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Dynamic Modeling, Optimization, and Control of Monoethanolamine Scrubbing for CO_2 Capture

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Dynamic Modeling, Optimization, and Control of Monoethanolamine Scrubbing for CO_2 Capture

by

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Dedication

With love to my parents, my husband and my daughter

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This work seeks to develop optimal dynamic and control strategies to operate post combustion CO_2 capture in response to various dynamic operational scenarios. For this purpose, a rigorous dynamic model of absorption/stripping process using monothanolamine was created and then combined with a simplified steady state model of power cycle steam turbines and a multi-stage variable speed compressor in Aspen Custom Modeler. The dynamic characteristics and interactions were investigated for the plant using 30% wt monoethanolamine (MEA) to remove 90% of CO_2 in the flue gas coming from a 100 MW coal-fired power plant.

Two load reduction scenarios were simulated: power plant load reduction and reboiler load reduction. An ACM® optimization tool was implemented to minimize total lost work at the final steady state condition by adjusting compressor speed and solvent

circulation rate. Stripper pressure was allowed to vary. Compressor surge limit, run off condition in rich and lean pumps, and maximum allowable compressor speed were found as constraints influencing the operation at reduced loads. A variable speed compressor is advantageous during partial load operations because of its flexibility for handling compressor surge and allowing the stripper and reboiler to run at optimal conditions. Optimization at low load levels demonstrated that the most energy efficient strategy to control compressor surge is gas recycling which is commonly applied by an anti-surge control system installed on compressors. Trade offs were found between initial capital cost and optimal operation with minimal energy use for large load reduction. The examples are, designing the stripper in a way that can tolerate the pressure two times larger than normal operating pressure, over sizing the pumps and over designing the compressor speed.

A plant-wide control procedure was used to design an effective multi-loop control system. Five control configurations were simulated and compared in response to large load variations and foaming in the stripper and the absorber. The most successful control structure was controlling solvent rate, reboiler temperature, and stripper pressure by liquid valve, steam valve, and compressor speed respectively. With the investigated disturbances and employing this control scheme, development of an advanced multivariable control system is not required. This scheme is able to bring the plant to the targeted set points in about 6 minutes for such a system designed initially with 11 min total liquid holdup time.Frequency analysis used for evaluation of lean and rich tanks on the dynamic performances has shown that increasing the holdup time is not always helpful to damp the oscillations and rejecting the disturbances. It means there exists an optimum initial residence time in the tanks. Based on the results, a 5-minute holdup can be a reasonable number to fulfill the targets.

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Chapter One: Introduction

1.1 Problem statement and literature review

Absorption/stripping using aqueous amine is a mature technology commonly used for removing CO_2 from natural gas, hydrogen, and other refinery gases, which makes it applicable to removing CO_2 from flue gas in coal-fired power plants. However, it is an energy intensive process and therefore needs special effort to be implemented economically in both design and operation.

For a coal-fired power plant using post-combustion amine absorption/stripping for CO_2 removal, full-load CO_2 capture could reduce net energy output by 11-40% from that of an equivalent plant without CO_2 capture. (Bergerson and Lave, 2007)

The bulk of this energy requirement is a consequence of the heat used for solvent regeneration and the work required to compress CO_2 to pipeline pressures for transport to a storage site. In a typical design, about 50% of the steam is extracted between the intermediate and low-pressure turbines, expanded in a let-down turbine that runs the CO_2 compression train, and then sent to the stripper column for solvent regeneration. The resulting increase in production costs, coupled with the high capital costs of CO_2 removal equipment, greatly hinder the economic viability of CO_2 capture.

A typical absorption/stripping system consists of two columns. In the absorber, which is operated at atmospheric pressure and 40-60°C, the flue gas from a coal-fired plant containing 10-12% CO_2 contacts an amine solution, and CO_2 is absorbed into the solution by physical and chemical mechanisms. The rich solution coming out of the absorber, which typically has a loading of 0.4-0.5 moles of CO_2/mole amine, is directed to the stripper, operating at 1.5-2 atm and 100-120°C. Water vapor accompanying CO_2 from the top of the stripper is condensed and returned to the water wash section of the absorber. The hot lean solution exiting the stripper is cooled by the cold rich solution in a cross heat exchanger (5-10°C temperature approach) and is furthered cooled to 40°C before entering the absorber.

There have been many efforts to enhance the energy performance of this process that mainly focused on steady state analysis and optimization. Several steady state models have been created to minimize energy consumption or maximize performance of the absorber and stripper at full load operation by investigating different solvent options, operating conditions, and various process configurations. (Freguia et al., 2003; Oyenekan et al., 2007; Plaza et al., 2010; Van Wagener et al., 2011). However, those models did not have the capability of predicting the dynamic characteristics of the plant during abnormal operation.

Although dynamic modeling is a helpful tool that is commonly used to understand the dynamic behavior and design control systems, there are very few studies on CO_2 capture that have used this tool for those purposes. Kvamsdal et al. (2009) studied the dynamic response of the absorber to the startup and power plant load variation. Lawal et al. (2010) combined the dynamic model of absorber and stripper and observed operation of the plant in response to the disturbances imposed by the upstream power plant. These studies have examined the capture behavior isolated from power plant and CO_2 compression system.

In this dissertation, a dynamic model of an absorption/stripping plant is combined with steady state models of steam turbines and CO_2 compression train using Aspen custom Modeler (ACM®). The dynamic models of the absorber and the stripper are developed with a non-equilibrium (rate-based) model. This approach has been defined and implemented in several studies (Gunaseelan et al, 2002 and Peng et al., 2003) on dynamic modeling of the reactive distillation columns. Peng et al. (2002) compared the results of equilibrium and rate-base modeling and found some differences in final steady state values, although dynamic responses were very similar. Coping with convergence of multi-segmented columns that are modeled with rate-based approach and then integration of the whole system is a technical challenge that is encountered in this dissertation and some guidelines are provided regarding convergence issues.

Optimizing the operation of a plant over a transition is an important technique for energy saving. Nevertheless, not much work has been done in this area. Schach et al. (2011) presented an optimal control structure designed by using self-optimized control for a MEA plant to operate at constant removal with minimal energy demand over 40–100% power plant load change. The optimal scheme was found based on stationary simulations with out any validation with respect to dynamic performances.

Partial load operation of post combustion capture has not been studied yet with respect to dynamics and strategies of operation. Coal-fired power plants generate electricity at the base load and might be expected to run CO_2 capture at its full capacity continuously. Operating CO_2 capture flexibly, i.e., implementing an on/off operation would be valuable for several reasons. By either turning off the capture or reducing the load at times with daily peak power demand or high electricity prices, all or part of the steam being used for solvent regeneration or for driving CO_2 compression can be used for power generation. Doing so allows stripping and compression systems to operate at reduced load, and while additional CO_2 may be emitted during part or zero-load operation, sufficient solvent storage could allow continued CO_2 capture in the absorber. (Chalmers et al., 2007). By giving a plant operator the option to choose a desired CO_2 capture operating condition based on current market conditions such as fuel prices, CO_2 prices, and electricity demand, flexible CO_2 capture can be utilized to operate more economically than if capture systems are restricted to continuous, full-load operation.

Load variation in the upstream power plant is another dynamic operation that influences the performance of the capture significantly. Understanding the effects and exploring energy efficient control strategies in the capture in response to power plant load variation is an important issue to investigate for developing an adequate control system. Previous work that studied the power plant load variation considered only the changes in flue gas inlet condition. They neglected the variation of total steam rate in the power cycle because of load variation. This is an important effect because it affects the operation of stripping and compression when reboiler steam is extracted from the power turbines.

Developing an effective control system requires implementation of a systematic and coherent strategy regardless of the fact that it may not provide the complete and unique solution. The plant wide control procedure recommended by Seborg et al.,(2004) is a general strategy that can assist the control system designer to determine how to match controlled and manipulated variables, when to use an advanced control technique, and how to select an appropriate decoupled multi-loop control system. In contrast to previous work that did not followed a systematic strategy , this dissertation follows the steps of this procedure to develop a multi-loop control system that can effectively handle load variations and disturbances and bring the plant to the optimal condition with a reasonable response time.

Storage tanks are typically designed for different control purposes such as smoothing the responses and rejecting the disturbances where the established control structure cannot bring further improvement. Based on the control role that they play in a specific process, they are called with different names such as surge tank, buffer tank, and neutralizer. (Faanes and Skogestad, 2000)

According to Luyben (1993), considering control performance when the tanks and reactors are designed is very important especially for recycle systems due to the trade off existing between design and control. However, tank sizing is typically by rule of thumb rather than based on dynamics and control targets. This work examines the role of lean and rich storage tanks in the improvement of capture dynamic performances in response to the various disturbance sources.

1.2 Research objectives

From the above literature review, it can be seen that there are very few publications on dynamic modeling of CO_2 capture plant. Among those, some of them just focused either on stripping or on absorption and neglected the effects of dynamics and operating condition variation in the other part. The papers that presented the integrated model of absorption/ stripping process did not consider the effects of CO_2 compressor performance on the operation of the stripper. They also did not include interactions between capture plant and power plant steam turbines that exist due to the extracting reboiler steam from steam turbines. Those works that studied the power plant load variation scenario made step changes just in flue gas inlet condition. They did not consider the variation of total steam rate in the power cycle as a consequence of load variation. This is an important issue because it affects the operation of stripping and compression when reboiler steam is extracted from the power turbines.

There is very limited number of studies on developing a control system for the integrated capture plant. None of the previous works that developed control systems followed a specific procedure. Some of them proposed control structures only based on steady state gain of the system and no further testing was performed on dynamic performance. Others simulated and compared the dynamics of pre-established control configurations without any reasoning for the selected control schemes. This work utilizes a plant wide control procedure recommended by Seborg et al.(2004) to develop a control structure that can effectively operate the plant in response to the main disturbances over both the transition time and final steady sate condition.

Determining the required residence time in solvent storage tanks on lean and rich sides of the capture loop for control purposes is an important issue in design of this plant. However, this issue has not been studied yet.

The motivation of this work is to understand the dynamic characteristics, optimize the operation in response to load reduction scenarios, develop a multi-loop control system that can work effectively over a wide range of operating conditions and analyze the effects of storage tanks residence time on dynamic performance of the capture plant.

For doing so, the model of integrated standard absorption/stripping was created in Aspen Custom Modeler® in which the major components in the flowsheet (absorber and stripper columns, reboiler, absorber sump and storage tanks) were modeled with a dynamic model; other components are modeled with simplified steady state models. The performance of the CO_2 compressor and solvent circulation pumps are included by employing general characteristics performance curves provided by manufacturers.

By employing the developed model for above-mentioned purposes, this dissertation will address the following questions:

1. How to develop rate-based dynamic model for the absorber and stripper column and then make the integrated model converge?
2. What is the optimal control strategy to operate the capture plant with minimal total lost work with load reduction scenarios?
3. What are the operational constraints associated with columns, pumps and CO_2 compressor during large load changes?

4. What are the advantages of a variable speed compressor over constant speed compressor?
5. When does the multi-stage CO_2 compressor reach the surge limit and what is the best surge control strategy to minimize energy penalty?
6. Is a multi-loop control system sufficient for our control objectives or is an advanced multi-variable control system required?
7. What is the appropriate scheme to control the capture smoothly and fast in response to major disturbances such as power plant load reduction, reboiler steam rate reduction, and foaming in the columns?
8. How does the liquid residence time in the lean and rich tank influence the dynamic performance such as response time of the plant and oscillation dampening?

1.3 DISSERTATION OUTLINE

This dissertation is divided in five chapters. After the introductory chapter, the second chapter describes the details of the CO_2 capture model created in Aspen Custom Modeler®. The plant uses Monoethanolamine as the solvent. This chapter summarizes the major assumptions made and major equations formulations used in modeling the absorption/stripping process with power cycle and CO_2 compression. It provides the details of thermodynamic and rate model, physical properties, hydraulic calculations along the packing, and mass and energy balances in the columns. It also describes the numerical problems encountered during model development and convergence. Some guidelines are suggested for troubleshooting and convergence for such a complicated model.

The third chapter of this dissertation presents the implementation of the model to analyze and optimize the operation of the CO_2 capture when it is affected by two load reduction scenarios; partial load operation of power plant and steam rate reduction in the reboiler. The case study is designed based on 90% removal using 30% wt MEA. The model employs a multi-variable optimization tool in ACM® to optimize solvent circulation rate and compressor speed in response to the load reduction scenarios over a wide range of reduction levels. The objective is to minimize the total lost work at a new steady state condition reached by the capture. This chapter also explores the operational boundaries created by compressor and pump limitations and proposes energy efficient surge control strategies for the compressor since it crosses the surge limit at low loads.

The fourth chapter consists of two parts. The first part addresses the development of multi-loop control systems using a plant wide control procedure. The pairing of controlled and manipulated variables is investigated using Relative Gain Array analysis (RGA). Five control schemes are proposed and closed loop simulations are carried out to compare the control schemes in response to four common disturbances. At the end of this part, the most successful control configuration in set point tracking and disturbance rejection over a wide range of operation is introduced. The second part of this chapter analyses the effects of storage tanks on the dynamic performance of the system. For this purpose, a variety of closed loop simulations are carried out to simulate sinusoidal inputs with different initial hold up time in the lean solution and rich solution storage tanks. Frequency plots are provided to compare the outputs and drive some conclusions on the required hold up time in the storage tanks.

The fifth chapter summarizes the overall conclusions of this dissertation and proposes recommendations for future work.

