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A Study into the Dynamic Behaviour of Packed Distillation Columns

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Abstract

The study of the dynamic behaviour of packed distillation column was studied by frequency response analysis using Matlab program. A packed distillation column (80 mm diameter) (2000 mm height) filled with glass packing (Raschig Rings 10mm), packing height (1500 mm) has been modified for separation of methanol-water mixture (60 vol%). The column dynamic behaviour was studied experimentally under different step changes in, feed rate (±30%), reflux rate (±22%), and reboiler heat duty (±150%), the top and bottom concentration of methanol were measured. A frequency response analysis for the above step response was carried out using Bode diagram, the log modulus and the phase angle were used to analyze the process model. A Matlab program was used to study the dynamic model for continuous packed distillation to predict the transient response to a step change in feed rate, reflux rate and reboiler heat duty. It also used to find the frequency response analysis using experimental data and the results were compared with ARX(Auto Recursive) model, then the plot of Bode diagram was carried. Finally the transfer function to step change in feed rate was found and represented by second order as shown in equation below.

$$G_{(S)} = \frac{K_P(\tau_2^2 s^2 + 2\Psi_2\tau_2 s + 1)}{(\tau_1{}^2 s^2 + 2\Psi_1\tau_1 s + 1)}$$

For reflux rate change, it was found that for the top concentration, it can be represented by first order (lead – lag system).

$$G_{(S)} = \frac{K_P(\tau_2 s + 1)}{(\tau_1 s + 1)}$$

Finally a comparison between the experimental and theoretical response curves were made, it was found that the model obtained from Matlab program (Bode diagram) gave a good agreement with experimental data while the model obtained using process reaction curve method shows a deviation between the theoretical and experimental data.

Keywords: packed distillation columns.

Introduction

Distillation columns are the subject of many dynamic and control studies because of their unique and challenging control problems. Considered five methods of solution to find the most rapid and general method for solving the equations governing mass transfer in distillation column[1].

The dynamic characteristic of a 21-plates distillation column has been investigated by [2]. The comparison has been made between the models and the experimental results.

Developed a general method for determining the dynamic characteristics of distillation system from steady state-operating conditions. The responses to such disturbances were approximated by two time constants which were fitted to the product streams composition transients [3].

Studied the dynamic behavior of thermally coupled distillation processes. A dynamic mathematical model has been developed which is suitable for thermally coupled distillation processes [4].

Mathematical models for the transient response of a packed distillation column in the reflux ratio have been given by Cohen in 1940, Marshall and Pigford in 1948, Jawson and Smith in 1954, and Heinke and Wagner in 1966.

The experimental work on the transient response of packed column was done by [5]. They studied the response of the composition to a step change in the reflux ratio using benzene-trichloroethylene mixtures[5].

formulated a rigorous dynamic model based on fundamental chemical engineering principles for a packed distillation column separating a mixture of cyclohexane and n-heptane. This model was simplified to a form suitable for use in on-line model predictive control calculations[6].

applied frequency response and impulse response method, in order to determine the coefficient of axial dispersion and internal diffusion in packed beds from experiments performed at various Reynolds numbers[7].

Today Matlab capabilities extend beyond the original "Matrix Laboratory" [9].

Matlab has grown into the best platform available for several specialized scientific and technical visualizations and simulations. It is a collection of files containing algorithms to be used for modeling, analysis and design of continuous and discrete systems [8].

Experimental Work

Experimental equipment

The packed distillation column is 2m high, 8cm in diameter filled with packing of height 1.5m. The subcooled feed is introduced to the column from constant head tank at mid of the column. The flowsheet illustrating the equipment is shown in fig.1.

A reboiler (B) operating on thermosyphone principle is heated by an electrical heater.

The vapour produced from the column are condensed at the top in a condenser (C) , the distillate is separated into reflux, which is passed back to the column via a rotameter (R-1) , and a product which passes through a rotameter (R-2), to a cooler (D) and then through a graduated pipe section (E) to a collection vessel.

Three vent lines are provided, the first one at the top of the column, the second, to the collecting vessel of the distillate and the third, to the collecting vessel of the bottom product.

The cooling water flowrate to the cooler and top condenser is measured using a rotameter (R-3), with capacity (0 - $25*10^{-5}$ m^3/sec).

