CONTROLLER DESIGN BASED ON MODEL PREDICTIVE CONTROL FOR A NONLINEAR PROCESS

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ABSTRACT

Nowadays process industries require accurate, efficient and flexible operation of the plants. The need for development of innovative technologies for process modeling, dynamic trajectory optimization and high performance industrial process control is always a challenge. The process considered for modeling is a conical tank liquid level system. Control of liquid level in a conical tank is nonlinear due to the variation in the area of cross section with change in shape. Black box modeling is used to identify the system, which is identified to be nonlinear and approximated to be a First Order Plus Dead Time (FOPDT) model. Here the controller design is compared based on conventional Proportional Integral (PI) based on Skogestad's settings with Model Predictive Control (MPC).

KEYWORDS: Model, PI Controller, Tuning, Model Predictive Controller.

1. INTRODUCTION

Chemical process systems present many challenging control problems due to their nonlinear dynamic behavior, uncertain and time varying parameters, constraints on manipulated variable, interaction between manipulated and controlled variables, unmeasured and frequent disturbances, dead time on input and measurements. Most of the systems have inherent nonlinearity and so chemical process industries are in need of traditional control techniques. Conical tank find wide application in industries. Control of a level in a conical tank is important because the change in shape gives rise to the nonlinearity.

The most basic and pervasive control algorithm used in the feedback control is the Proportional Integral and Derivative (PID) control algorithm. PID control is a widely used control strategy to control most of the industrial automation processes because of its remarkable efficacy, simplicity of implementation and broad applicability.

Long history of its practical use and proficient working dynamics are some of the pivotal reasons behind the large acceptance of the PID control. In principle, the action of the controller is calculated by multiplying a constant factor with the error, the integral of the error and the derivative of the error [1]. Ziegler- Nichols [2] has developed a well known design methods to provide a closed-loop response with a quarter-decay ratio. A simple PI controller design method has been proposed by Wang and Shao [3] that achieves high performance for a wide range of linear self-regulating processes.

Ari Ingimundarson and Tore Hagglund [4] have compared the performance of PI, PID and dead-time compensating controllers based on the IAE criterion. A design method for robust PID controller to address the model uncertainty has been proposed by Ming Ge et al. [5]. Nithya et al. [6] have discussed about the control aspects of spherical tank using Internal Model based Controller [IMC] PI tuning settings in real time. They discussed that the IMC gives better performance in tracking the set point and load changes with faster settling time and exhibit less overshoot with no oscillation.

MPC refers to a family of controllers that employ a distinctly identifiable model of the process to predict its future behaviour over an extended prediction horizon. Richalet [7] have discussed advantages of multi variable predictive control. Deshpande et al. [8]. have discussed the importance of MPC in industries. Several review articles consider MPC from an academic perspective, e.g., Garcia et al. [9]. Morari, Ricker [10]. Rawlings and Muske [11] which discusses the existing linear model predictive control concepts in a unified theoretical framework based on a stabilizing, infinite horizon, linear quadratic regulator... as well as from an industrial perspective e.g. Richalet [7] , Froisy [12] and Camacho and Bordons [13].Y.L.Lee et al have discussed the effect of Constrained receding horizon predictive control for nonlinear systems[15]. Nithya et al [16] discussed about the predictive controller design for a shell and tube heat exchanger. The proved that the transient and steady state results obtained using MPC gives the better results compared to PI controller.

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In this work, real time model is designed for controlling the liquid level in a conical tank. The process model is experimentally determined from step response analysis and is interfaced to real time with MATLAB using simple cost effective ADAM's module. The different time domain comparison such as rise time, settling time and overshoot have compared based on model predictive controller tuning with conventional PI Controller settings.

2.EXPERIMENTAL SETUP

The laboratory set up for this system consists of a conical tank ,a water reservoir, pump, rotameter, a differential pressure transmitter, an electro pneumatic converter (I/P converter), a pneumatic control valve, an interfacing ADAM's module and a Personal Computer (PC). The differential pressure transmitter output is interfaced with computer using ADAM's 5000 Advantech module in the RS-232 port of the PC. This module supports 8 analog input and 4 analog output channels with the voltage range of ±10 volt. The sampling rate of the module is 18 samples per sec and baud rate is 9600 bytes per sec with 16-bit resolution. The programs written in script code using MATLAB software is then linked via this ADAM's module with the sampling time of 60 milliseconds.