Chapter Two: Dynamic modeling of post combustion CO_2 capture with monoethanolamine

2.4. Introduction

Dynamic modeling of a process is a helpful tool that is commonly used not only for understanding the dynamic behavior and designing control strategies but also for optimizing the operation of the plant in response to possible disturbances. However, there are very few studies that have used this useful tool for those purposes. There are several works that implemented steady state simulators to reduce overall energy consumption and improvement of absorption performance. (e.g., Kvamsdal et al., 2008; Oyenekan et al., 2006; Plaza et al., 2010; Van Wagener et al., 2011). Since those studies are based on steady state analysis of the plant, they cannot provide insight into dynamic and control performance of the system during transitional operation.

Due to the importance of understanding the dynamics of CO_2 capture, there has been growing interest in developing dynamic capture processes using process simulation. Kvamsdal et al. (2009) studied the dynamic responses of the absorber to the startup and power plant load variation. Lawal et al. (2010) combined the dynamic model of absorber and stripper and observed operation of the plant in response to the disturbances imposed by the upstream power plant. Those studies have examined the capture behavior isolated from the power plant and CO_2 compression system.

In contrast to previous work, this study combines the dynamic model capture plant with models of steam turbines and a multi-stage variable speed compressor to take into account all interactions during dynamic operation. It incorporates practical performance models for pumps and a CO_2 compressor to explore the operational boundaries created by compressor and pump limitations for further studies on dynamics and operation.

The dynamic models developed for the absorber and the stripper are rate-based using the film theory for liquid and vapor phases. They take into account the impact of equilibrium reactions (for the stripper) and kinetic reactions (for the absorber) on the mass transfer, thermodynamic non idealities, and hydraulics of the structured packing.

This chapter presents the formulations implemented for modeling the absorption/stripping process with power cycle and CO_2 compression in the following sections. The details of thermodynamic and rate model, physical properties, hydraulic calculations along the packing, and mass and energy balances in the column segments are provided. One of the sections describes the numerical problems encountered during model development and convergence. Some guidelines are suggested for troubleshooting and convergence of such a complicated model.

2.2. MODEL FORMULATION

The model formulation includes both molar and energy hold-up in liquid and vapor phases. It leads to a system of differential and algebraic equations (DAEs). The resulting set of equations forms an index one system, which can be solved by numerical solvers of ACM®.

2.2.1. THERMODYNAMICS AND RATE MODEL

In the stripper, mass transfer and chemical reactions occurring in the liquid phase result in desorption of CO_2 from the rich solution. Due to the higher temperature in the stripper, the reactions can be considered as instantaneous and attain equilibrium.

Schneider et al. (2003) presents different theoretical model approaches to describe mass transport and chemical reactions in multi-component systems. In this work the stripper was modeled by a rate-based approach based on film theory.

The governing reactions in the stripper are carbamate and bicarbonate formation:

$$2MEA + CO_2 \overset{K_{carbamate}}{\leftrightarrow} MEACOO^- + MEA^+ \tag{2.1}$$

$$MEA + CO_2 \overset{K_{bicarbonate}}{\leftrightarrow} HCO_3^- + MEA^+ \tag{2.2}$$

The equilibrium constants, heat of desorption and partial pressure of CO_2 are represented by empirical expressions regressed from flash results of the Aspen plus® electrolyte-NRTL model developed by Hilliard (2008). This model regresses and adequately represents data for CO_2 solubility, heat of CO_2 absorption and heat capacity over a wide range of condition. The regressed equilibrium constants, listed in table 2.1, are concentration based but include the rigorous effects of predicted activity coefficients.

Table 2.1. Equilibrium constants of equilibrium reactions obtained from Hilliard E-NRTL model

Equilibrium constant	$\ln(K_{eq}) = a + \frac{b}{T} + c\ln(T) + dT + eldg - fC$					
	a	b	c	d	e	f
$K_{eq,carbamate} = \frac{[MEACOO^-][MEA^+]}{P^*_{CO_2}[MEA]^2}$	-1294	46361	216.977	-0.335	7.2816	-0.307
$K_{eq,bicarbonate} = \frac{[HCO_3^-][MEA^+]}{P^*_{CO_2}[MEA]}$	2727.5	-78283	-465.545	0.605	8.1898	-0.334

Where,

ldg : Loading (mole CO_2/mole MEA)

C : MEA concentration (molal)

T : Temperature (K)

$P^*_{CO_2}$: Partial pressure of CO2 (Pa)

$[HCO_3^-],[MEA^+],[MEA],[MEACOO^-]$: Concentration (mole/liter)

The following correlations are obtained for vapor pressure, Henry's constant and heat of absorption of CO_2 as a function of temperature, loading and concentration:

$$ln(P_{CO_2}(Pa)) = 35.2329 + 16.9227ldg - \frac{9446}{T} + 6961600(\frac{ldg}{T})^2$$
$$-1230100(\frac{ldg}{T^2}) - 12469(\frac{ldg}{T}) + 0.3445[CO_2] \tag{2.3}$$

$$\Delta H_{absorption,CO_2}(J/mol) = 8.314(-9446 + 13923200(\frac{ldg^2}{T})$$
$$-2460200(\frac{ldg}{T}) - 12469ldg) \tag{2.4}$$

$$ln(H_{CO_2}) = 17.7135 - \frac{957.8597}{T} + 23771(\frac{ldg}{T}) + 194360(\frac{ldg}{T})^2$$
$$-3385500(\frac{ldg}{T^2}) + 37.442ldg + 0.1158[CO_2] \tag{2.5}$$

Where, $H_{CO_2} = \dfrac{P^*_{CO_2}(Pa)}{[CO_2](mol/lit)}$

2.2.2. PHYSICAL PROPERTIES OF LOADED MEA SOLUTION

Density and viscosity of loaded MEA solution was correlated using two sets of data. The first set of data, provided by Weiland et al. (1998), are experimental data that include densities and viscosities of loaded MEA for different loadings and concentration at 25 °C.

The second data set by Littel et al. (1991) is a correlation for density and viscosity as a function of concentration and temperature for unloaded MEA. Based on those data the following correlations are found for MEA solution as a function of MEA concentration, loading and temperature.

$$\ln \mu_l(mPa.sec) = A(w) + B(w)ldg + C(w)/T(K) \tag{2.6}$$

$$A(w) = \ln(0.0022 * w^2 - 0.0536w + 2.0497) + (0.0006w^2 - 0.1028w - 5.5445)$$

$$B(w) = 0.0398w - 0.2631$$

$$C(w) = -0.1788w^2 + 30.6344w + 1652.3$$

$$\rho_l(kg/m^3) = -0.4614(T(K) - 298.15) + (6.2842w + 17.425)ldg + 0.484w + 997.9 \tag{2.7}$$

Where

w : MEA concentration (weight %)

The Hilliard (2008) heat capacity model is used to calculate the heat capacity of the loaded MEA solution. Other physical properties of liquid and vapor phases such as diffusivity and heat conductivity are calculated by empirical equations from literature. (Snijder et al. (1993), Reid et al. (1978))

2.2.3. MASS TRANSFER AND HYDRAULIC MODELS

Mass transfer coefficients in the liquid and vapor phases are estimated by using equations provided by Onda et al. (1992). The Chilton-Colburn analogy is used to calculate the heat transfer coefficient in the vapor phase.

$$\frac{h}{cp.G}.Pr^{\frac{2}{3}} = \frac{k^V}{\upsilon}.Sc^{\frac{2}{3}}$$

It is assumed that heat transfer coefficient in the liquid phase is significantly large that leads in approaching liquid temperature to the interface temperature.

Mellapak 250Y was selected as the packing for both absorber and stripper columns. The pressure drop through packing beds is calculated by the generalized pressure drop correlation of Kister et al. (2007). The model incorporates the correlations provided by Suess et al. (1992) and Tsai et al. (2008) to calculate the liquid hold up on the packing and effective interfacial area respectively.

2.2.4. MASS AND ENERGY BALANCES IN THE ABSORBER

This model, which is based on the film theory, enables the calculation of effective mass transfer coefficient in the presence of reactions occurring in the liquid phase between MEA and CO_2. The packed column is divided into several segments, and time varying energy and mass balances are solved at each time step for both phases for each segment. The following assumptions are made:

1. The variation of the conditions in radial direction is negligible in both liquid phase and gas phase.
2. Mixed-flow model is applied to determine the bulk properties, meaning that the outlet conditions are equal to the bulk conditions for each phase at each segment.

3. The heat transfer coefficient of the liquid phase is much bigger than that of the vapor phase due to very high thermal conductivity of aqueous solution; therefore, the dominant heat transfer resistance is assumed to be in the vapor phase.

The absorber column should contain liquid distributors and redistributors which help to distribute the liquid evenly over a section of packing and therefore increase the mass transfer efficiency. The liquid residence time of the distributors is comparable to the hold up time on the packing and consequently has a big contribution to the response time of the plant. This work has not included the distributors for columns to simplify the model however it recommends to consider this important parameter for future studies.

The following equations are mass and energy balances for liquid and gas phases for components i=CO_2, H_2O, N_2, O_2 in the jth segment of the absorber column:

$$\frac{dM_{i,j}^{L}}{dt} = L_{j-1}x_{i,j-1} - L_j x_{i,j} - \frac{\pi}{4} D_c^2 l_j a_j N_{i,j} \tag{2.8}$$

$$\frac{dM_{i,j}^{V}}{dt} = V_{j+1}y_{i,j-1} - V_j y_{i,j} + \frac{\pi}{4} D_c^2 l_j a_j N_{i,j} \tag{2.9}$$

$$\frac{dE_j^{L}}{dt} = L_{j-1}H_{j-1}^{L} - L_j H_j^{L} - \frac{\pi}{4} D_c^2 l_j a_j \left(h_j^{L}(T_j^{L} - T_j^{I}) + N_{CO_2,j}\overline{H}_{CO_2,j}^{L} + N_{H_2O,j}\overline{H}_{H_2O,j}^{L}\right) \tag{2.10}$$

$$\frac{dE_j^{V}}{dt} = V_{j+1}H_{j+1}^{V} - V_j H_j^{V} + \frac{\pi}{4} D_c^2 l_j a_j \left(h_j^{V}(T_j^{V} - T_j^{I}) + N_{CO_2,j}\overline{H}_{CO_2,j}^{V} + N_{H_2O,j}\overline{H}_{H_2O,j}^{V}\right) \tag{2.11}$$

In this work I assumed that heat transfer coefficient is so high that $T_j^L - T_j^I = 0$

$$\frac{dE_j^{total}}{dt} = L_{j-1}H_{j-1}^{L} - L_j H_j^{L} + V_{j+1}H_{j+1}^{V} - V_j H_j^{V} \tag{2.12}$$

$$M_{i,j}^{L} = \frac{\pi}{4} D_c^2 l_j h_{tj}^{L} C_j^{L} x_{i,j} \tag{2.13}$$

$$M_{i,j}^{V} = \frac{\pi}{4} D_c^2 l_j (\varepsilon - h_{tj}^{L}) C_j^{V} y_{i,j} \tag{2.14}$$

$$E_j^{L} = \frac{\pi}{4} D_c^2 l_j h_{tj}^{L} C_j^{L} H_j^{L} \tag{2.15}$$

$$E_j^{V} = \frac{\pi}{4} D_c^2 l_j (\varepsilon - h_{tj}^{L}) C_j^{V} H_j^{V} \tag{2.16}$$

$$E_j^{total} = E_j^{V} + E_j^{L} \tag{2.17}$$

$$\overline{H}_{i,j}^{L} = \frac{\partial}{\partial x_i} H_j^{L} \tag{2.18}$$

$$\overline{H}_{i,j}^{V} = \frac{\partial}{\partial y_i} H_j^{V} \tag{2.19}$$

$$\begin{aligned} H_j^{L} = {} & x_{CO_2} H_{CO_2}^{ref,V} - x_{CO_2} \Delta H_{CO_2}^{des}(ldg_j, T_{ref}) + x_{H_2O} H_{H_2O}^{ref,V} \\ & - x_{H_2O} \Delta H_{H_2O}^{vap}(T_{ref}) + \int_{T_{ref}}^{T^L} Cp^{L}(ldg_j, T)\, dT \end{aligned} \tag{2.20}$$

$$H_j^{V} = \sum_i y_{i,j} H_{i,j}^{ref,V} + \int_{T_{ref}}^{T^V} \sum_i y_{i,j} CP_i^{V,ideal}\, dT \tag{2.21}$$

It is assumed that MEA is a non-volatile solvent and O_2 and N_2 are not solved in the solution. The mass flux of CO_2 and H_2O is calculated from the following equation:

$$N_{CO_2} = KG_{CO_2} (P_{CO_2}^{*} - P y_{CO_2}) \tag{2.22}$$

Where KG_{CO_2} is a total mass transfer coefficient that involves the combination of the resistance to mass transfer in both liquids phase (kg'_{CO_2}) and gas phase (kg_{CO_2}).

$$\frac{1}{KG_{CO_2}} = \frac{1}{kg'_{CO_2}} + \frac{1}{kg_{CO_2}} \tag{2.23}$$

Liquid side mass transfer coefficient, kg'_{CO_2}, is calculated from a correlation as a function of partial pressure of CO_2 based on data provided by Aboudhier et al.(2006).

$$\log kg'_{CO_2} = -0.42 \log P_{CO_2}^{*}(Pa) - 4.98 \tag{2.24}$$

The mass transfer resistance for H_2O in the liquid phase is negligible and H_2O mass flux is calculated from the following equation:

$$N_{H_2O} = Kg_{H_2O}(P^{*}_{H_2O} - Py_{H_2O}) \tag{2.25}$$

2.2.5. MASS AND ENERGY BALANCES IN THE STRIPPER

Similar to the absorber column, the stripper column is divided into several segments. In addition to the assumptions made for the absorber, the following assumptions are made for stripper segments model:

1. MEA is non-volatile and the vapor phase contains only water and CO_2.
2. The liquid-gas interface is at equilibrium. There is no accumulation of CO_2 at the liquid-gas interface. $(N^{V}{}_{CO_2} \cong N^{L}{}_{TotalCO_2})$

Time varying energy and mass balances (Equations (2.8) to (2.21)) are solved along with steady state phase interfacial equilibrium equation, molar and charge balances for components i=CO_2, H_2O in each segment of the stripper bed.