The feed is kept in a 25 liter size vessel (F), and then it is pumped to the column by means of a centrifugal pump (G) via a constant head tank to give constant flowrate to the column. The feed rate is measured by a rotameter (R-4) over a range of ($83*10^{-8}$-$15*10^{[illegible]}$ m^3/sec).

Experimental procedure

The solution with the desired concentration of (methanol-water system) was prepared using. A step by step start up producer as follows.

1. Initially the column was empty. A certain liquid level of feed mixture (methanol-water) was maintained in the reboiler (vessel & heater) through the charge port, using the bottom level controller.
2. The electrical reboiler heater was switched on maintaining the heat supply at the required constant value by the adjustment of the heater controller (HC), vapours started moving up, got internally condensed and swept from the packing.
3. The overhead condenser started to operate as the vapours left top section and totally condensed, then the reflux separator started to fill up.
4. Close the valve of the product to get total reflux condition, so as to maintain constant level in the reflux separator.

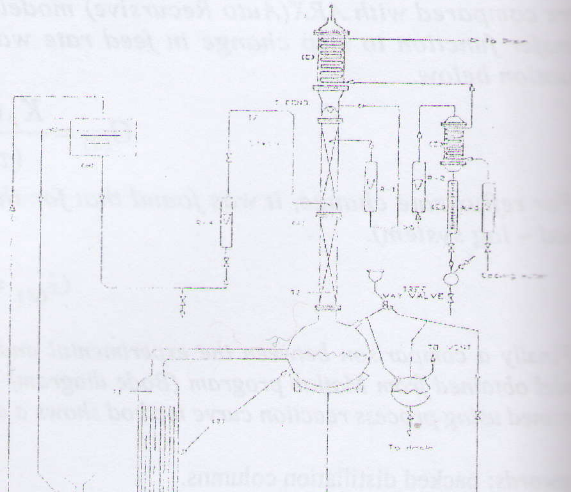

Fig. 1 Experimental apparatus flow diagram

5. After reaching steady state condition, subcooled feed (25°C) and 60 vol% was started to flow in to the heated column through the rotameter (R-4) at a fixed rate.
6. After the column reached steady state under the above conditions, its operation was slowly changed from total reflux to the operating reflux, by adjustment the valve opening, and the product was taken out.
7. Column was allowed to run without changing operating condition until steady state was reached.

The time required for steps (1-7) was about (1-1.5) hour. A fter steady state conditions were achieved, three separate experiments were done for positive and negative step changes.

Computer simulation

Direct method: time-domain fitting of step test data

The most direct way of obtaining an empirical linear dynamic model of a process is to find the parameters (dead time, time constant, and damping coefficient) that fit the experimentally obtained step response data. The process being identified is usually open loop, but experimental testing of closed loop systems is also possible [10].

Direct method: direct sine wave testing

The input of the plant, which is usually a control valve position or a flow controller set point, is varied sinusoidally at a fixed frequency ω. After waiting for all transients to die out and for a steady oscillation in the output to be established, the amplitude ratio and phase angle are found by recording input and output data. The data point at this frequency is plotted on a Nyquist, Bode, or Nichols plot.

Step testing

To calculate the frequency response characteristics, the transfer function which is in the (s) domain can be found. In general this can be represented as:

$$G(s) = \frac{X(s)}{Q(s)} \tag{1}$$

We multiply both numerator and denominator by s, which is equivalent to differentiation in the time domain [10].

$$G(s) = \frac{SX(s)}{SQ(s)} \tag{2}$$

$$G(s) = \frac{\int_0^\infty \left(\frac{dx}{dt}\right) e^{-st}\,dt}{\int_0^\infty \left(\frac{dQ}{dt}\right) e^{-st}\,dt} \tag{3}$$

MATLAB Program

The calculated frequency response from experimental tests can be done by using Matlab program.

The input and output functions are the form of Fourier transform are divided to give the system transfer function in the frequency domain G (i□). These calculations can be done using the Spectral Analysis function (**spa**) in Matlab. The vector of input values (u) and output values (y) are combined into the vector z.

$$z = [y \quad u];$$

The sampling time (ts) and the frequency range of interest (□are defined; then spa is used to get the frequency response. The simple version is

$$g = spa(z);$$

Bode plots can be generated by calculating the magnitude ratios and phase angles of G by using the getff command.

$$[\omega, mag, phase] = getff(g);$$

We want to obtain an experimental linear dynamic model of the system in the form of G (i□). It must be a linear model since notion of a transfer function applies only to a linear system. The process is usually nonlinear, and we are obtaining a model that is linearized around the steady- state operation level.

