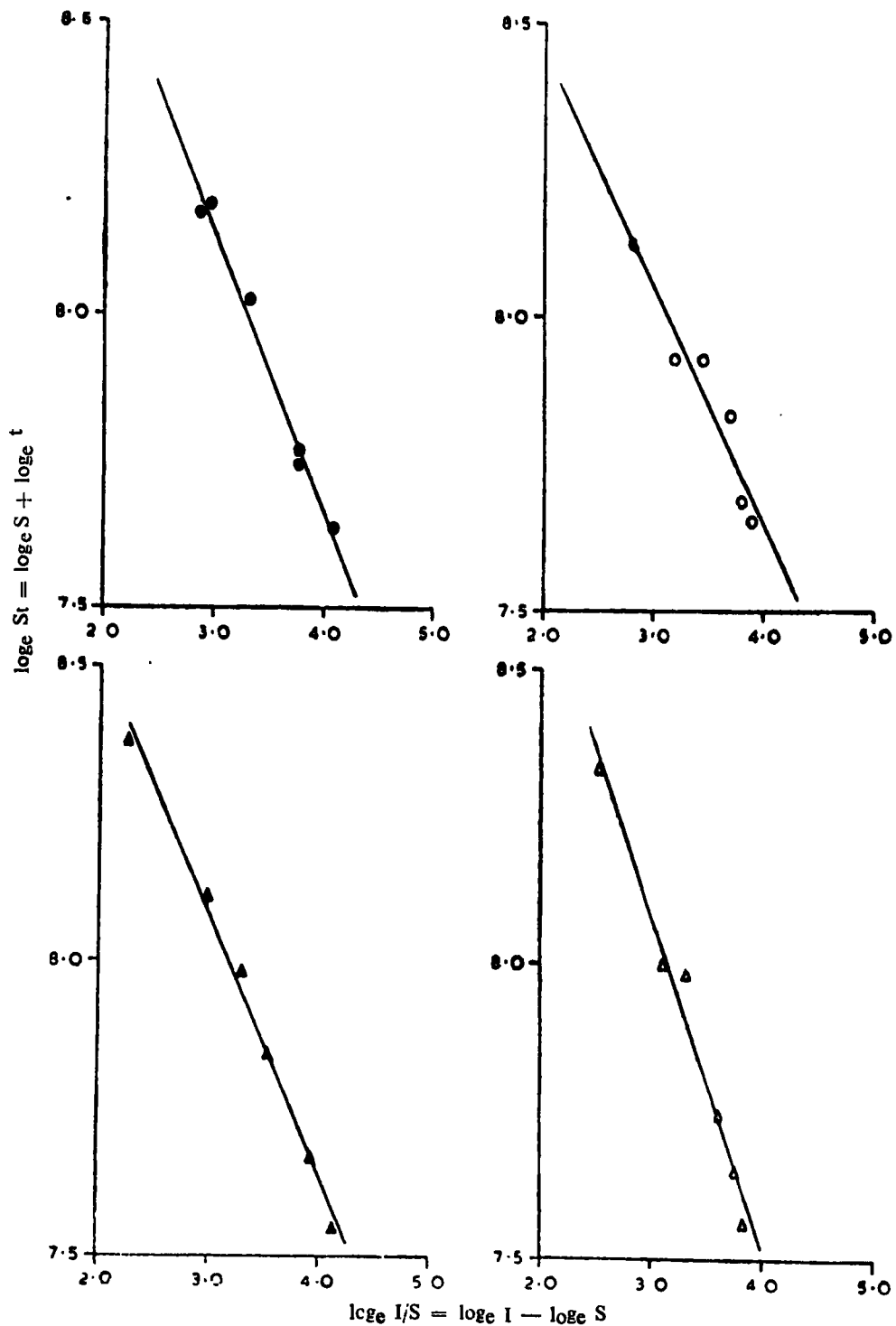


FIGURE 5 — Plots of values of $\log_e St$ against values of $\log_e I/S$ for rotor shaft speeds of 16, 25.5 36 and 50 rpm