The pneumatic control valve is air to close, adjusts the flow of the water pumped to the conical tank and spherical tank from the water reservoir. The level of the water in the tank is measured by means of the differential pressure transmitter and is transmitted in the form of (4-20) mA to the interfacing ADAM's module to the Personal Computer (PC). After computing the control algorithm in the PC control signal is transmitted to the I/P converter in the form of current signal (4-20) mA, which passes the air signal to the pneumatic control valve. The pneumatic control valve is actuated by this signal to produce the required flow of water in and out of the tank. There is a continuous flow of water in and out of the tank. Figure 1 shows the experimental set up of tank used for study. Table 1 gives the technical details of the experimental setup.

Figure 1: Real time experimental setup of conical tank

Table 1: Technical Specifications of Experimental Setup

Part Name	Details
Conical tank	Stainless Steel Height - 49.3 cm, Top Diameter - 33.74 cm, Bottom Diameter - 0.8 cm, α - 30'
Spherical tank	Stainless Steel Diameter - 50 cm
Differential Pressure Transmitter	Type Capacitance, Range (2.5 - 250)mbar, Output (4 - 20)mA Siemens make
Pump	Centrifugal 0.5 HP
Control valve	Size ¼" Pneumatic actuated Type: Air to close Input (3 - 15) psi
Rotameter	Range (0 - 18) Lpm
Air regulator	Size 1/4" BSP Range (0 - 2.2)bar
E/P converter	Input (4-20) mA Output (0.2 - 1) bar
Pressure gauge	Range (0 - 30) psi Range (0 - 100)psi

3.SYSTEM IDENTIFICATION

3.1Black Box Modeling

Here in real time implementation, system identification of this nonlinear process is done using black box modeling. For fixed input water flow rate and output water flow rate of the conical tank, the tank is allowed to fill with water from (0-50) cm. At each sample time the data from differential pressure transmitter i.e. between (4-20) mA is being collected and fed to the system through the serial port RS - 232 using ADAM's interfacing module. Thereby the data is scaled up in terms of level (in cm).Using the open loop method, for a given change in the input variable; the output response for the system is recorded. Ziegler and Nichols [17] have obtained the time constant and time delay of a FOPTD model by constructing a tangent to the experimental open loop step response at its point of inflection. The tangent intersection with the time axis at the step origin provides a time delay estimate; the time constant is estimated by calculating the tangent intersection with the steady state output value divided by the model gain.

Cheng and Hung [18] have also proposed tangent and point of inflection methods for estimating FOPTD model parameters. The major disadvantage of all these methods is the difficulty in locating the point of inflection in practice and may not be accurate. Prabhu and Chidambaram [19] have obtained the parameters of the first order plus time delay model from the reaction curve obtained by solving the nonlinear differential equations model of a distillation column. Sundaresan and Krishnaswamy [20] have obtained the parameters of FOPDT transfer function model by letting the response of the actual system and that of the model to meet at two points which describe the two parameters τ and θ. The proposed times t_1 and t_2 , are estimated from a step response curve. This time corresponds to the 35.3% and 85.3% response times. The time constant and time delay are calculated as follows

$$\tau = 0.67(t_2 - t_1) \quad (1)$$

$$\tau_D = 1.3t_1 - 0.29t_2 \quad (2)$$

At a fixed inlet flow rate, outlet flow rate, the system is allowed to reach the steady state. After that a step increment in the input flow rate is given, and various readings are noted till the process becomes stable in the conical tank. The experimental data are approximated to be a FOPDT model the model parameters are given for a conical tank,

$$G(s) = \frac{12.6\, e^{-.2.05s}}{53.6s + 1} \quad (3)$$

3.2 DESIGN OF MPC CONTROLLER

MPC refers to a family of controllers that employ a distinctly identifiable model of the process to predict its future behavior over an extended prediction horizon. A performance objective to be minimized is defined over the prediction horizon, usually as a sum of quadratic set point tracking error and control effort terms. This cost function is minimized by evaluating a profile of the manipulated input moves to be implemented at successive sampling instants over the control horizon. Closed loop optimal feedback is achieved by implementing only the first manipulated input move and repeating the complete sequence of steps at the subsequent sample time. This “moving horizon” concept of MPC, where the controller looks a finite time into the future, is illustrated in Figure 2.