Results and Discussion

The responses of the outlet concentration of a binary mixture to different step changes in feed rate of water-methanol mixture, reflux rate and reboiler heat duty are shown. The system responses were analyzed and studied in both time and frequency domains.

Effect of reboiler duty

Time domain

The distillation column was operated at different heat duties for fixed feed and reflux rates. The responses of top and bottom concentrations to negative and positive step changes in reboiler heat duty are shown in fig. 2 to 5. Fig. 2 & 3 show the time and step response of top and bottom concentration for 150% positive step change. From these figures it can be seen that as the heat duty of reboiler increases the top and bottom concentrations decrease.

To represent the dynamics process model, two-transfer function can be drawn using: -

A. Bode diagram method.
B. Process reaction curve method.

The transfer function obtained using Bode diagram method is a lead and lags process (first order) for top and bottom.

$$G_{(S)} = \frac{K_P(\tau_2 s + 1)}{(\tau_1 s + 1)} \quad (4)$$

The numerical values of K_p, τ_1 and τ_2 for positive and negative step change are shown in table 1.

The transfer function obtained using process reaction curve method is first order lag with dead time process.

$$G_{(S)} = \frac{K_p e^{-t_d s}}{(\tau_p s + 1)} \quad (5)$$

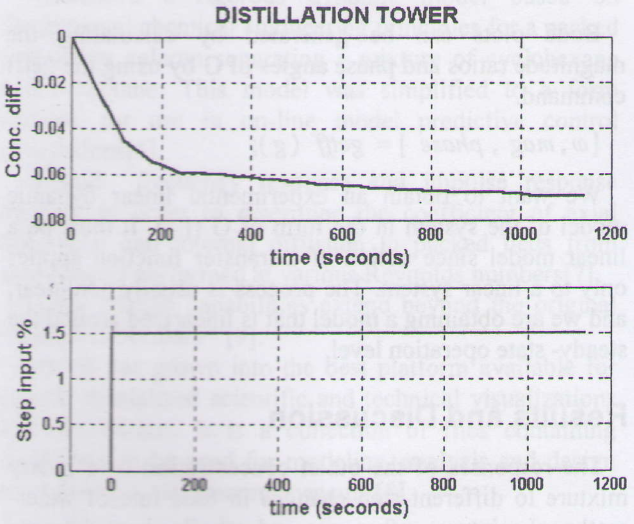

Fig. 2 Top concentration response to positive step change in heat duty

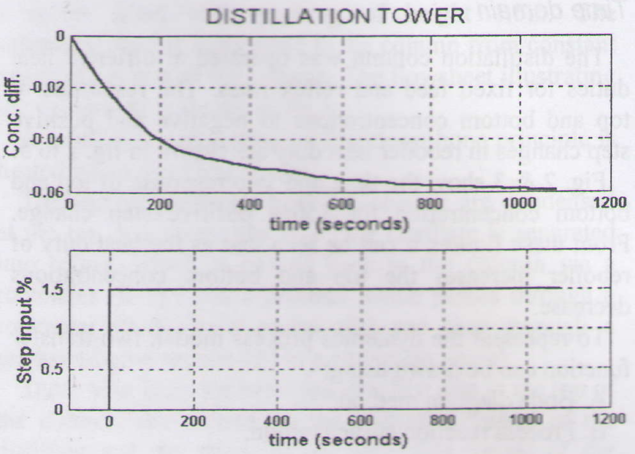

Fig. 3 Bottom concentration response to positive step change in heat duty

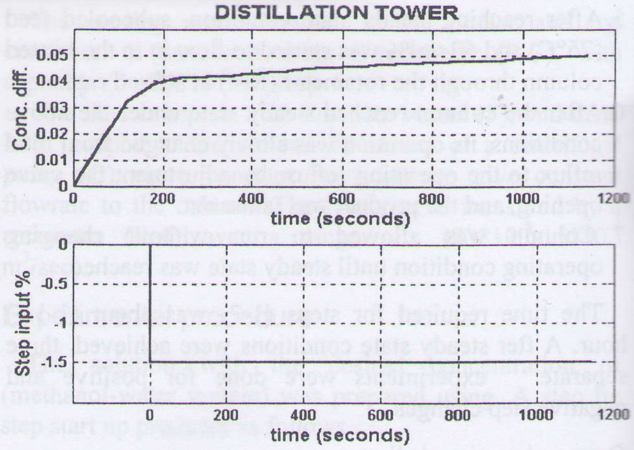

Fig. 4 Top concentration response to negative step change in heat duty

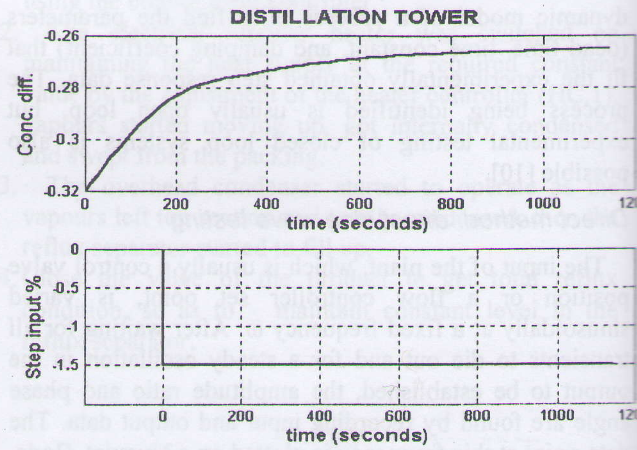

Fig. 5 Bottom concentration response to negative step change in heat duty

Frequency domain

To study the behavior of the packed distillations column, frequency analysis technique was used namely bode diagram.

Useful qualitative information on the parameter on the dynamic behavior about the packed distillation column can be obtained from Bode diagram.

Fig. 6 to 9 shows Bode plot for experimental data and ARX model at positive and negative step changes in heat duty of reboiler.

By analysis of Bode plot, first order lead with lag transfer function were obtained to represent the packed distillation column, the transfer function is:

$$G_{(S)} = \frac{K_P(\tau_2 s + 1)}{(\tau_1 s + 1)} \quad (6)$$

The numerical values of K_p, τ_1 and τ_2 are shown in table 1.

