FLOW CHARACTERISTICS IN A COLUMN AGITATED BY BLADE IMPELLERS.

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Abstract—Flow characteristics, axial dispersion coefficients in the continuous phase, and holdup of the dispersed phase were studied in a 4.66 cm inside diameter and 100 cm height column agitated by blade impellers.

Flow characteristics were analyzed by residence time distribution using impulse input of a tracer. The best reasonable values of Peclet number and holding time were able to obtain by using the response surface method.

The axial dispersion coefficients in the single phase flow, and in the two-phase countercurrent flow have been correlated within a confidence level of ±10% when impeller diameter, impeller speed and compartment height, were used as variables. The holdup of the dispersed phase was also correlated in terms of impeller diameter and the operating variables.

INTRODUCTION

The mass transfer rate in solvent extraction equipments can be greatly enhanced by increasing the contacting area between two phases when mechanically mixed.

Such a mechanical mixing, however, necessarily results in backmixing in local compositions, and reduces the concentration driving force between the two phases. In fact, the overall performance of the column is not much increased as anticipated. Therefore, the backmixing effect due to several factors of the equipment is recognized to be very important in the analysis of micromechanism of a mass transfer operation as well as on the performance of various extraction columns [1,2,4,5,6,7,10,].

The purposes of this study are to find the axial dispersion coefficient and hold-up of dispersed phase in a column agitated by blade impellers affected by variables such as the dimensions of the equipment, fluid velocities, and impeller speed.

THEORETICAL BACKGROUND

It is known that when the number of plates in an extraction column is large, a dispersion model can explain the flow characteristics of the system with mechanical mixing [8]. In the axial dispersion model, if impulse input of a tracer is used, the response in normalized form over open-open system is expressed as [3],

$$C(1, \theta) = \frac{1}{2\bar{t}}\left(\frac{Pe}{\pi\theta}\right)^{1/2} \exp\left(-\frac{Pe(1-\theta)^2}{4\theta}\right) \qquad (1)$$

where $Pe = uL/E_C$

$\theta = t/\bar{t}$

E_c = axial dispersion coefficient

$\bar{t}$ = holding time

Moment matching method is widely used to find an axial dispersion coefficient or Peclet number. Further, for an optimum value which expresses satisfactorily the flow characteristics of the equipment, the response surface method [9] has advantages of its simpler algorithm and higher computing efficiency by using multi-linear regression and factorial design.

In following regression equation,

$$y_j = b_0 + b_1X_{1j}(Pe) + b_2X_{2j}(\bar{t}) + \varepsilon_j \qquad (2)$$

X_1 and X_2 are the functions of the parameters Pe and $\bar{t}$ respectively, in the dispersion model, and response, y, is the sum of square of concentration differences between the experimental and theoretical values as expressed in the following equation.

$$y = \sum_{i=1}^{n} (C_{i,exp} - C_{i,theo})^2$$

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Regression coefficients (b_0, b_1, b_2) in the Equation (2) can be found with a two-level two-factor factorial design upon the two independent variables for minimizing the errors. These coefficients give the steepest decent path that minimizes the y values. Therefore, Pe and $\bar{t}$ can be approached to its desired values along the path.

If the regression equation is represented in a matrix form, it is shown that

$$Y = XB + E \tag{4}$$

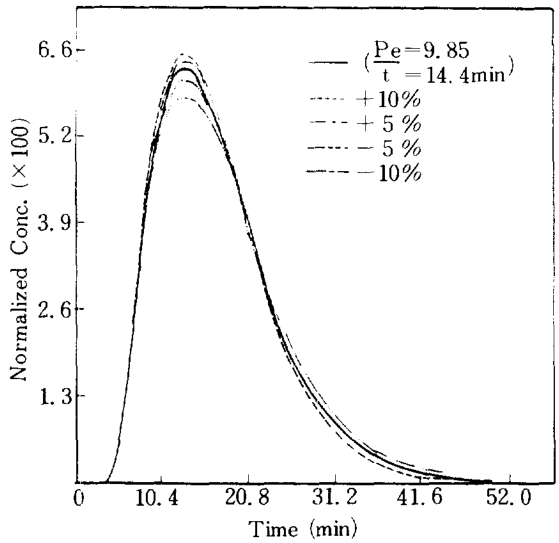


Fig. 1. Effect of Peclet Number on Residence Time Disribution Curve.