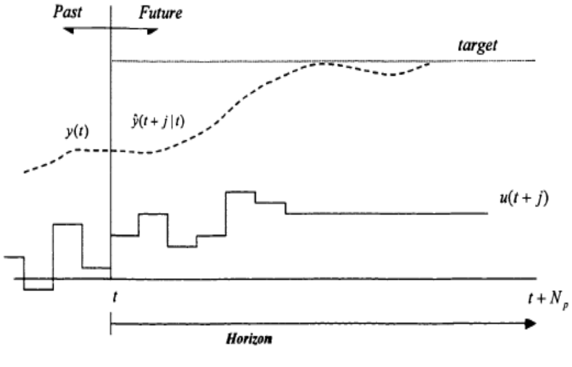

Figure 2: Moving horizon approach of Model Predictive Control

The Tuning Strategy for the MPC is done using Sridhar and Cooper [14] method. The idea behind predictive control is at each iteration to minimize a criterion of the following type:

$$J(t,U(t)) = \sum_{i=N_1}^{N_2} [r(t+1) - \hat{y}(t+i)]^2 + \rho \sum_{i=1}^{N_u} \Delta u(t+i-1)^2] \quad (4)$$

With respect to the Nu future control inputs

$$U(t) = [u(t)....u\ (t + N_u - 1)]^2 \quad (5)$$

and subject to the constraint

$$\Delta u(t + i) = 0,\ N_u \le i \le N_2 - d \quad (6)$$

r denotes the reference (the desired output), $\hat{y}$ a prediction of the output, and u the control input. Δ is the difference operator, $\Delta u(t) = u(t) - u(t-1)$. The tuning parameters of the controller are N_1 , N_2 , N_u and ρ .N_1 is called the minimum cost horizon, N_2 the prediction (or maximum cost) horizon, N_u and the (maximum) control horizon. ρ is a weighting factor penalizing changes in the control inputs. Figure 3 depicts the structure of MPC. Another important attribute is the notion of a control horizon which is smaller than the prediction horizon. The objective is that only the first N_u future control inputs are determined. From that point on, the control input is assumed constant. A long horizon allows a more active control signal, therefore enabling a higher performance, while a short horizon generally makes the control system more robust.

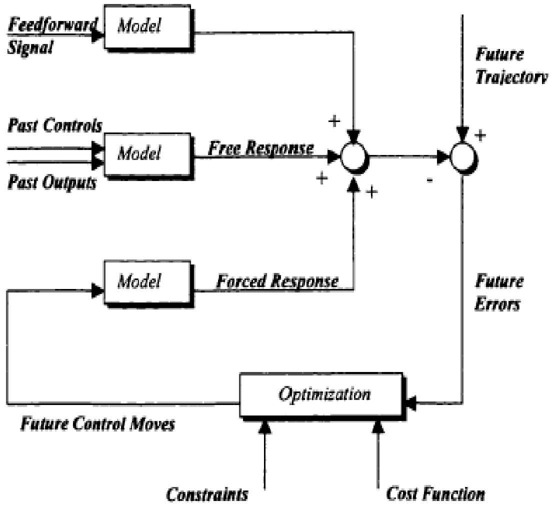

Figure 3: Structure of MPC System

4.RESULTS AND DISCUSSIONS

The adjustable parameters in this MPC controller that affect closed loop performance include the sample time, T, model horizon, N, finite prediction horizon, P and control horizon, M, the move suppressing weights for the manipulated and controlled variables. The controller was tuned using Sridhar and Cooper [14] tuning formula for an unconstrained system. The tuned parameters are listed in the Table 2 for conical tank. The weighting parameters are slightly detuned from the originally derived one and controllers tracking performance as shown in the Figure 4 – 6 for a set point of 7, 23 and 32 cm for the conical tank set up.