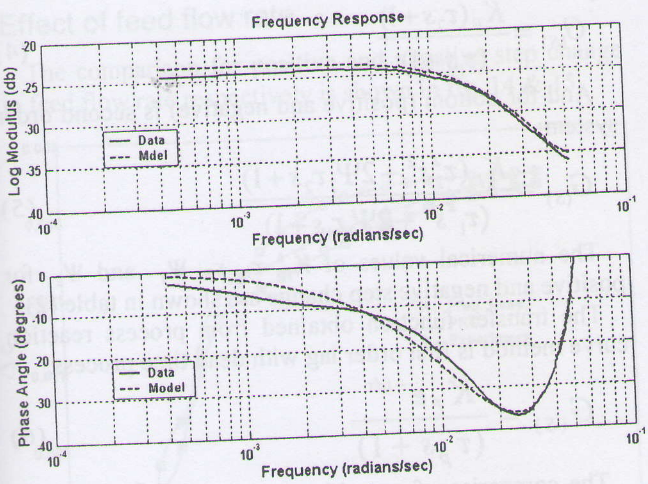

Fig. 6 Bode diagram of top Conc. for positive step change

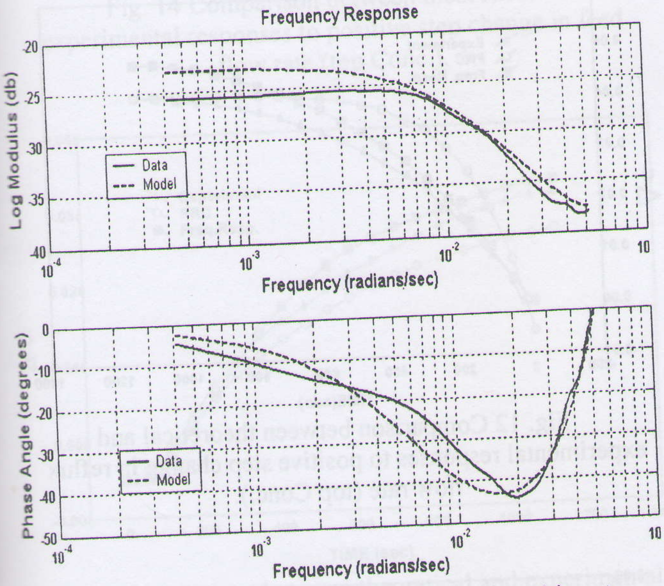

Fig. 7 Bode diagram of bottom Conc. for positive step change

Table 1 Parameters of transfer function for reboiler load step change

Experiments		Bode method			PRC Method		
Parameters		K_p	τ_1	τ_2	K_p	τ_p	t_d
Positive Step	Top	0.067	0.99	0.49	-0.0218	3.32	0.2
	Bottom	0.071	2.12	0.72	-0.018	3.42	0.2
Negative Step	Top	0.046	0.95	0.47	0.017	2.37	0.2
	Bottom	0.069	2.26	0.74	0.015	3.4	0.2

From above figures; it can be seen that the response of positive step change in top and bottom columns is the same as the response of negative step change.

And also we know the gain is equal to the output steady state divided by the input steady state that means gain effect on steady state for transient response, while in frequency response its effect on magnitude gives phase shift equal to zero.

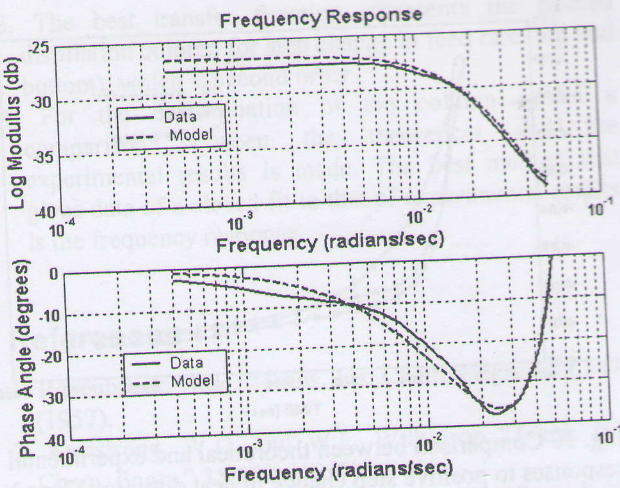

Fig. 8 Bode diagram of top Conc. for negative step change

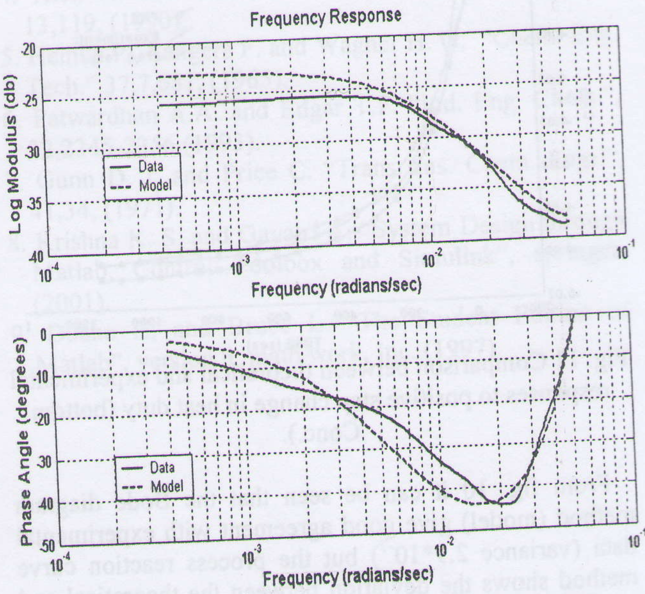

Fig. 9 Bode diagram of bottom Conc. for negative step change

Comparison between theoretical and experimental responses

Theoretical responses curve for distillation column analysis by two methods Bode diagram and process reaction curve were compared with experimental results.

The comparison was made in time domain for the step change in heat duty as shown in fig. 10 & 11 for positive step change; the negative step change response is the same as positive step change.