Vapor-liquid equilibrium at the interface:

$$P^{I}_{CO_2,j} = P^{*I}_{CO_2,j} \tag{2.26}$$

$$P^{I}_{H_2O,j} = P^{*I}_{H_2O,j} \tag{2.27}$$

Molar fluxes of CO_2 and H_2O in gas phase (general case of binary diffusion and convective flow using film theory)

$$N_{CO_2,j} + N_{H_2O,j} = k^{V}_{j} \ln\left(\frac{\dfrac{N_{CO_2,j}}{N_{CO_2,j} + N_{H_2O,j}} - y_{CO_2,j}}{\dfrac{N_{CO_2,j}}{N_{CO_2,j} + N_{H_2O,j}} - y^{I}_{CO_2,j}}\right) \tag{2.28}$$

Molar balance in the bulk liquid:

$$C^{L}_{j} x_{MEA,j} = [MEA]^{B}_{j} + \left[MEA^{+}\right]^{B}_{j} + \left[MEACOO^{-}\right]^{B}_{j} \tag{2.29}$$

$$C^{L}_{j} x_{CO_2,j} = [CO_2]^{B}_{j} + \left[MEACOO^{-}\right]^{B}_{j} + \left[HCO_3^{-}\right]^{B}_{j} \tag{2.30}$$

Molar transfer flux in liquid phase:

$$N_{CO_2,j} = k_j^L\left([CO_2]_j^B + \left[MEACOO^-\right]_j^B + \left[HCO_3^-\right]_j^B - [CO_2]_j^I - \left[MEACOO^-\right]_j^I - \left[HCO_3^-\right]_j^I\right) \tag{2.31}$$

$$0 = \left([MEA]_j^B + \left[MEA^+\right]_j^B + \left[MEACOO^-\right]_j^B - [MEA]_j^I - \left[MEA^+\right]_j^I - \left[MEACOO^-\right]_j^I\right) \tag{2.32}$$

Equilibrium reactions:

$$K_{eq,carb,j} = \frac{\left[MEACOO^-\right]_j^B\left[MEA^+\right]_j^B}{P_{CO_2,j}^{*B}\left([MEA]_j^B\right)^2} \tag{2.33}$$

$$K_{eq,carbamate,j} = \frac{\left[MEACOO^-\right]_j^I\left[MEA^+\right]_j^I}{P_{CO_2,j}^{*I}\left([MEA]_j^I\right)^2} \tag{2.34}$$

$$K_{eq,bicarbonate,j} = \frac{\left[HCO_3^-\right]_j^B\left[MEA^+\right]_j^B}{P_{CO_2,j}^{*B}[MEA]_j^B} \tag{2.35}$$

$$K_{eq,bicarb,j} = \frac{\left[HCO_3^-\right]_j^I\left[MEA^+\right]_j^I}{P_{CO_2,j}^{*I}[MEA]_j^I} \tag{2.36}$$

Charge balance in the liquid bulk:

$$0 = \left[MEA^+\right]_j^B - \left[MEACOO^-\right]_j^B - \left[HCO_3^-\right]_j^B \tag{2.37}$$

Charge balance at the interface:

$$0 = \left[MEA^+\right]_j^I - \left[MEACOO^-\right]_j^I - \left[HCO_3^-\right]_j^I \tag{2.38}$$

2.2.6. THE MODEL OF OTHER COMPONENTS

The models of the reboiler, absorber sump, and storage tanks are equilibrium stages that solve time variant energy and mass balances. Therefore, their dynamic effects are considered in further studies. Since the dynamics of heat exchangers, pumps, CO_2 compressor, control valves and steam turbines are relatively fast, their dynamic effects are ignored by using steady state equations. To simplify the heat exchanger model it is assumed that the overall heat transfer coefficient is constant during operation after it is initially designed with a specified minimum temperature approach. The fluid flow is assumed to vary proportional to the pressure drop on each side of heat exchangers. The ellipse law is used to model the variation of steam flow and pressure at the inlet and outlet of each stage of steam turbine during dynamic operation. (Lucquiaud,2010)

$$m\frac{\sqrt{T_0}}{P_0} = k\sqrt{1-\left(\frac{P_1}{P_0}\right)^2} \tag{2.39}$$

Where m is mass flow rate, T_0 and P_0 are the temperature and pressure at the inlet and P_1 is the pressure at the outlet of a stage of steam turbines and k is a constant. A typical steady state performance curve of a radial flow centrifugal pump is implemented to model the operation of pumps. The following equations represent the head and efficiency versus inlet volumetric flow.

$$Hr = -40(V_r/100)^3 + 42(V_r/100)^2 - 22(V_r/100) + 121$$
$$efficiency(\%) = -10(V_r/100)^5 - 20(V_r/100)^4 + 50(V_r/100)^3 - 97(V_r/100)^2 + 180(V_r/100) - 0.33$$

(2.40)

The model of the variable speed centrifugal compressor is obtained based on a general performance map by a manufacturer. Closed form equations are found for polytrophic head as a function of inlet volumetric flow and compressor speed and for polytrophic efficiency as a function of head and inlet volumetric flow.

The typical performance map of centrifugal compressor used in this study, reported by Ludwig et al. (1995), is shown in figure 2.1.

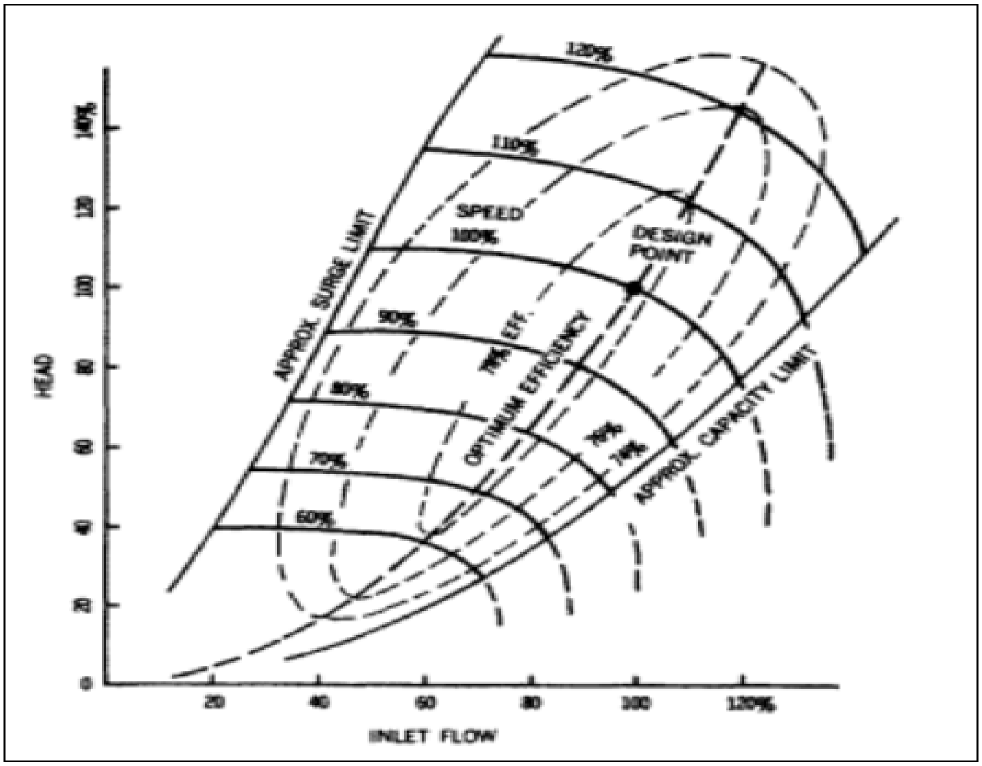

Figure 2.1: Manufacturer's typical performance map of centrifugal compressors reported by Ludwig et al. (1995).

A digitizer software is used to read the data from this graph and a regression function in MATLAB is employed to fit polynomials for head and efficiency, surge line, and capacity limit:

$$efficiency(\%) = 66.7679 + 0.2816V_r + 0.0064H_r - 0.0028V_r^2 - 0.0016H_r^2 + 0.0027H_r V_r - 0.000027V_r^3 + 0.0000154H_r^3 + 0.0000651V_r^2 H_r - 0.000053804V_r H_r^2 \tag{2.41}$$

$$Hr = -206.0373 + 0.8433V_r + 9.2734N_r - 0.0265V_r^2 - 0.1576N_r^2 + 0.0121V_r N_r - 0.00051185V_r^3 + 0.0016N_r^3 + 0.0017V_r^2 N_r - 0.0014V_r N_r^2 - 0.0000039541V_r^4 - 0.0000079056N_r^4 - 0.000027289N_r^2 V_r^2 + 0.000016876V_r^3 N_r + 0.000018234V_r N_r^3 \tag{2.42}$$

Where H_r, V_r, and N_r are percent of rated head, volumetric inlet flow, and speed, respectively.

2.4. NUMERICAL SOLUTIONS

The dynamic model of absorber and stripper columns that includes both molar and energy hold-up in liquid and vapor phases, leads to a system of differential and algebraic equations (DAEs). The resulting set of equations forms an index one system, which can be solved by numerical solvers of ACM®.

In order to prevent high index problems in this system, the model of the columns is established in the manner that no algebraic variables appear exclusively in the differential equations. For example, by taking into account the hydraulics of the column as a function of liquid and vapor flow rates, these variables appear in the mass and heat balances and in algebraic hydraulic equations.

This work integrates the model of all the components including both the dynamic and steady state ones in one flow sheet. The convergence of the whole system was so challenging that a step-wise strategy has been explored and implemented. The creation of this flow sheet was initially started by inserting the model of one segment of the stripper and the absorber separately and tried to make them converge in the steady state mode. Then the number of segments were added and converged gradually until the model of the multi-segment stripper and absorber was built and converged. It is found that specifying reasonable initial guess for unknown variables is a helpful strategy to make the model of columns converge easier. For example, inlet streams conditions were used as the initial guess for compositions, temperature and flow rates through the columns.

As the column models were converged, other components were added and run gradually and eventually were combined with the columns. By using this method, it was much easier to locate numerical problems, trouble shoot and eventually make the whole system converged.

Although the same model is run in steady state or dynamic mode, the specifications are different. The plant should be initially designed based on design specifications in the steady state mode. Before switching to the dynamic mode, the design specification should be replaced by dynamic specifications.

2.4. PACKING HEIGHT AND SEGMENTATION IN THE STRIPPER

For the investigation of the influence of the number of segments on the stripper solution and finding a reasonable number of segments, the stripper has been solved with different number of segments and in each run, the heat requirement has been calculated with various packing height.

In this analysis, the stripper column is designed at 160 kPa with 5°C approach on the cold side in the cross heat exchanger. The rich and lean loadings are 0.53 and 0.4 moles of CO_2 /mole MEA, which should permit 90% CO_2 removal in an absorber of reasonable design. As demonstrated in Figure 2.2, calculations were performed with 1 to 10 segments with the same total height of the packing. For the number of segments from 1 up to 5, adding a segment resulted in a 2% change in the calculated reboiler heat duty. By increasing the number of segments from 5 to 10, less than 0.01% difference of heat duty was achieved. Therefore, five segments would adequately represent the packing of the stripper working in this condition. Additionally, 5 segments may represent the number of equilibrium stages of the column since the impact of number of segments on the reboiler duty is independent of the height of packing.

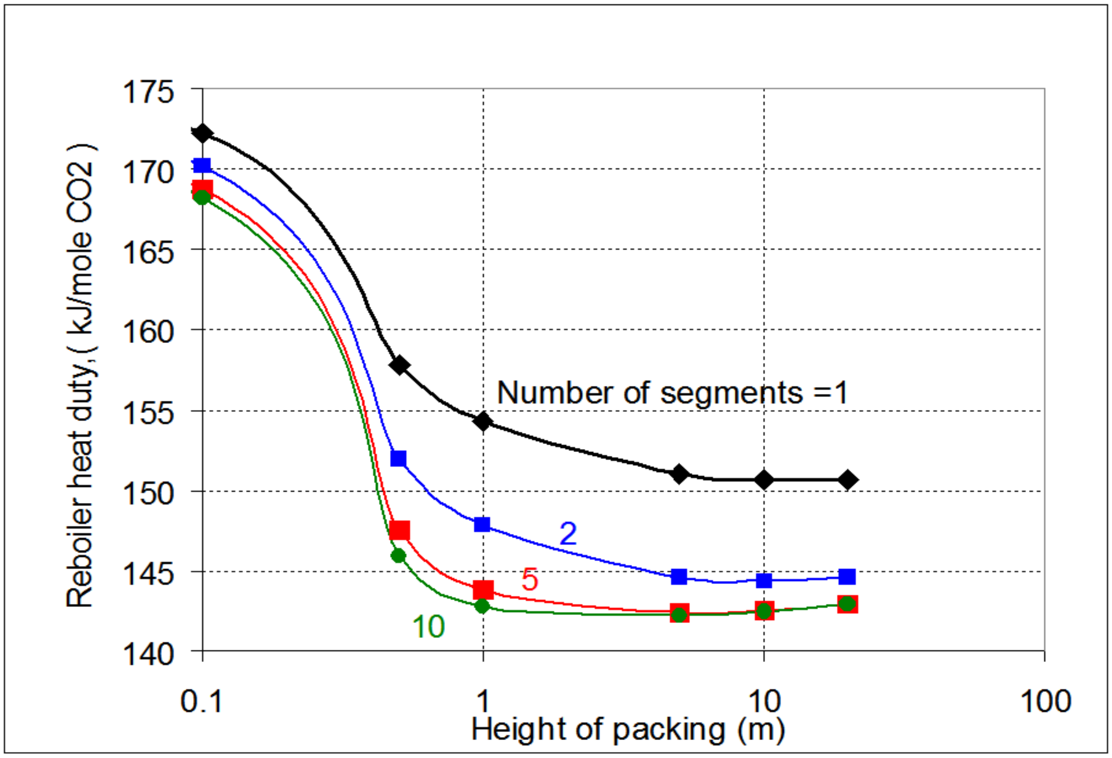

Figure 2.2. The influence of number of segments and height of packing on the heat requirement of the stripper, 90% removal, P=160 KPa, lean loading=0.4, rich loading=0.527, 5° C hot-end approach in the cross heat exchanger.