Table 2: Tuning for conical tank

Tuning Parameters	Values
Sampling time	1.025
Prediction horizon	264
Control horizon	55

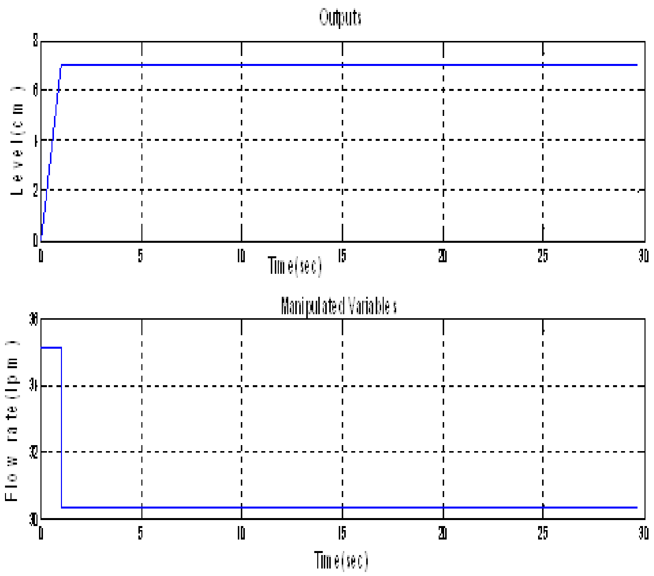

Figure 4: Sridhar and Cooper tuning for set point 7 cm

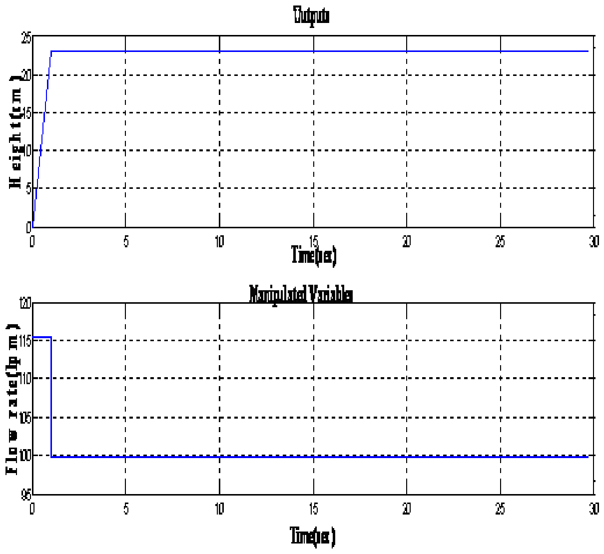

Figure 5: Sridhar and Cooper tuning for set point 23 cm

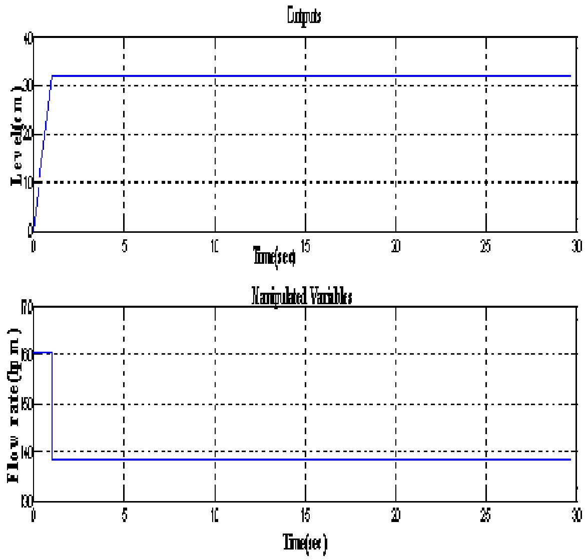

Figure 6: Sridhar and Cooper tuning for set point 32 cm

It was found that that the performance of MPC based tuning is better than a conventional PI controller tuning method. The performance of PI controller for different set points is shown in Figure 7-9.