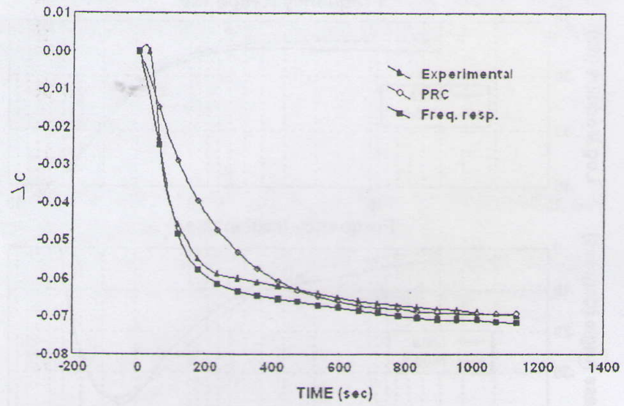

Fig. 10 Comparison between theoretical and experimental responses to positive step change in heat duty (top Conc.)

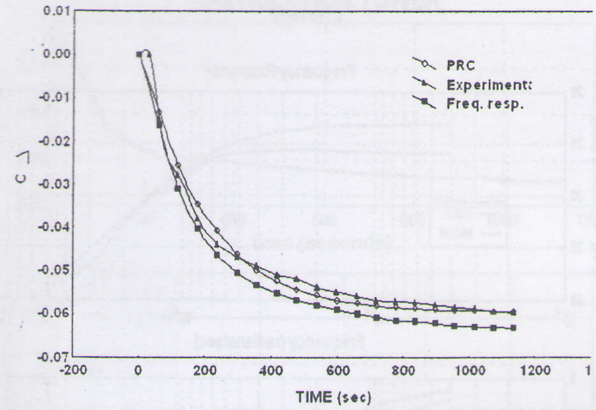

Fig. 11 Comparison between theoretical and experimental responses to positive step change in heat duty (bottom Conc.).

From fig. 10 it can be seen that the Bode diagram method (model) give good agreement with experimental data (variance $2.9*10^{-7}$) but the process reaction curve method shows the deviation between the theoretical and experimental data, then the transfer function obtained from Bode diagram method (model) does fairly good job for predicting the experimental results, such that it should be adequate for use in the design of control system.

Fig. 11 shows that the Bode diagram method (model) and process reaction curve method (variance = $5.5*10^{-7}$) are in good agreement with experimental data, then the transfer function obtained from any methods gives good job for predicting the experimental results, such that it should be adequate for use in the design of control system.

Effect of reflux ratio

The transfer function obtained using Bode diagram method is a lead and lag process (first order) for top (positive and negative).

$$G_{(S)} = \frac{K_P(\tau_2 s+1)}{(\tau_1 s+1)} \tag{4}$$

And for bottom (positive and negative) is second order system: -

$$G_{(S)} = \frac{K_P(\tau_2^2 s^2 + 2\Psi_2\tau_2 s+1)}{(\tau_1{}^2 s^2 + 2\Psi_1\tau_1 s+1)} \tag{5}$$

The numerical values of K_p, τ_1, τ_2, Ψ_1 and Ψ_2 for positive and negative step change are shown in table (2).

The transfer function obtained from process reaction curve method is first order lag with dead time process.

$$G_{(S)} = \frac{K_p e^{-tds}}{(\tau_p s+1)} \tag{6}$$

The comparison for positive and negative step change in reflux flow rate respectively is shown in fig. 12 and 13.

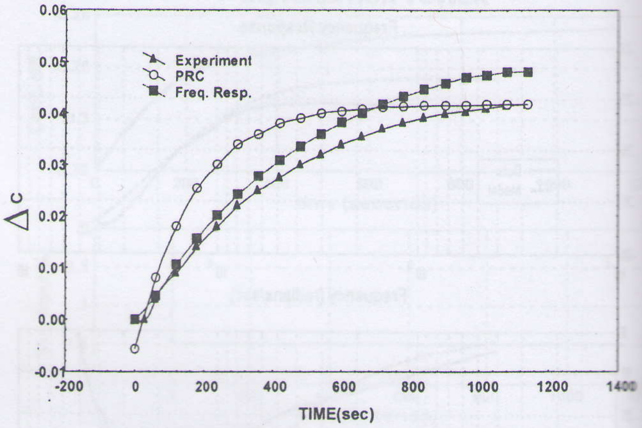

Fig. 12 Comparison between theoretical and experimental responses to positive step change in reflux flow rate (top Conc.).