2.5. SUMMARY AND CONCLUSIONS

This chapter presents the details of dynamic modeling of post combustion CO_2 capture along with the model of power cycle steam turbines and CO_2 multi-stage compressor. This integrated model, created in Aspen custom modeler, is used for the dynamic and control studies described in the next chapters.

By running the combined model of stripper column and reboiler in the steady state mode, an analysis performed on the effect of number of segments and height of the packing on the reboiler heat duty. It shows that regardless of packing height there is a segment number where the reboiler heat duty starts to reach an asymptote. That number may represent the number of equilibrium stages in the stripper column. It shows that 1 m of packing height with 5 segments is enough. A taller stripper column just increases pumping and compression work without any improvement in the performance of the stripper.

Regarding convergence bottlenecks specifically those encountered for packed columns, it is recommended to start in steady state model with converging one segment of each column in the flow sheet and then gradually increase the number of segments. After both columns are converged separately, insert and converge the other components and eventually close the absorption/stripping loop. To switch to the dynamic mode, make sure that steady state specifications are replaced with dynamic ones.

To make the convergence feasible and easier for columns, try to initialize proper guess for unknown variable. For example, use inlet stream conditions as initial guess for those variables.

Chapter Three: Steady state optimization of partial load operations in CO_2 capture

Absorption/stripping process is a mature technology commonly used for removing CO_2 from refinery gases, which makes it applicable to removing CO_2 from flue gas in coal-fired power plants. However, it is an energy intensive process and therefore needs special efforts to be implemented economically in both design and operation.

This chapter is devoted to exploring energy efficient control strategies for a capture plant designed to remove 90% of inlet CO_2 using aqueous MEA solution in response to two load reduction scenarios: power plant load reduction and reboiler steam rate reduction.

For this purpose, the absorption/stripping dynamic model was integrated with the steady state model of power cycle steam turbines and general performance curves of the CO_2 compressor to take into account operational interactions. The operational scenarios were analyzed and then optimized by adjusting solvent circulation rate and compressor speed to minimize total lost work at the new steady state in the presence of operational limitations. Those constraints are related to the thermal degradation of solvent, runoff conditions in circulation pumps, and surge conditions of the CO_2 compressor. Surge control strategies are explored and compared for both scenarios and guidelines for optimally operating the integrated plant during the transitional operations are presented.

3.1. INTRODUCTION

Absorption/stripping with aqueous amine is one of the commercial technologies for post-combustion CO_2 capture that can be used in coal-fired power plants, but the drawback of this chemical reaction-based technology is the high energy requirement.

There have been many efforts to enhance the energy performance of this process that mainly focused on static analysis of capture when it is operating at full load. Consequently, numerous publications on this topic exist and several steady state models have been created. Those studies minimized energy consumption or maximized performance of the absorber and stripper at full load operation by investigating different solvent options, operating conditions, and various process configurations. (e.g., Freguia et al., 2003; Oyenekan et al., 2007; Plaza et al., 2010; Van Wagener et al., 2011).

Steady-state analysis does not reflect issues related to transitional behavior and operation of the plant in response to possible disturbances and potential dynamic operational scenarios. Besides employing appropriate solvent and process configurations, with regard to the operation, the strategy and structure of control play an important role in energy saving and performance enhancement.

According to Bergerson et al. (2007), CO_2 capture operating at full load could reduce net energy output of a coal-fired power plant by 11–40% from that of an equivalent gross size plant without CO_2 capture. This energy requirement mainly includes the heat required for solvent regeneration and the energy for CO_2 compression. The regeneration heat can be provided by the steam extracted between the intermediate- and low-pressure turbines.

By giving a plant operator the option to choose a desired CO_2 capture operating condition based on current market conditions such as fuel prices, CO_2 prices, and electricity demand, flexible CO_2 capture can be utilized to operate more economically than if capture systems are restricted to continuous, full-load operation (Ziaii et al., 2009).

Transitional conditions that commonly occur in power plants, such as startup, shutdown, and load variation, influence the operation of downstream processes such as CO_2 capture. These operational scenarios, along with the requirement of capture flexibility, are important issues that must be investigated in order to develop efficient control strategies.

Due to the importance of understanding the dynamics of CO_2 capture, there has been growing interest in developing dynamic capture processes over recent years using process simulation. Kvamsdal et al. (2009) studied the dynamic responses of the absorber to the startup and power plant load variation. Ziaii et al. (2009) presented the dynamic response of the stripper to step changes in the reboiler steam rate. Lawal et al. (2010) combined the dynamic model of absorber and stripper and observed operation of the plant in response to the disturbances imposed by the upstream power plant. Most previous studies have focused on understanding dynamics of either absorber and stripper or integrated plant and have not performed operation optimization. Schach et al. (2011) optimized the operation of CO_2 capture with MEA and designed a control structure for operating the capture at constant removal with minimal energy demand over 40–100% power plant load change. All previous work that studied the power plant load variation scenario assumed a change only in flue gas inlet condition. However, the variation of total steam rate in the power cycle is a consequence of load variation that strongly influences the operation of capture mainly in stripping and compression parts for the cases that extract required reboiler steam from steam turbines. How to operate the CO_2 compressor during dynamic operations is another important issue that affects the operation of capture and plays an important role in minimizing energy consumption. Previous studies have ignored that effect.

In contrast to previous work, this study integrates the dynamic model of the absorber and stripper. It combines the capture plant with a steady state model of steam turbines and a multi-stage variable speed compressor to take into account all interactions during power plant load and reboiler steam load reduction scenarios. In addition, by incorporating practical performance models for pumps and the CO_2 compressor, it explores the operational boundaries created by compressor and pump limitations and performs optimization to minimize total lost work in the presence of those constraints.

This work is unique in the field since it simulates the operations with a fully integrated model and avoids most of the deficiencies found in previous works. It presents a comprehensive analysis and provides new results on control strategies for optimal operation in response to partial load operations.

The following sections detail the plant specifications and the method of simulation of partial load operation, present the results and discussion for both scenarios, and summarize the conclusions.

3.2. METHODOLOGY

The simulation of partial load operation scenarios for CO_2 capture with MEA is initially designed with following specifications:

Gas rate and composition: 5.48 kmol/s , 13% CO_2

Electric rate: 100 MW

Absorber packing height: 15 m.

Stripper packing height: 10 m.

CO_2 removal with 30 wt % MEA: 90%.

Optimum lean loading = 0.233 mole CO_2/mole MEA

Reboiler temperature: 120 °C.

CO_2 discharge pressure compressor: 150 bar.

Extracted reboiler steam = 30% total power cycle steam rate

Steam turbine initial design condition (Lucquiaud, 2010):

PHPin= 290 bar, PIPin= 60 bar, PLPin= 2.65 bar, PLPout= 0.04 bar.

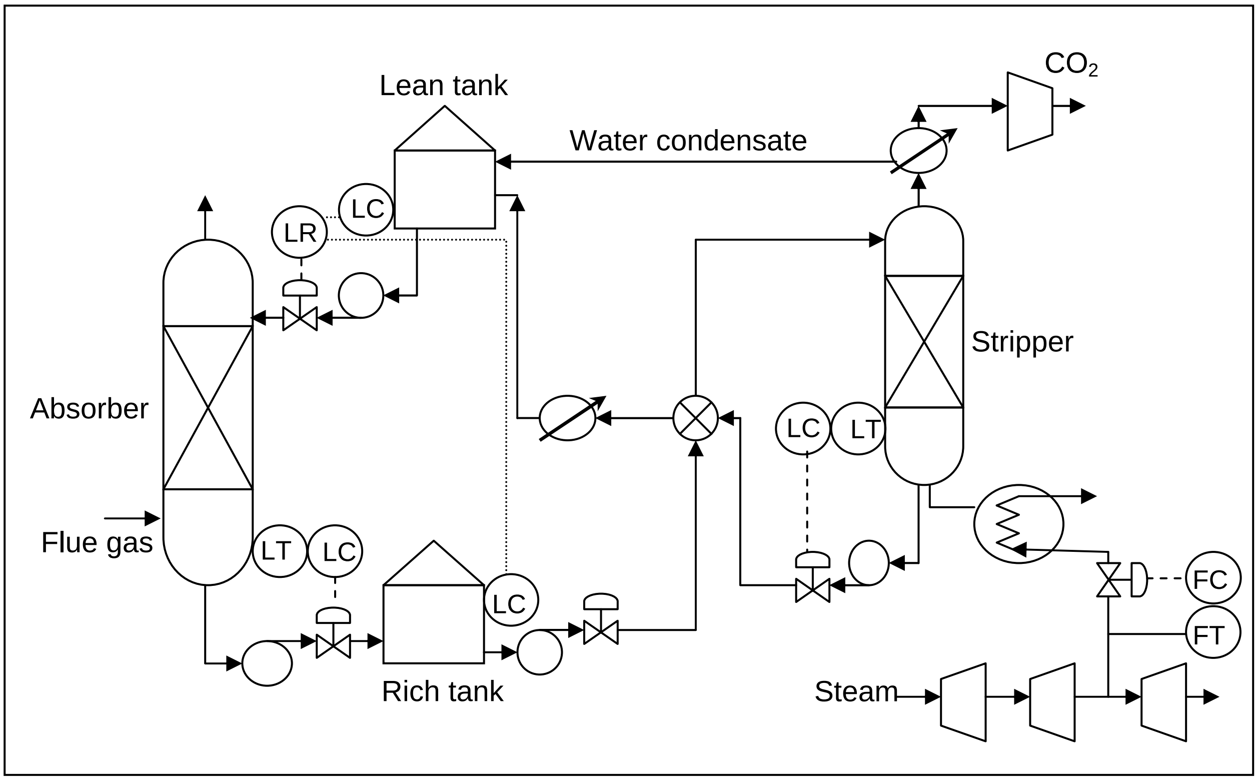

Figure 3.1: Process flow sheet of absorption/stripping process integrated with CO_2 compressor and power cycle steam turbines, used for simulation of dynamic operation. The plant is initially designed to the following specifications: H_{Abs} = 15 m, H_{Stripp} = 10 m, ΔT_{HX} = 5 °C, T_{Reb} = 120 °C, T_{Cooler} = 40 °C P_{HP}^{in} = 290 bar, P_{IP}^{in} = 60 bar, P_{LP}^{in} = 2.65 bar, P_{LP}^{out} = 0.04 bar.

As illustrated in Figure 3.1, the liquid levels in the sumps and the ratio of liquid levels in storage tanks are controlled via three downstream valves to keep the liquid holdup in balance. In order to save energy during power plant load reduction, the steam valve is kept wide open during operation while in reboiler steam load reduction it is employed to control the steam rate. The compressor speed and the position of the liquid valve downstream of the rich storage tank are two variables that can be manipulated to maximize the energy performance of the plant in response to both partial load scenarios.

During power plant load variation, at least two input conditions are subject to change. One of those variables is the property of flue gas entering the absorber. Based on findings by Kvamsdahl et al. (2009) about the effects of power plant load reduction on exhausted gas, the rate of flue gas is reduced accordingly while the composition and temperature are constant. The other issue resulting from boiler load change is related to the steam cycle and further impact on the operation of the stripping section since the reboiler steam is extracted from IP/LP cross point. Accordingly, the total steam rate in steam turbines changes with boiler load and no action is performed to control the pressure at turbine inlet/outlet conditions. This analysis takes into account both effects on the plant at the same time.

The objective of this chapter is to analyze and optimize capture plant operating conditions in response to those operational scenarios. It does not include results and discussion of the transitional behavior of the MEA plant during operation. For each scenario, the corresponding disturbances are applied, the simulation is run at dynamic mode until the new steady state is reached, and the simulation outputs are then recorded. For optimization cases, the ACM® dynamic optimization tool is used to simulate and ultimately minimize the total lost work of CO_2 capture in the presence of constraints and provide optimum final values for variables.

$$W_{lost} = 0.75 Q_{Reb} \left(\frac{T^{sat}(P_{extract}) - T_{sink}}{T^{sat}(P_{extract})} \right) + W_{compressor} + W_{pumps} \qquad (3.1)$$

2.5. RESULTS AND DISCUSSION

This section discusses the results of analyses and optimization of capture plant operation when it is operated in two load reduction scenarios: partial load operation of the power plant, and reboiler steam rate reduction.