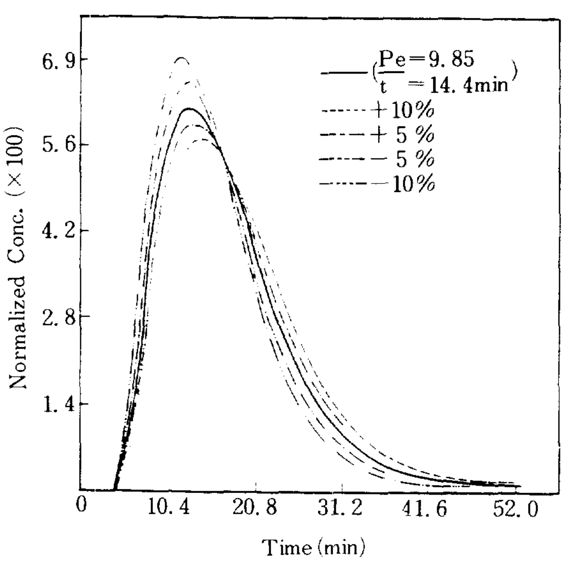


Fig. 2. Effect of Holding Time on Residence Time Distribution Curve.

The regression coefficient vector (B) is calculated from the following transformation.

$$B = (X^T X)^{-1} (X^T Y) \tag{5}$$

The deviations of the RTD (residence time distribution) curve caused by the change in Pe and $\bar{t}$ are shown in Fig. 1 and 2. Because deviations of the experimental values from the theoretical ones obtained by moment matching method were within the range of ± 10%, the initial values used in factorial design were obtained by the moment matching method. And ±5% of the initial values were considered as two levels of factorials, high and low.

Fig. 3 illustrates the steepest path by 2-level 2-factor factorial design and the hypothetical response surface of Pe and $\bar{t}$.

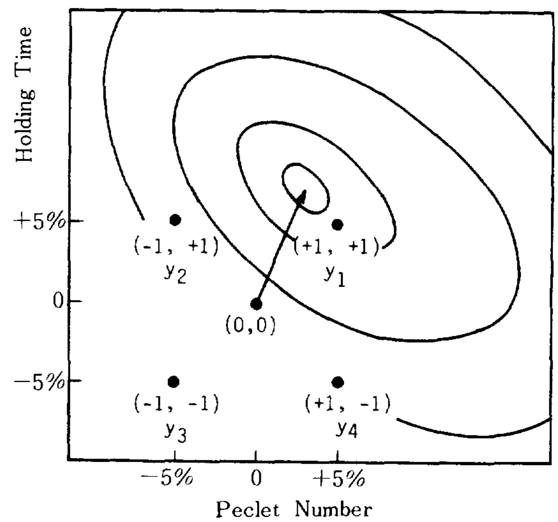


Fig. 3. Hypothetical Response Surface and Factorial Design.

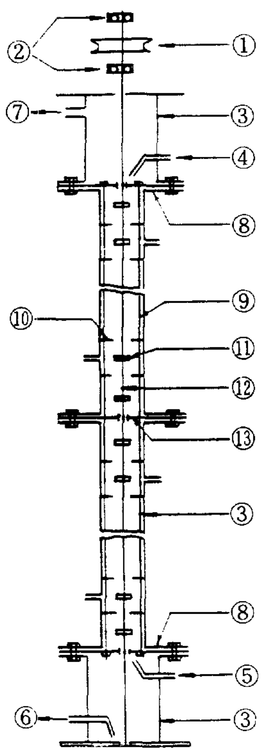
EXPERIMENT

1. Experimental apparatus

Fig. 4 shows the agitated blade impeller column used in this study. The column was made of Pyrex glass, 4.66 cm I.D.,and impellers were attached to the rotating shaft at a regular distance apart (2.5cm). All parts contacted with the solution in the column were made of stainless steel 304L.

The schematic flow diagram of the equipment is shown in Fig. 5. An air bottle was located between the pump and the rotameter to prevent severe fluctuation of the float in the rotameter due to pulsation generated by the pump. Solenoid valves were set up at the inlet and outlet of the fluid to measure the hold-up.