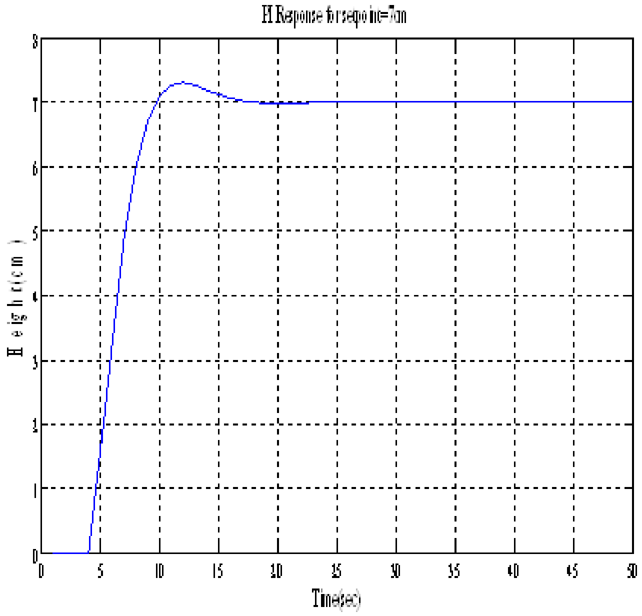

Figure 7: PI response for set point 7 cm for conical tank

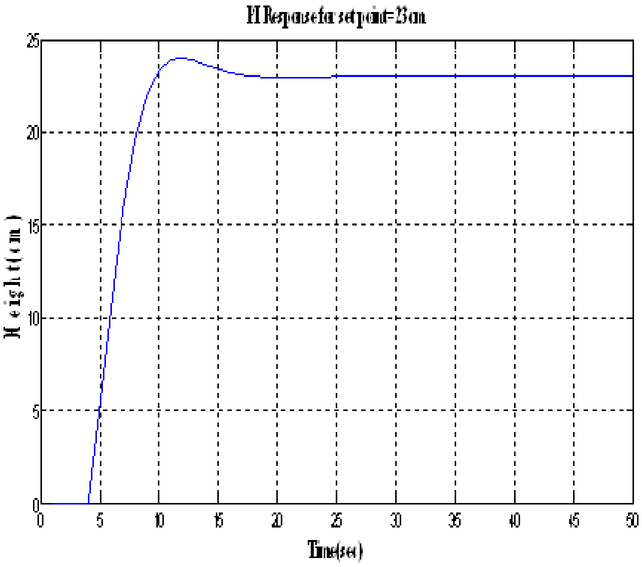

Figure 8: PI response for set point 23 cm for conical tank

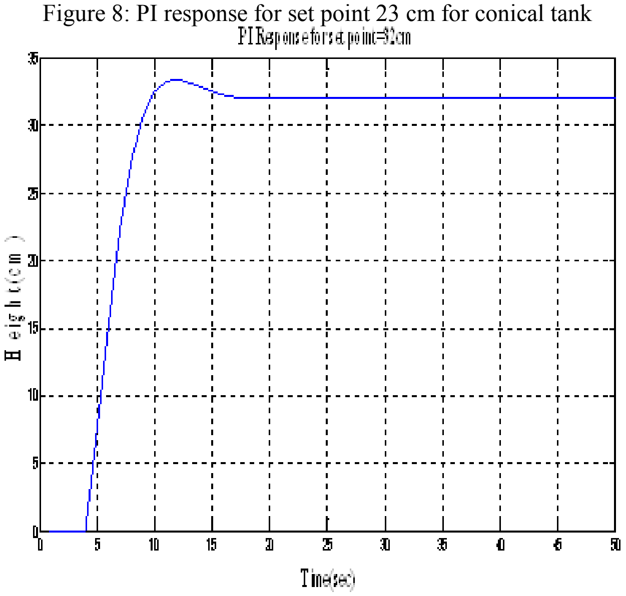

Figure 9: PI response for set point 32 cm for conical tank

It was found that the performance of MPC based tuning is better than a conventional PI controller Skogestad's tuning method. There is a strong demand for control in energy conservation in process control applications. It was observed that by carefully tuning the MPC using Sridhar and cooper method it was found that the overshoot of the system has drastically reduced when compared to a conventional PI controller. By repeated simulation it was found that the output prediction horizon should be larger than the system settling time. The control horizon should be larger than the expected transient time. For tracking problem the impact of the weighting vectors are very minimal. The effect of changes of control weighting seems that more the weighting the less active the input changes are. The transient and steady state performance comparison of a conventional PI controller tuned by Skogestad's method and a MPC is as shown in the Table 3.It was observed that MPC had almost eliminated the overshoot when compared to PI controller which shows a 4.3 % overshoot. The settling time was observed to be very less for a MPC and the performance was much faster also. The MPC based controller tracks the set point with faster rise time for the both cases.