3..1. POWER PLANT LOAD REDUCTION SCENARIO

As explained in section 3.2, this work simulates partial load operation of a power plant by reducing the inlet flue gas rate of the absorber and inlet total steam rate of the steam turbines at the same time and with the same percentage change. As power plant load is reduced, the extracted steam pressure decreases due to decreasing inlet flow to the turbines and initially less steam is condensed in the reboiler. In this condition, if the compressor continues to work at its rated speed or higher speed, the stripper and reboiler pressure and temperature tend to decrease initially, which gradually results in condensing more steam at lower pressure and subsequently vaporizing more CO_2 and water and pressurizing the stripper and reboiler. Another potential strategy is to reduce compressor speed, which initially results in pressurizing the stripper. Dynamically, this effect reverses the operation by reducing steam condensation, CO_2 and water vaporization, and finally reducing stripper and reboiler pressure and temperature.

The final pressure and temperature primarily depend on the degree of load reduction in the steam cycle of the power plant and the direction and degree of change in the compressor speed, and depends to a much less extent on the solvent circulation rate. As shown in Figure 3.2, base on 90% load operation of the power plant, increasing solvent circulation rate increases the amount of CO_2 absorbed in the absorber and desorbed in the stripper and consequently leads to pressurizing the stripper and reboiler.

The solvent rate may vary over a range set by operational constraints for compressor and pumps. At the minimum solvent rate, which is independent of reboiler temperature, the CO_2 rate entering the compressor is low enough that it causes the compressor to surge. The maximum flow rate is set by one of the pumps that first reaches runoff (maximum flow). For the highest temperature, e.g., 120 °C, the pump sending rich solution to the top of the stripper reaches its maximum flow while at lower temperature, 117 °C and 119 °C, the pump handling lean solution reaches maximum flow earlier.

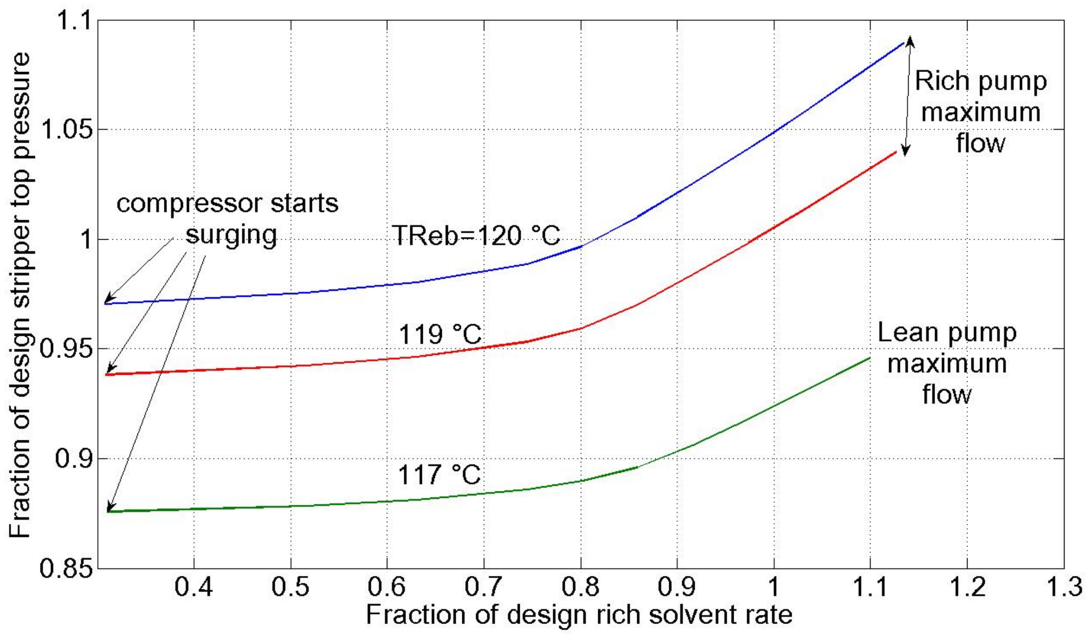

Figure 3.2: Output with boiler load reduction: the effects of rich solvent rate and reboiler temperature (adjusted by compressor speed) on the stripper top pressure at new steady state condition when the plant is operated at 90% boiler load.

Figure 3.3, representing the operating curves on the multi-stage compressor performance map, indicates how increasing temperature or decreasing solvent rate moves the compressor operating curve to the surge limit curve. For each isothermal curve there is a turning point, which is associated with the turning point on stripper pressure around 80% of design solvent rate (Figure 3.2). At solvent rate less than the turning point, the suction pressure is relatively low and constant such that as the solvent rate increases the compressor volumetric inlet flow increases. At the turning point, the change rate of the compressor suction pressure becomes greater and consequently, as the solvent rate goes up, inlet gas density increases and volumetric flow decreases.

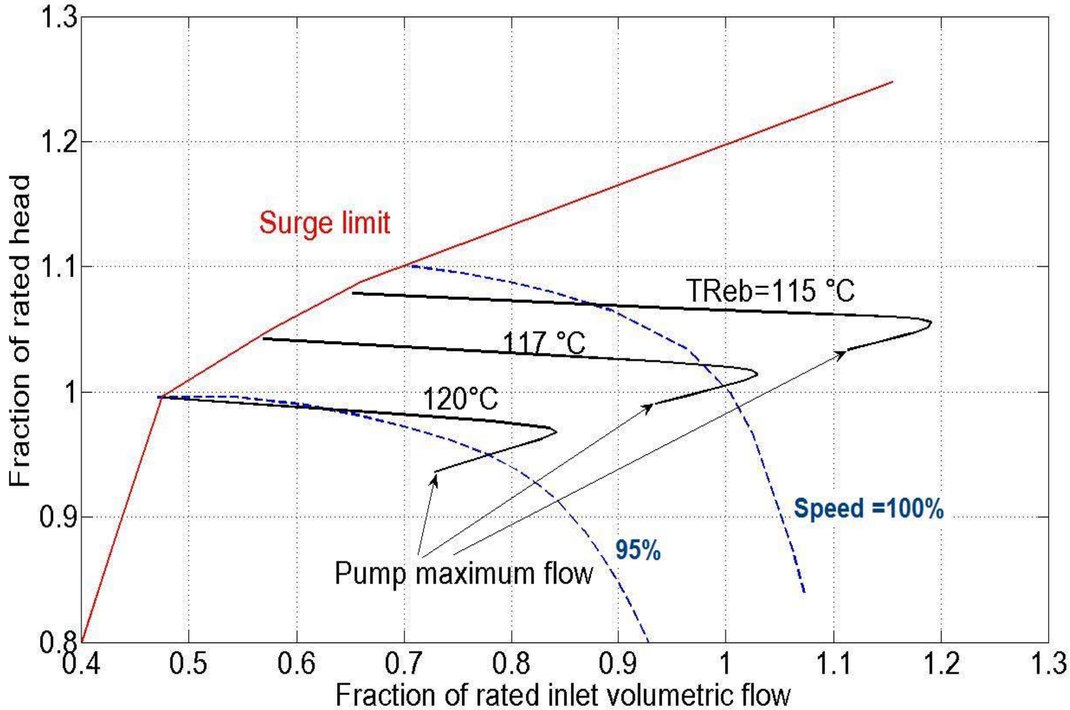

Figure 3.3: The performance map of a multi-stage (5 stages) CO_2 compressor when the power plant is operated at 90% load. The operating curves are associated with different reboiler temperatures (adjusted by compressor speed), while the solvent rate is varied over the range constrained by compressor surge and maximum pump flow.

The results show that when reboiler temperature is set by compressor speed there is an optimum solvent rate that minimizes reboiler equivalent work and, consequently, total equivalent work. There is also an optimum solvent rate that maximizes CO_2 removal; however, those optima are not identical (see Figures 3.4 and 3.5).

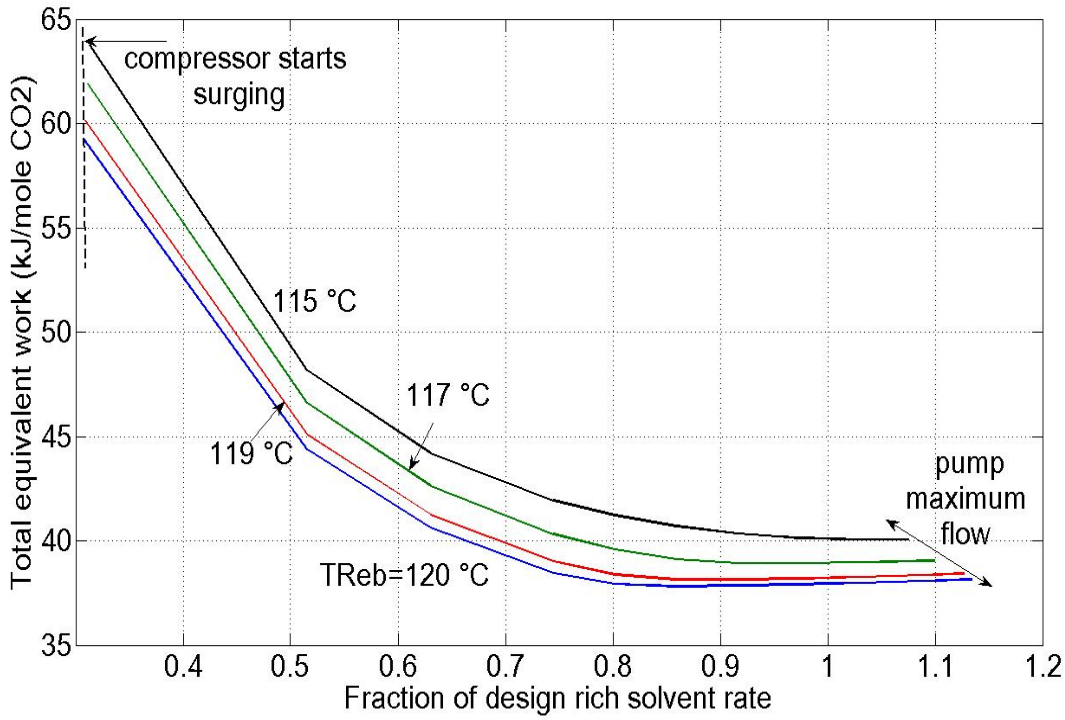

Figure 3.4: The effects of rich solution rate and reboiler temperature (adjusted by compressor speed) on total equivalent work when the power plant is operated at 90% load.

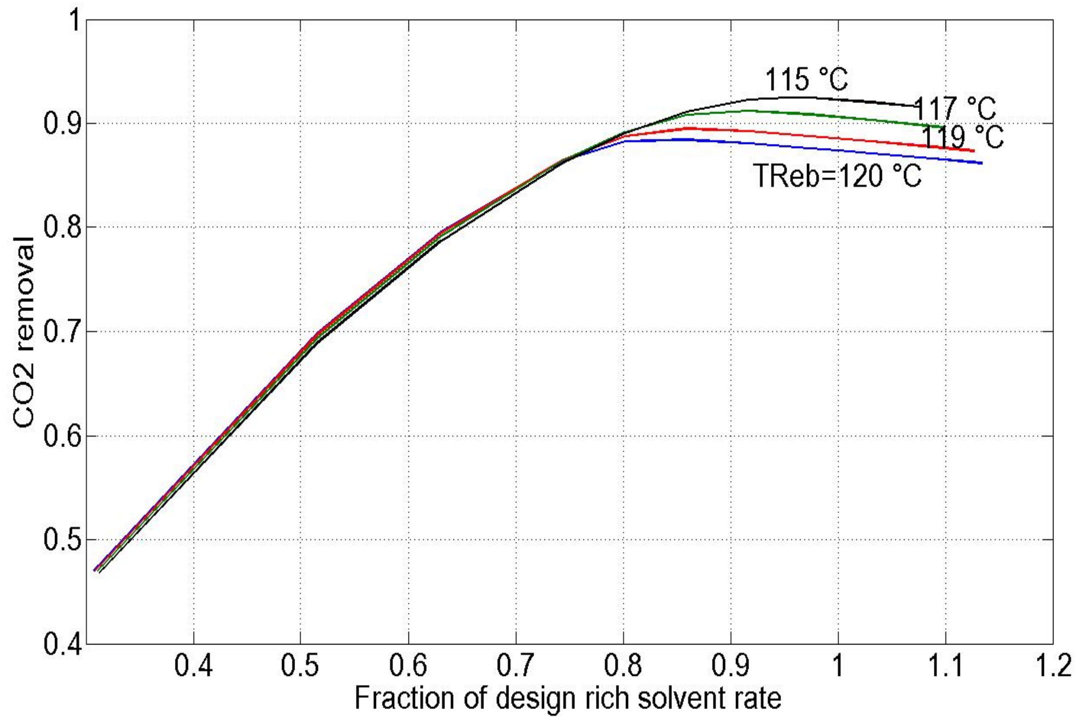

Figure 3.5: The effects of rich solution rate and reboiler temperature (adjusted by compressor speed) on CO_2 removal when the power plant is operated at 90% load.

The maximum reboiler temperature is set at 120 °C, where MEA thermal degradation starts. The minimum temperature for 90% operating load is 115 °C where the compressor speed exceeds 120% of its rated speed. As seen in Figure 3.4, the higher the temperature in the reboiler, the lower the equivalent work. Since the total steam rate in the power cycle is reduced in this scenario, the pressure drops at the extracting point and consequently less steam is condensed in the reboiler and less CO_2 is stripped. Decreasing temperature in the reboiler results in extracting more steam and increasing CO_2 removal.