A tracer was injected at 18 cm below the upper end of the mixing zone, and a little amount of the solution was withdrawn at 83 cm below that end, then passed through a phase separator and to an electric cell. Because of this arrangement the end effects in the column were eliminated, and the boundary conditions of the open-open system could be used satisfactorily. The tracer concentrations were measured with a capacitance bridge.



1 Pulley
2 Bearing
3 Pyrex glass
4 Heavy phase inlet
5 Light phase inlet
6 Heavy phase outlet
7 Light phase outlet
8 Acryl flange
9 Spacer
10 Stator ring
11 Blade impeller
12 Rotating shaft
13 Shaft holder

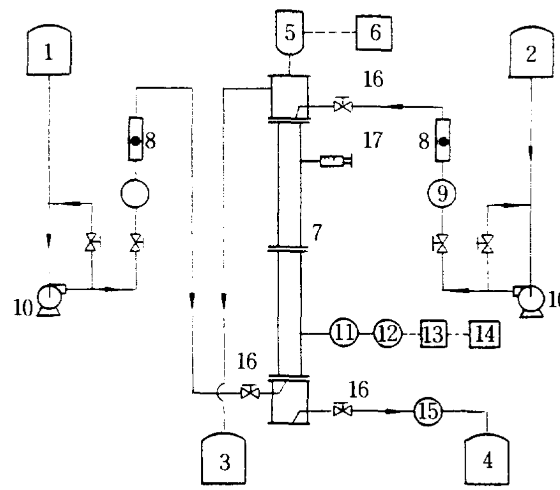
Fig. 4. Details of Agitated Blade-Impeller Column.

2. Experimental Procedure

The experiment was conducted in the system where distilled water as continuous phase and alkali-washed kerosene as dispersed phase.

Fig. 6 shows the operating state of the equipment, and the experiment was performed in the range of perfect mixing. The operating ranges for the experiment are listed in Table 1. As the tracer 0.2 M KCL solution was used, and its concentration in the continuous phase was measured by a capacitance bridge.

In analysis of the RTD curve, time lag was corrected by rechecking the exit flow rate of each phases and measuring the exit velocity of the tracer during the experiment. When the tail end of the RTD curve approached the base line and not changed, the RTD experiment was ended.



1 Org. feed tank
2 Aq. feed tank
3 Org. reservior
4 Aq. reservior
5 DC Motor
6 DC Power supply
7 Agitated column
8 Rotameter
9 Air bottle
10 Pump
11 Phase separator
12 Electric cell
13 Capacitance bridge
14 Recorder
15 Level adjuster
16 Solenoid valve
17 Tracer injection

Fig. 5. Schematic Flow Diagram.

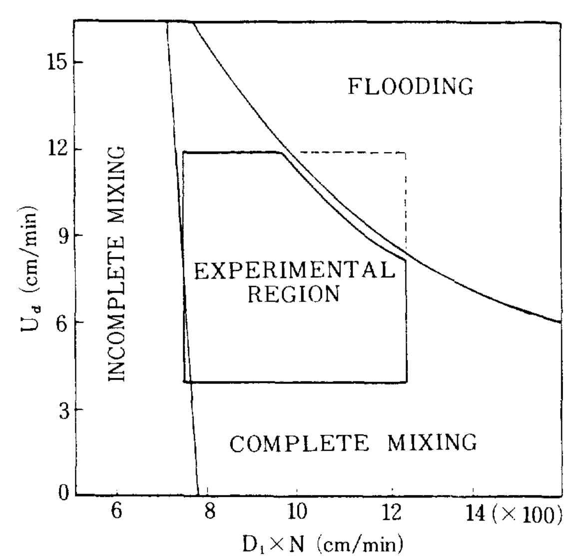


Fig. 6. Operating Region.

The hold-up of the dispersed phase was measured by reading volume ratio of the two phases in the column after closing inlet and outlet by using the solenoid valves.

Table 1. Experimental Variables.

Variable	Range
impeller diameter (D_i, cm)	2.5—3.0
impeller speed (N, rpm)	250—500
compartment height (H, cm)	2.4—9.6
velocity of water (U_c, cpm)	4.0—12.0
velocity of kerosene (U_d, cpm)	4.0—12.0

RESULTS AND DISCUSSION

1. Flow characteristics

An experimental curve by means of the impulse input of tracer in the single phase and the theoretical values calculated from the axial dispersion model is given in Figure 7. Peclet number was obtained by using the moment matching method and the response surface method. In comparison of the standard deviation of 1st moment (mean) with that of 2nd moment (variance), theoretical values by 2nd moment were better represented to the experimental values, and that by optimization was shown to be the best to the experimental.