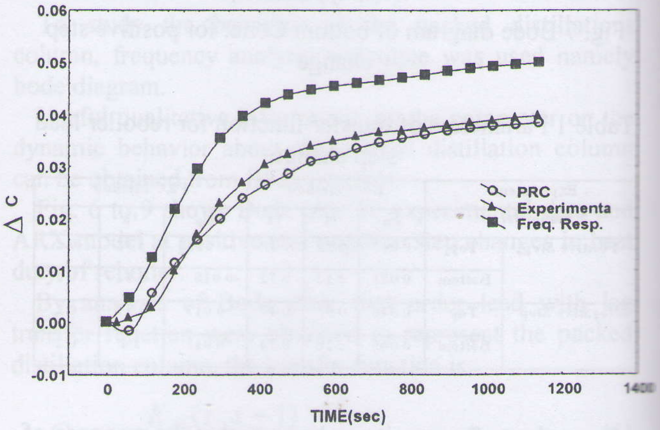

Fig. 13 Comparison between theoretical and experimental responses to positive step change in reflux flow rate (bottom Conc.).

Effect of feed flow rate

The comparison for positive and negative step change in feed flow rate respectively is shown in fig. 14 & 15.

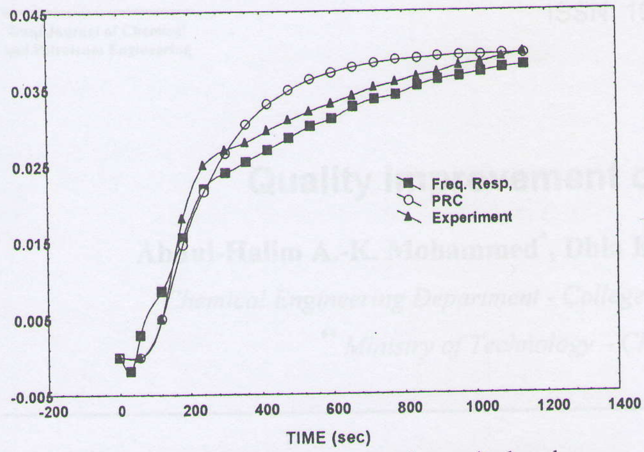

Fig. 14 Comparison between theoretical and experimental responses to positive step change in feed flow rate (top Conc.).

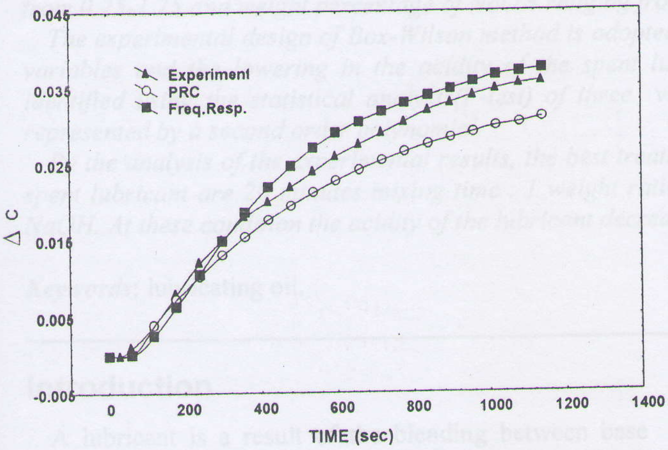

Fig. 15 Comparison between theoretical and experimental response to positive step change in feed flow rate (bottom conc.).

Conclusions

The following conclusions have been made from the results obtained: -

1. The capacity of distillation increases with increasing feed rate and reflux rate, while it decreases with the increasing heat duty of the reboiler.
2. The best transfer function represents the packed distillation column for step change in heat duty of reboiler (top and bottom), which is a first order (lead and lag)

$$G_{(S)} = \frac{K_p(\tau_2 s + 1)}{(\tau_1 s + 1)}$$

3. The best transfer function represents the packed distillation column for step change in feed rate (top and bottom), which is second order.
4. For the determination of the column model a comparison between the theoretical and the experimental results is made. The best method that gives data of a closed fit to that of experimental results is the frequency response.

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