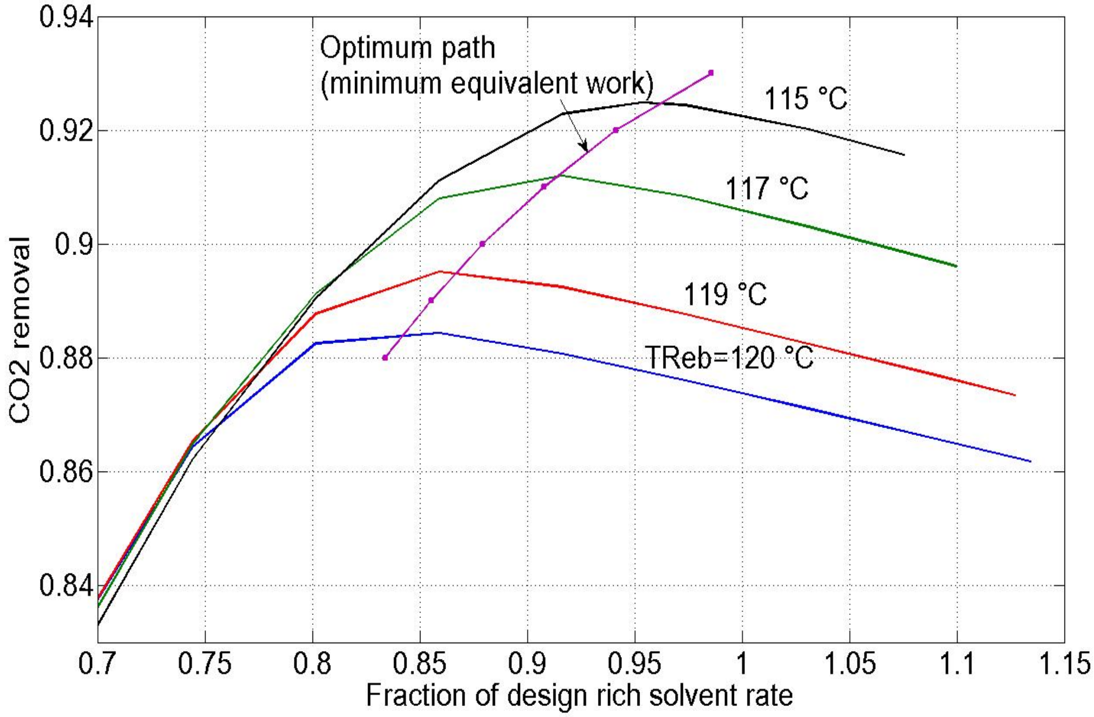

Figure 3.6: Steady state optimization of solvent rate and compressor speed when the power plant is operated at 90% load.

Operating capture with low liquid circulation is not beneficial because when the equivalent work is high, CO_2 removal is low and increasing reboiler temperature does not influence the removal. The solvent rate that maximizes removal is not the same as the one that minimizes equivalent work; however, both optima increase with decreasing reboiler temperature. Figure 3.6 locates optimum solvent rate and reboiler temperature as a function of desired removal when the power plant load is reduced to 90% of full load. These optimum points minimize total equivalent work at a specific removal level. Figure 3.6 also gives an optimum range for reboiler temperature (115–120 °C), fractional solvent rate (0.84–0.96), and removal (88.5–92.5%).

If we assume that there is not an advanced multivariable control system to regulate control loops in response to the upstream load change, we should find a control strategy that allows the plant to reach an optimum steady state condition with a multi-loop control system, if possible.

One of the strategies commonly used in similar plants is ratio control between two variables, where one process variable is controlled in a manner that varies in proportion to the change in another variable. Mathematically, the variables should move along a line with slope 1 (or diagonal line).

Figure 3.7 shows the normalized optimum solvent rate and the CO_2 rate in the rich and lean solution versus normalized reboiler steam rate for the practical range of CO_2 removal when the power plant is operated at 90% load. The normalization is achieved by dividing the flow rates at new steady state condition by the initial design value. This figure shows that flow rates vary linearly with steam rate, however none of the lines has slope 1. Ratio control between steam rate and CO_2 rate in rich solution seems to keep the plant closer to the optimum path.

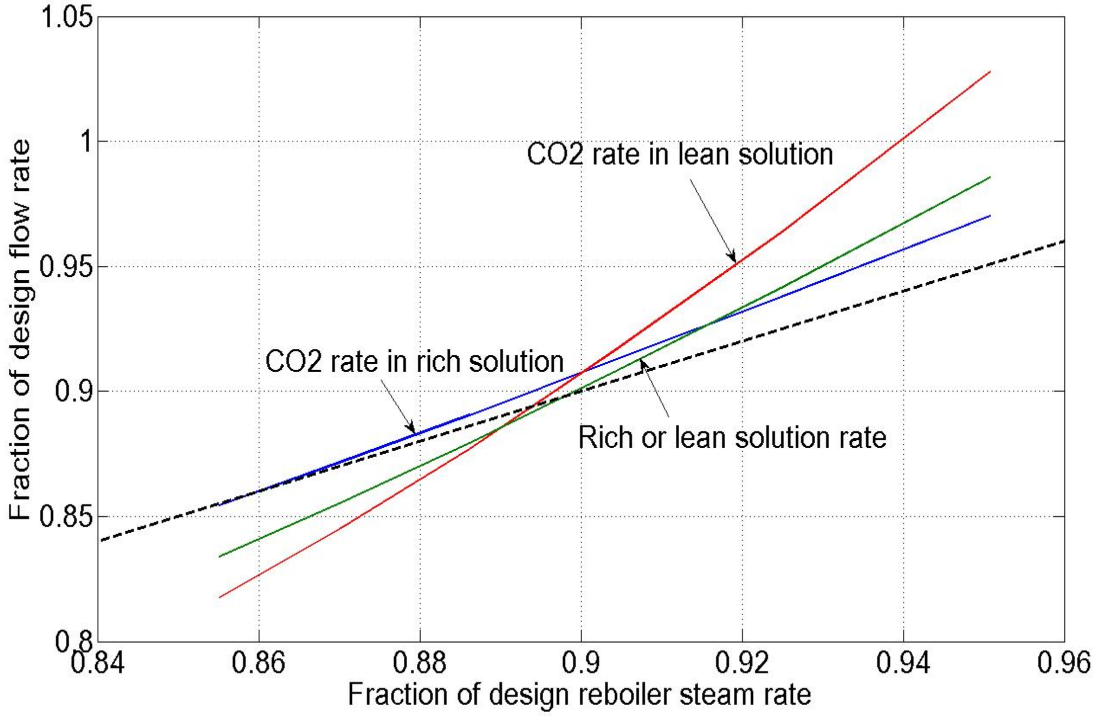

Figure 3.7: Optimum normalized solvent rate, CO_2 rate in lean and rich solution vs. normalized reboiler steam rate when the power plant is operated at 90%.

The same analysis has been performed where the plant is operated at 80% load (see Figure 3.8). The shape of curves and distances from the diagonal line vary as load changes from 90% to 80%. Controlling the ratio of total solvent rate and the reboiler steam rate at the initial value is the best choice to control the plant close to the optimum path for 80% load. Comparing Figures 3.7 and 3.8, we conclude that no general rule exists for optimum ratio control over a wide range of operation.

Normalized optimum lean loading and normalized removal are found to be another potential pairing for ratio control. Figures 3.9 and 3.10 show the relation of these variables for 90% and 80% boiler load. For both cases, the curves are close to the diagonal line; however, as load decreases from 90% to 80%, the maximum deviation increases from 2% to 4%. Based on this analysis, if the objective in this case study is to keep the removal at its initial value (90%) while final total equivalent work is minimum in response to the power plant load reduction, the lean loading could be controlled at its initial value.

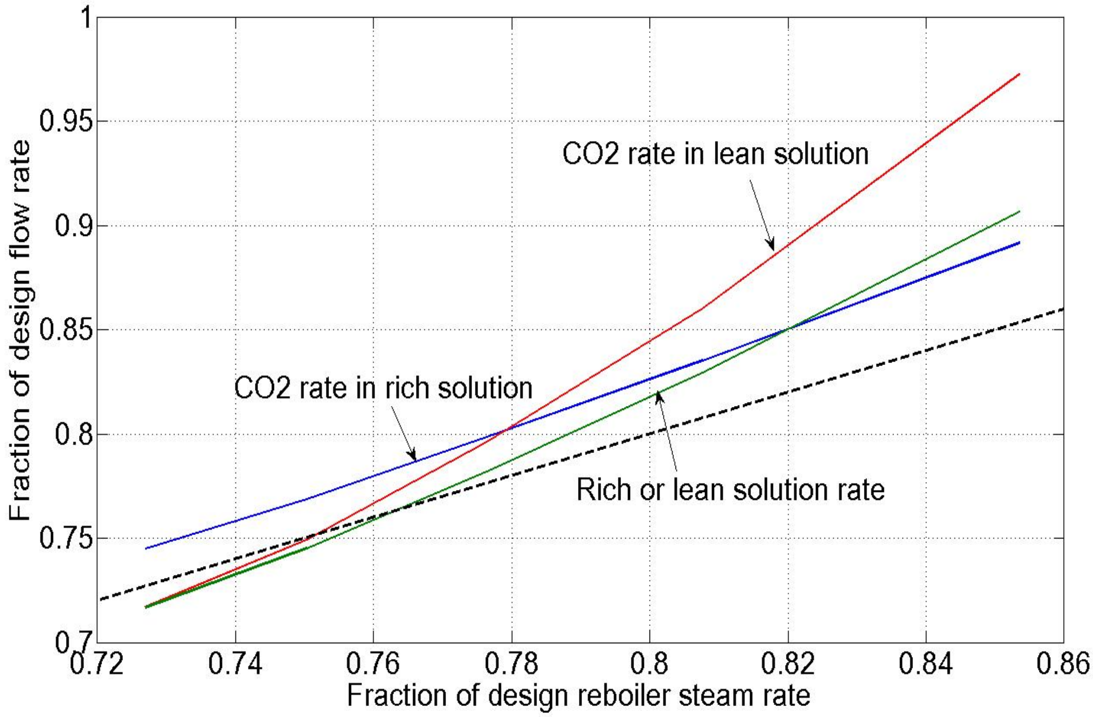

Figure 3.8: Optimum normalized solvent rate, CO_2 rate in lean and rich solution vs. normalized reboiler steam rate when the power plant is operated at 80%.

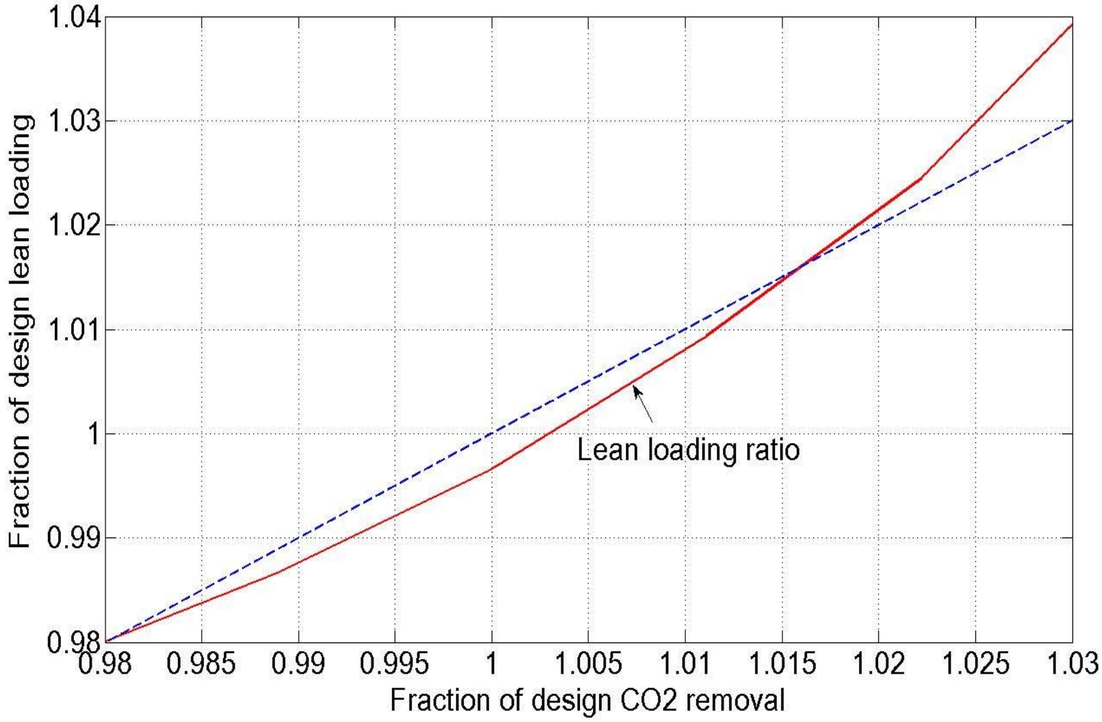

Figure 3.9: Optimum normalized loading of lean solution vs. normalized CO_2 removal when the power plant is operated at 90%.