- — 16 rpm
- — 25.5 rpm
- ▲ — 36 rpm
- △ — 50 rpm

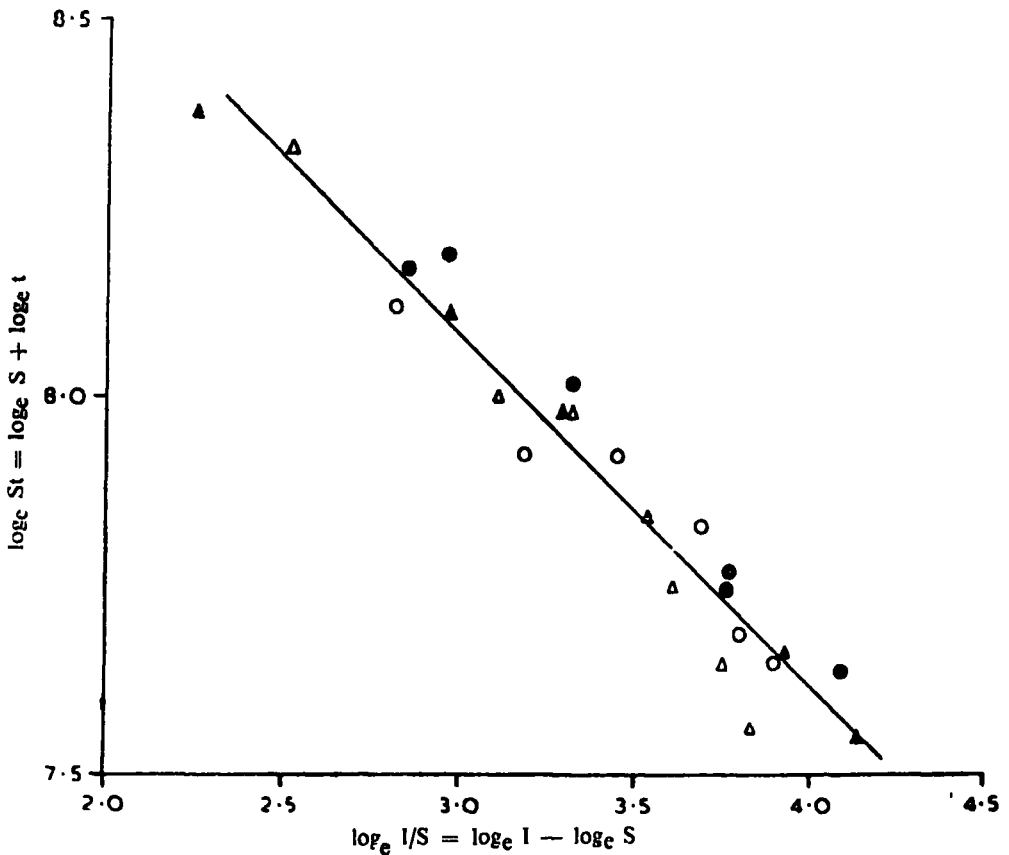


FIGURE 6— Plots of values of $\log_e St$ against values of $\log_e I/S$ at 4 different rotor shaft speeds

- — 16 rpm
- — 25.5 rpm
- ▲ — 36 rpm
- △ — 50 rpm

From equation (2) we have :

$$St = \frac{9.4853 e}{(I/S)^{.4665}} = K \quad (3)$$

Under dynamic equilibrium conditions the quantity of leaf M held inside the Rotorvane barrel at any instant θ is given by :—

$$M = \int_{\theta-t}^{\theta} \frac{I d \theta}{3600}$$

If the feeding rate I is constant in interval of time between θ and $\theta - t$:

$$\text{then } M = \frac{I}{3600} \int_{\theta-t}^{\theta} d \theta$$

$$ie \quad M = \frac{It}{3600} \dots\dots\dots (4)$$

Combining equations 3 and 4 we have

$$M = \frac{It}{3600} = \frac{K}{3600} (I/S) \dots\dots\dots (5)$$

Since I is the absolute feeding in lb/hr and S is the rotor shaft speed in revs/min, the relative feeding rate of leaf in lb per revolution of the rotor shaft denoted by ϕ is given by

$$\phi = \frac{I}{60 S} \dots\dots\dots (6)$$

Combining equations (5) and (6) and (3) we have

$$M = \frac{It}{3600} = \frac{K}{3600} (I/S) = \frac{K}{60} \phi = \frac{St}{60} \phi$$

where $K = \frac{9.4853}{e \cdot 0.4665 (I/S)}$ for the arrangement of vanes, resistors and end-plates in the Rotorvane under investigation.