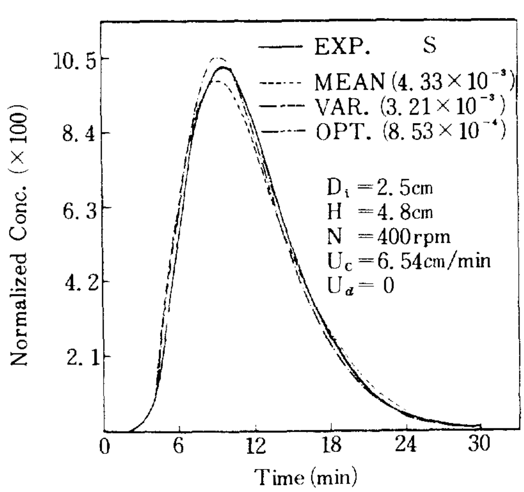


Fig. 7. Comparison between Experimental and Theoretical Concentration in Single-Phase Flow System.

In operation for a kerosene-water system, since droplets in the dispersed phase were accumulated in the column and the effective cross sectional area of the column was not constant, the observed holding time could be longer than the designed. Therefore, the holding time was corrected by the optimization method and the parameters (Pe and $\bar{t}$) were obtained by the moment matching method and response surface method. The theoretical values calculated from these parameters would fit well with the experimental ones as shown in Fig. 8. Therefore, in the range of perfect mixing in Fig. 6, flow characteristics of the agitated blade impeller column could be well expressed with the axial dispersion model.

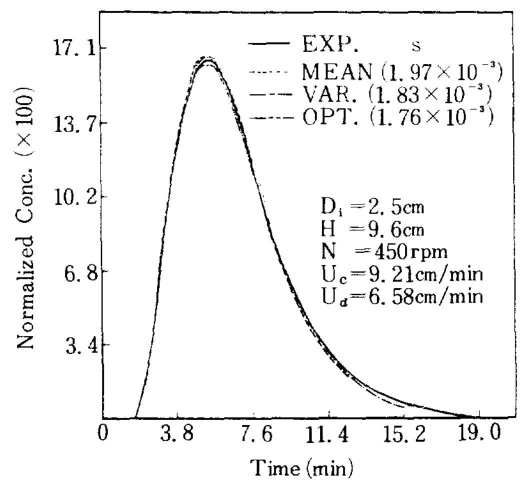


Fig. 8. Comparison between Experimental and Theoretical Concentration in Two-Phase Flow System.

2. Axial dispersion coefficient in single-phase flow

Peclet number and holding time were obtained by the optimization technique described in previous section and the axial dispersion coefficient was obtained from these values.

As the dispersion coefficient showed the degree of backmixing, its correlation was investigated on the design factor of the equipment and the operational variables. It was found that impeller diameter and rotating speed had a large influence on the dispersion coefficient, while flow velocity had little influence on it. From regression of 130 data, following correlation equation was obtained.

$$E_c = 0.015\, D_i^{0.74} N^{1.07} H^{0.39} u_c^{0.02} \quad (6)$$
$$(s = 2.514)$$

As shown above the influence of flow velocity was small, and could be neglected. When regressed with no velocity term, the dispersion coefficient were correlated by the following equation with standard deviation of 2.535, and the deviation was almost the same in Eq. (6).

$$E_c = 0.015\, D_i^{0.74} N^{1.08} H^{0.39} \quad (7)$$
$$(s = 2.535)$$

Fig. 9 illustrates the values calculated from Equation (7) and experimental data. Most of the experimental values were within the range of ± 10% of the calculated.