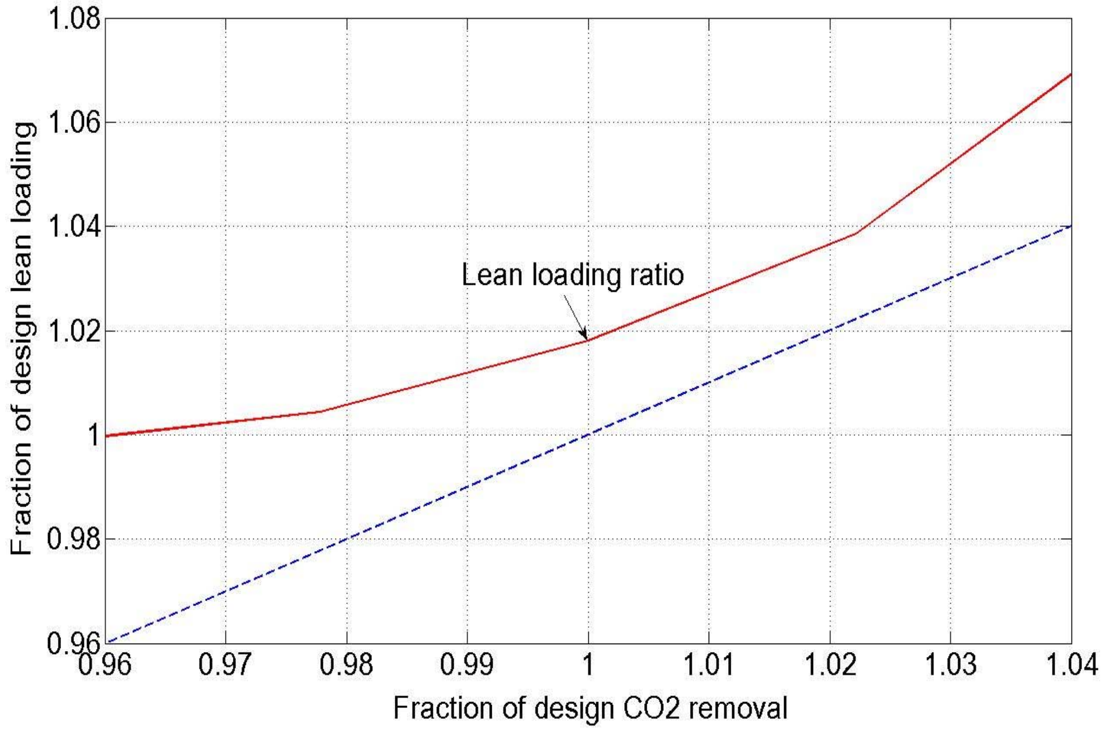

Figure 3.10: Optimum normalized loading of lean solution vs. normalized CO_2 removal when the power plant is operated at 80%.

For 80% load operation, similar to 90% load, the maximum solvent rate is set by maximum flow of rich or lean pumps and minimum flow is set by the compressor surge limit. The maximum and minimum reboiler temperature is set by thermal degradation of MEA and compressor speed limit, respectively. As shown in Figure 3.11, for 80% load operation, the operating range of the fractional solvent rate, reboiler temperature, and removal could be 0.71–0.91, 110–120 °C, and 85.5–94%.

As shown in Figure 3.12, at 60% boiler load the minimum temperature, which is set by maximum compressor speed, is 106 °C. At low reboiler temperature such as 106 and 112 °C, maximum solvent flow is set by the lean pump runoff. However, at higher temperature, 114–118 °C, the first stage of the compressor starts to surge before the pumps reach their maximum flow. At minimum solvent rate, the operating curve intersects the upper part of the surge limit, where the 5th stage is surging. At maximum flow it intersects the lower part of surge limit where the 1st stage is surging. As the reboiler temperature goes up, the operating curve of the compressor gets closer to the surge limit, such that the range of solvent rate that keeps the compressor away from surge is getting smaller and smaller. For 60% boiler load, the solvent rate range is very small for 118 °C and at 120 °C, the compressor curve is always on surge limit and no single value of solvent rate is found to exclude the compressor from this undesirable condition.

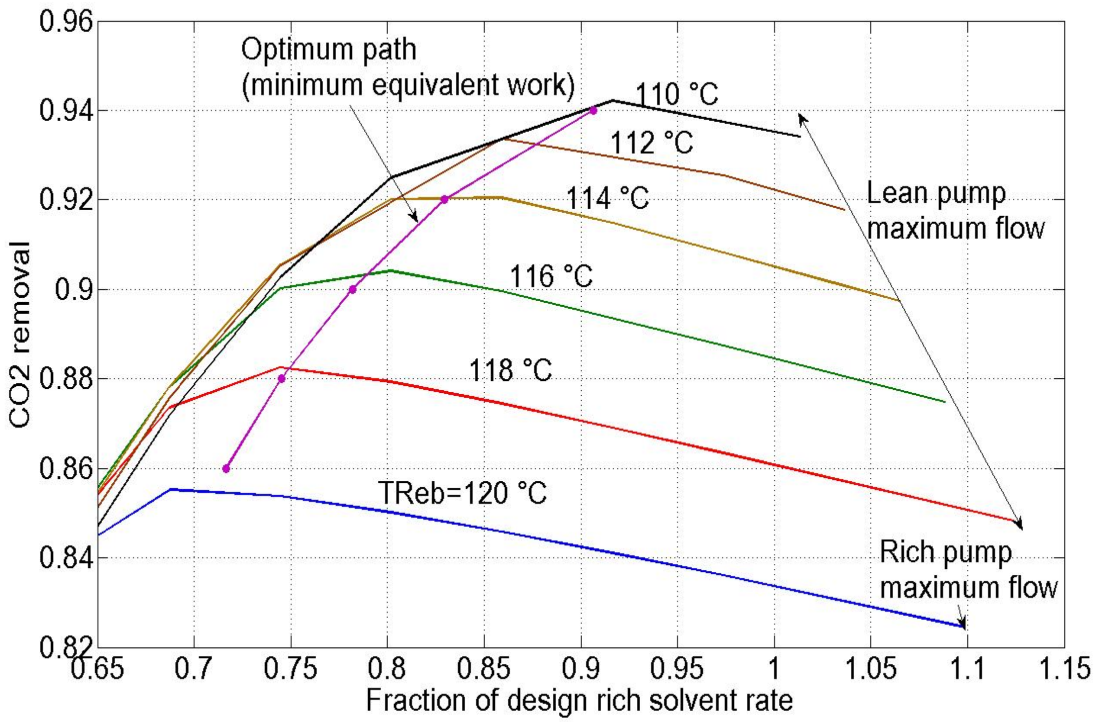

Figure 3.11: Optimum path for reboiler temperature and solvent rate minimizing total equivalent work over an applicable CO_2 removal range when the power plant is operated at 80%.

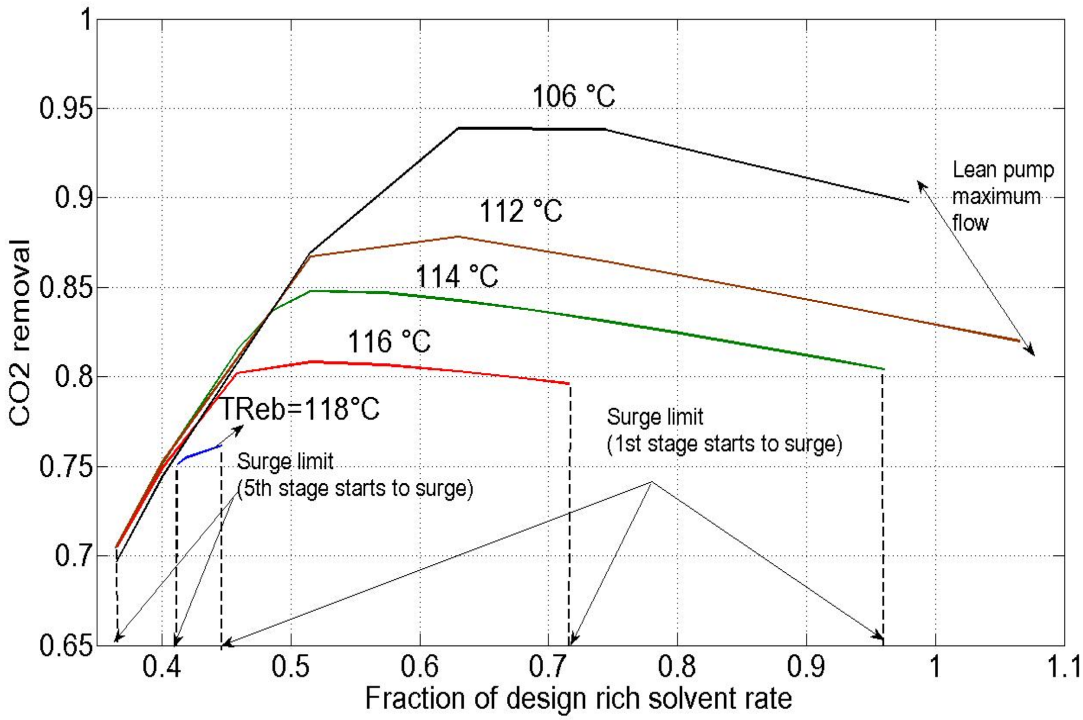

Figure 3.12: Optimum reboiler temperature and solvent rate minimizing total equivalent work over an applicable CO_2 removal range when the power plant is operated at 60% load.

The other factor pushing the compressor to surge condition is decreasing reboiler steam rate, which results from boiler load reduction. Figure 3.13 demonstrates the effect of decreasing boiler load on the operation of the compressor as the reboiler temperature is kept fixed for all three loads. For loads less than 58%, both maximum and minimum solvent rates are set by compressor surge conditions. As load decreases, the operating curve gets closer and closer to the surge limit. At 40% load, which is a common minimum load in a power plant, the compressor is always on surge and changing solvent rate and adjusting compressor speed are no longer beneficial to push it away from this condition. The only way to protect the compressor from surging is to activate anti-surge control in which a portion of gas stream is circulating through the stage that is starting to pass the surge limit.

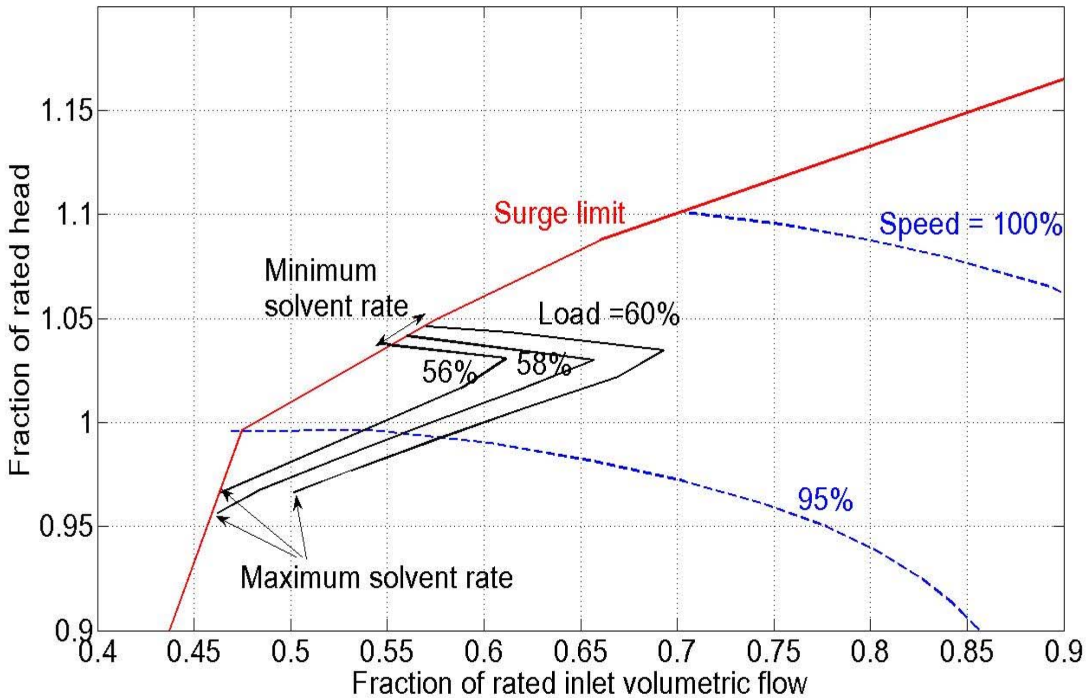

Figure 3.13: The performance map of multi-stage (5 stages) CO_2 compressor at 56% to 60% boiler load and112^{o}C reboiler temperature adjusted by variable compressor speed and solvent rate.

3..2. REBOILER STEAM RATE REDUCTION

As explained in section 3.2, partial load operation of reboiler steam is simulated by manipulating the steam valve to achieve the desired steam rate. The simulation is run in dynamic mode and outputs are recorded when the plant reaches the new steady state.

The objective of this work is to find the solvent circulation rate and compressor speed that minimize total equivalent work at a new steady state condition after the steam rate is reduced in the presence of operating constraints. As with boiler partial load, both solvent rate and compressor speed influence the equivalent work and CO_2 removal (Figures 3.14 and 3.15).

Reboiler temperature is adjusted by compressor speed and changed in the range between 115 °C and 120 °C to prevent the compressor from over-speeding and the MEA solution from thermal degradation for 90% load. Solvent rate varies in a range limited by compressor surge and maximum pump flow. There is an optimum solvent rate that minimizes total lost work and maximizes removal, and it increases as the steam rate is reduced such that at 60% load, the optimum solvent rate exceeds the maximum flow of the rich solution pump (Figure 3.16).

Figures 3.14 and 3.15 demonstrate that maximum reboiler temperature provides minimum total equivalent work and maximum removal. As proved by previous studies on steady state lost work minimization in amine plants, higher temperature always provides less equivalent work associated with both reboiler heat duty and CO_2 compression. For this specific operational scenario in which the extracted steam rate is reduced by closing the steam valve, operation at higher temperature is optimum because the steam is available at higher pressure at the extraction point relative to the design condition. In order to keep the reboiler temperature high in response to steam rate reduction, the compressor speed should be reduced.