Table 3: Time domain performance analysis for conical tank

Specifications	Set Point (cm)	PI	MPC
Overshoot (%)	7 cm	4.28	0
	23cm	4.34	0
	32 cm	4.36	0
Rise time (sec)	7 cm	9	1
	23 cm	9	1
	32 cm	9	1
Settling time (Sec)	7 cm	22	1.1
	23cm	25	1.1
	32 cm	26	1.1

5.CONCLUSION

An MPC based controller was designed for a conical tank system. The controller was tuned by using standard tuning technique and the transient and steady state performances were studied and compared with a conventional PI controller. This study was done in MATLAB simulation environment. It was observed that MPC based controller tuned by Sridhar and Cooper has performed well and it shows a better tracking capability than a conventional PI controller.

REFERENCES

[1] Luyben,W.L. Process modeling, simulation and control for chemical engineers,second edition, Tata McGraw Hill International : USA, 1990.
[2] Zeigler, J.G.; Nichols, N.B ; Optimum settings for automatic controllers Trans.ASME , 64, 759 – 768, 1942
[3] Ya-Gang Wang ; Hui-He Shao; Optimal tuning for PI controller. Automatica,,36, 147-152 , 2000
[4] Ari Ingimundarson.; Tore Hagglund .; Performance comparison between PID and dead-time compensating controllers. J. Proc. Cont, 12,887 – 895 , 2002
[5] Ming Ge.; Min-Sen Chiu.; Qing_Guo Wang.; Robust PID controller design via LMIapproach. J. Proc. Cont,, 12, 3-13, 2002

[6]Nithya ,S, Sivakumaran, N, Balasubramanian ,T, and Anantharaman, N, ,IMC based controller design for a spherical tank process in real time , National conference in Advanced Techniques in Instrumentation Control and Communication Engineering , Jan-2008. 173-178, 2008

[7] J. Richalet, "Industrial Applications of Model Based Predictive Control", Automatica, 29 (5), 1251, 1993

[8] P.B.Deshpande, J.A. Caldwell, S.S. Yerrapragada and M.A Bhalodia, "Should You Use Constrained Model Predictive Control" chem. Eng. Prog, March, 65, 1995.

[9] C.E Garcia, D.M.Prett and M. Morari, "Model Predictive Control: Theory and Practice-A Survey", Automatica ,vol 25 (3), 335, 1989.

[10] N.L.Ricker, "Model Predictive Control: State of the Art", In Proc.Chem. Process Cont. Conf., CPC IV, Fourth International Conference on Chemical Process Control, Amsterdam, Holland, 1991.

[11] J.Rawlings, K. Muske, "The Stability of Constrained Receding Horizon Control", IEEE Trans. Autom. Control, 38, pp 1512, 1993.

[12] J.B.Froisy, "Model Predictive Control Past, Present and Future", Trans., 33, 235.1994.

[13] E.F. Camacho, C. Bordons, "Model Predictive Control in the Process industry", Springer - Velag, London, 1995.

[14] R.Shridhar, D.J.Cooper, "A tuning strategy for unconstrained multivariable model predictive control", Ind & Eng.Chem.Res. vol. 37, pp 4003 - 4016, 1998.

[15] Y. I. Lee, B. Kouvaritakis and M. Cannon, "Constrained receding horizon predictive control for nonlinear systems", University of Oxford 13 June 2002.

[16] S.Nithya ,Abhay Singh Gour , N.Sivakumaran , T.Radhakrishnan and N.Anatharaman , Predictive controller design for a shell and tube heat exchanger , International Conference on Intelligent & Advanced Systems ICIAS 2007, Malaysia,2007.

[17] Ziegler, G. and Nichols, N. B,Optimum settings for automatic controllers, *Trans. ASME*, 64,759-768, 1942

[18] Cheng,G.S.; Hung,J.C ,A least-squares based self-tuning of PID controller, Proceedings of the IEEE South East Conference, North Carolina, 325-332, 1985

[19] Prabhu,E.S.; Chidambaram, M. ,Robust control of a distillation column by the method of inequalities, Indian Chem.Engr *,* 37, 181 – 187, 1991

[20] Sundaresan,K.R.;Krishnaswamy,R.R.,Estimation of time delay,Time constant parameters in Time, Frequency and Laplace Domains, Can.J.Chem.Eng,, 56,.257, 1978

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