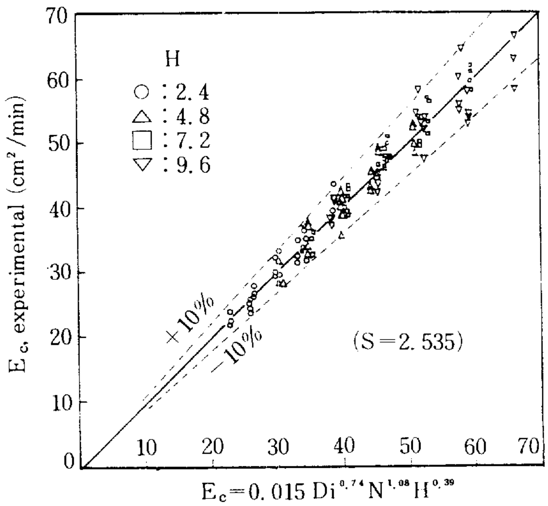


Fig. 9. Correlation of Axial Dispersion Coefficient in Continuous Phase.

On the other hand, a correlation of the reciprocal of local Peclet number (E_c/U_cH) and the Reynolds number of the impeller was illustrated in Fig. 10 in comparison with the results of Bibaud and Treybal [10]. Axial dispersion coefficient of the equipment was also shown to be within the range of the rotary disc column. Though the result of Bibaud [2] was much the same with this work in its tendency, their values were a little higher. It is probably due to the difference of geometrical structures of the impeller.

3. Axial dispersion coefficient in the two-phase counter-current flow

In the operation of two-phase flow, as in the case of the single-phase flow, diameter of impeller, rotating speed of the impeller and compartment height had a large influence on the axial dispersion coefficient but flow velocity change of each phase had little influence. The coefficient in the two-phase flow was shown to be a little higher than in the single phase. It seems to be due to following facts; the existance of droplets increased the mixing effect and, at the same time, backmixing was increased by the rising droplets in the opposite direction to the flow of continuous phase.

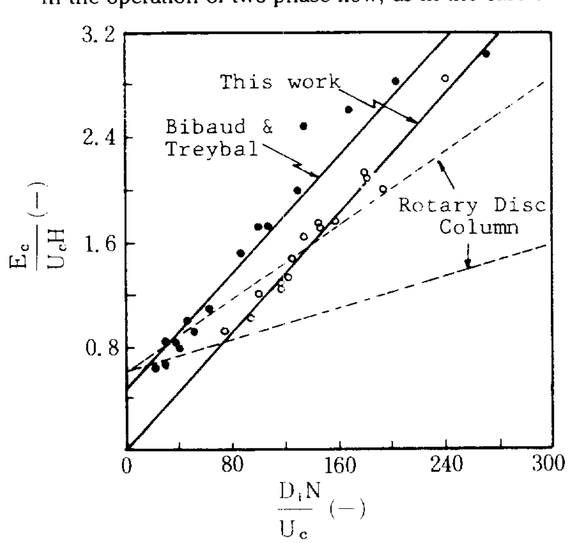


Fig. 10. Axial Dispersion Coefficient in Single-Phase System.

The following empirical equation was obtained with regression of 100 data

$$E_c = 0.109\, D_i^{1.16}\, N^{0.69}\, H^{0.48} u_c^{0.02}\, u_d^{0.03} \qquad (8)$$

As shown in this equation, the effect of flow velocity of each phase on E_c was small, and could be neglected. By regression of without these velocities, the empirical equation was expressed as follow;

$$E_c = 0.119\, D_i^{1.14}\, N^{0.70}\, H^{0.48} \qquad (9)$$

$$(s = 2.88)$$

Fig. 11 shows that the calculated values of Eq. (9) compared with experiments. Most of experimental values were within the range of ± 10% of the calculated.

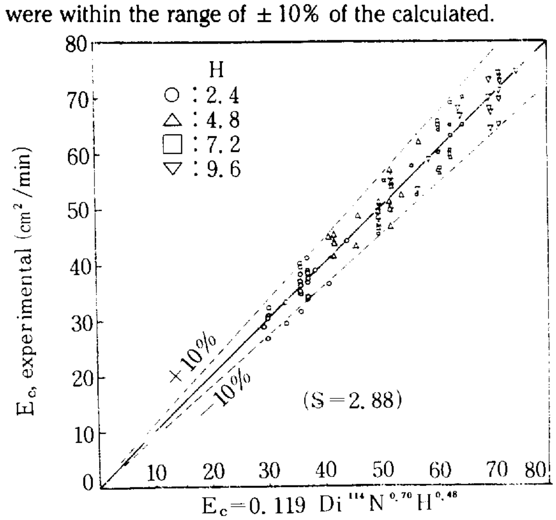


Fig. 11. Correlation of Axial Dispersion Coefficient for Continuous Phase in Two-Phase Flow System.

4. Hold-up of the dispersed phase

In two-phase operation, the higher the degree of mixing by an impeller, the smaller the size of droplet in the dispersed phase. As the droplets become smaller, the droplets rised in the column more slowly. In fact, the residence time and the hold-up on the dispersed phase increased.

The following correlation equation was made by regression of 95 measured data of the hold-up;

$$\phi d = 8.33\times10^{-17}\, D_i^{6.20}\, N^{4.37}\, H^{-0.06}\, u_c^{0.31}\, u_d^{1.23} \qquad (10)$$

$$(s = 0.019)$$

As shown in this equation, impeller diameter and rotating speed had a great influence on the hold-up of the dispersed phase. Also the influence by the velocity of the dispersed phase could not be negligible. However, the effect of the compartment height was small compared with other factors, and could be neglected. The correlation equation neglecting the height effect was given, and most experimental values were within the range of ± 20% of the calculated values as shown in Fig. 12.

$$\phi_d = 7.05 \times 10^{-17} D_i^{6.19} N^{4.38} u_c^{0.33} u_d^{1.23} \quad (11)$$

(s = 0.20)

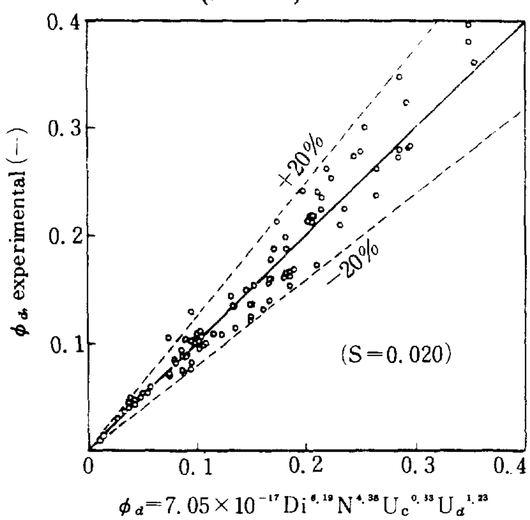


Fig. 12. Correlation of Dispersed Phase Holdup Ratio(organic/total).

CONCLUSIONS

1. Flow characteristics in the column with agitated blade impellers used in this study could be well expressed by an axial dispersion model.
2. The most reliable values of Peclet number and holding time were obtained with response surface method. Axial dispersion coefficients were obtained from these values with using the axial dispersion model.
3. The correlation equations for axial dispersion coefficient (E_c) of the continuous phase and hold-up (ϕ_d) of the dispersed phase were obtained by regression of experimental data.
   a. Axial dispersion coefficients in the single-phase flow:
   $$E_c = 0.015\ D_i^{0.74}\ N^{1.08}\ H^{0.39}$$
   b. Axial dispersion coefficients of the continuous phase in the two-phase countercurrent flow;
   $$E_c = 0.119\ D_i^{1.14}\ N^{0.70}\ H^{0.48}$$
   c. Hold-up of the dispersed phase;
   $$\phi_d = 7.05 \times 10^{-17}\ D_i^{6.19}\ N^{4.38}\ u_c^{0.33}\ u_d^{1.23}$$

NOMENCLATURES

- b : regression coefficient
- B : regression coefficient vector
- C : normalized tracer concentration (-)
- D_i : impeller diameter (cm)
- E_c : axial dispersion coefficient for continuous phase (cm^2/min)
- E : error (ε) vector
- H : compartment height (cm)
- L : column length (cm)
- Pe : uL/E_c, Peclet number
- s : standard deviation
- t : time (min)
- $\bar{t}$: L/u, holding time (min)
- u : superficial velocity (cm/min)
- x : independent variable
- X : matrix of independent variable
- X^T : transpose of X
- y : response
- Y : response vector
- ε : error
- θ : $t/\bar{t}$, dimensionless time
- ϕ_d : fractional holdup

Subscripts

- c : continuous phase
- d : dispersed phase
- exp : experimental
- theo : theoretical

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