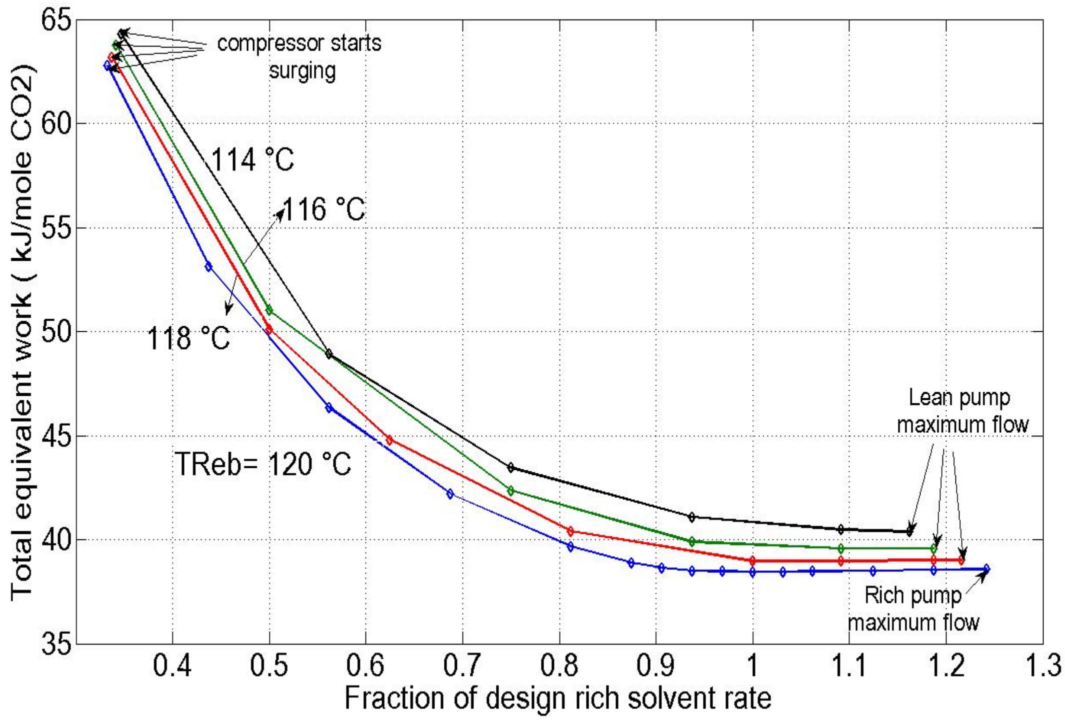

Figure 3.14: Simulation of reboiler steam rate reduction: the effects of rich solution rate and reboiler temperature (adjusted by compressor speed) on total equivalent work at new steady state condition when the plant is operated at 90% reboiler load.

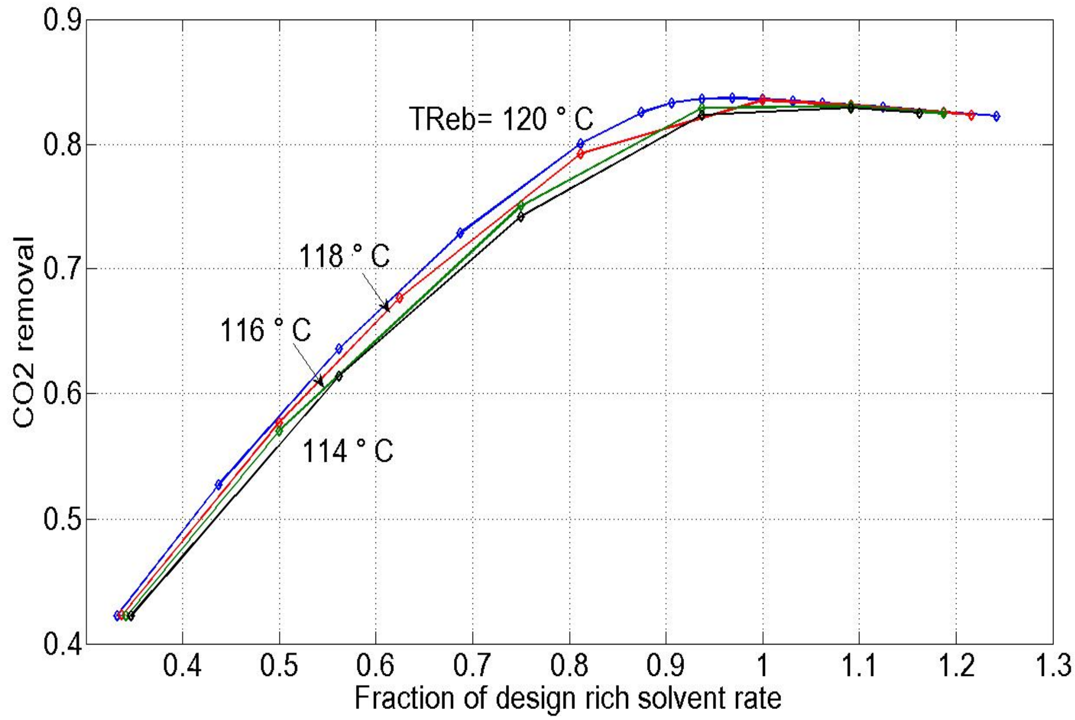

Figure 3.15: Reboiler steam rate at 90%: the effects of rich solvent rate and reboiler temperature (adjusted by compressor speed) on CO_2 removal.

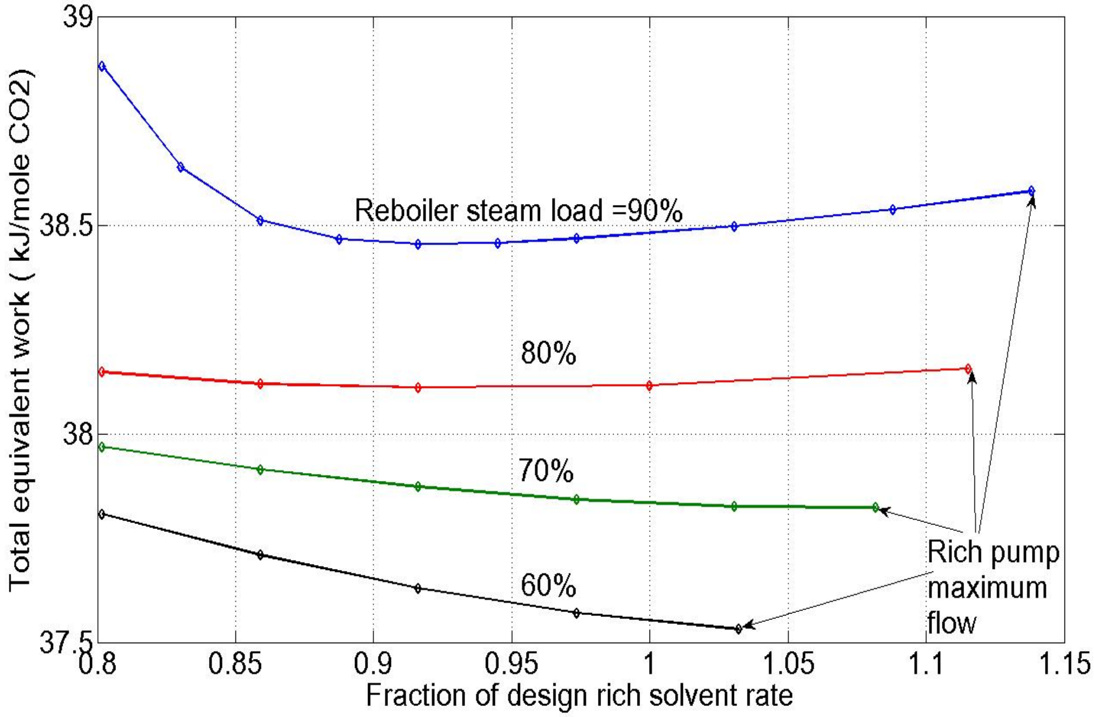

Figure 3.16: Effects of reboiler steam rate reduction on total equivalent work, 120 °C Reboiler, variable compressor speed.

Regarding CO_2 compressor operation, reducing the steam rate in the reboiler pushes the compressor operation to the surge limit. The simulation results show that 60% steam rate is the minimum load where the compressor operates in the non-surge region in the presence of controlling reboiler temperature at 120 °C. Below 60% load, a control strategy should be applied to prevent the compressor from surging. This study proposes and compares two surge control strategies. The first one activates anti-surge control, which is typically installed on the compressor package by manufacturers. In this strategy, a portion of gas exiting of a compressor stage starting to surge is recycled back to the entrance of that stage in order to provide minimum inlet volumetric flow. The disadvantage of this strategy is the addition of energy cost due to gas recycling during surge condition. The second strategy, which is explored in this study, does not implement a built-in compressor anti-surge control system. This strategy controls the compressor speed and solvent rate to keep the operating curve on the surge limit.

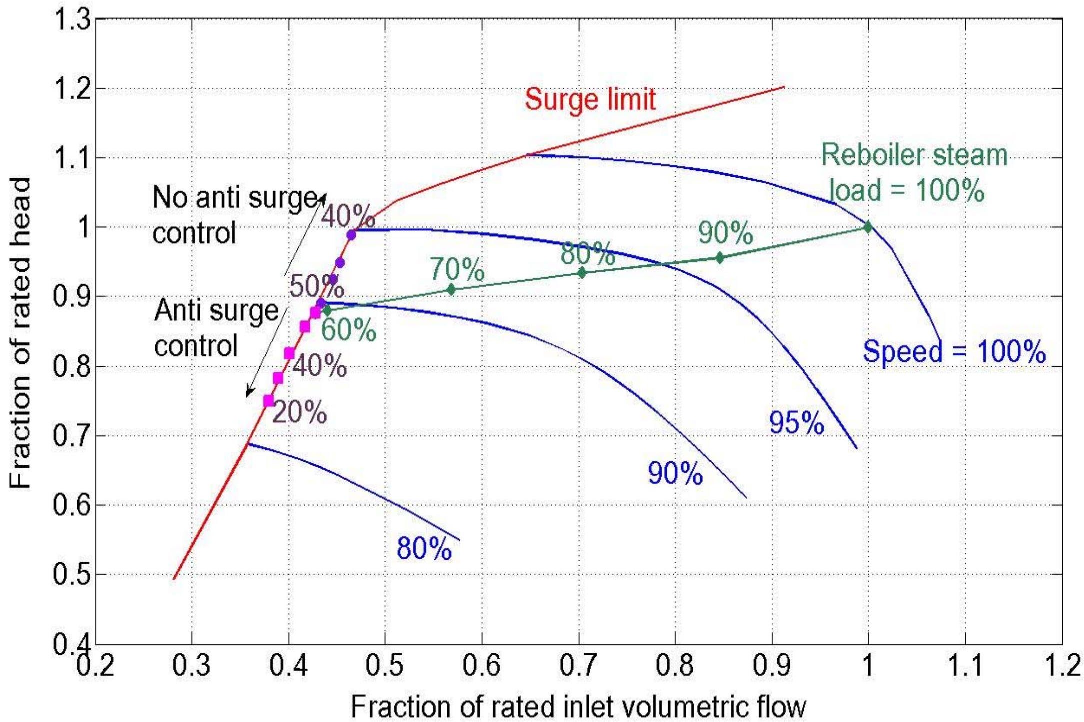

Figure 3.17: The performance map of a multi-stage (5 stages) CO_2 compressor for reduced reboiler steam rate. Operating points are the results of minimization of total equivalent work by optimizing compressor speed and solvent rate. ♦- represent unique optimum points when the plant is operated at 60–100% reboiler steam load. ■- represents optimum points for operating the plant at 20–59% using anti-surge control on the compressor. ●- represents optimum points for operating the plant at 40–59% without using anti-surge control on the compressor.

This work optimizes both solvent rate and compressor speed to minimize total lost work at steady state condition for different levels of load reduction. Figure 3.17 presents the obtained optimum path on the 5-stage compressor performance map. As shown in this figure, for loads between 60% and 100%, the compressor is operating normally in non-surge region and as the steam load is reduced, the compressor speed should be reduced. For loads lower than 60%, where the surging begins, operating curves resulting from the two surge control strategies discussed above are shown. Both optimum curves lie on the surge limit but move in opposite directions.

In the anti-surge control strategy, the reboiler temperature (and stripper pressure) remain at maximum value by reducing compressor speed and, as load reduces, the compressor speed is further reduced. That is why the optimum path associated with this strategy is going down on the surge limit as shown in Figure 3.17. In the second strategy, without anti-surge control on the compressor, the compressor speed should increase, such that at around 40% load, the operating point reaches the turning point of the surge line. After passing the turning point, we need to reduce the stripper pressure and temperature much more than before because the reboiler downstream pump loses its suction pressure and fails to pump the liquid. One of the interesting results from this analysis is that anti-surge control has the capability to operate the plant at a wider range of steam load (up to 80% reduction) while the second strategy is not applicable when more than 60% steam load reduction is desired unless it employs an oversized pump to handle lean solution coming from the reboiler.

As shown in Figure 3.18, it would be optimum if the reboiler temperature were controlled at 120 °C (the highest allowable temperature) as long as compressor operation permits. In the non-surge region it is not a problem to run the reboiler at this temperature. In the surge region, the activation of anti-surge control (strategy 1) allows us to operate the reboiler temperature at this optimum value; however, there is additional lost work due to gas recycling in the surging stages. In the second strategy, the reboiler temperature should be reduced to keep the compressor from surging. This avoids energy cost due to gas recycling, but it increases lost work associated with reboiler heat duty and compression because of reduced pressure and temperature.

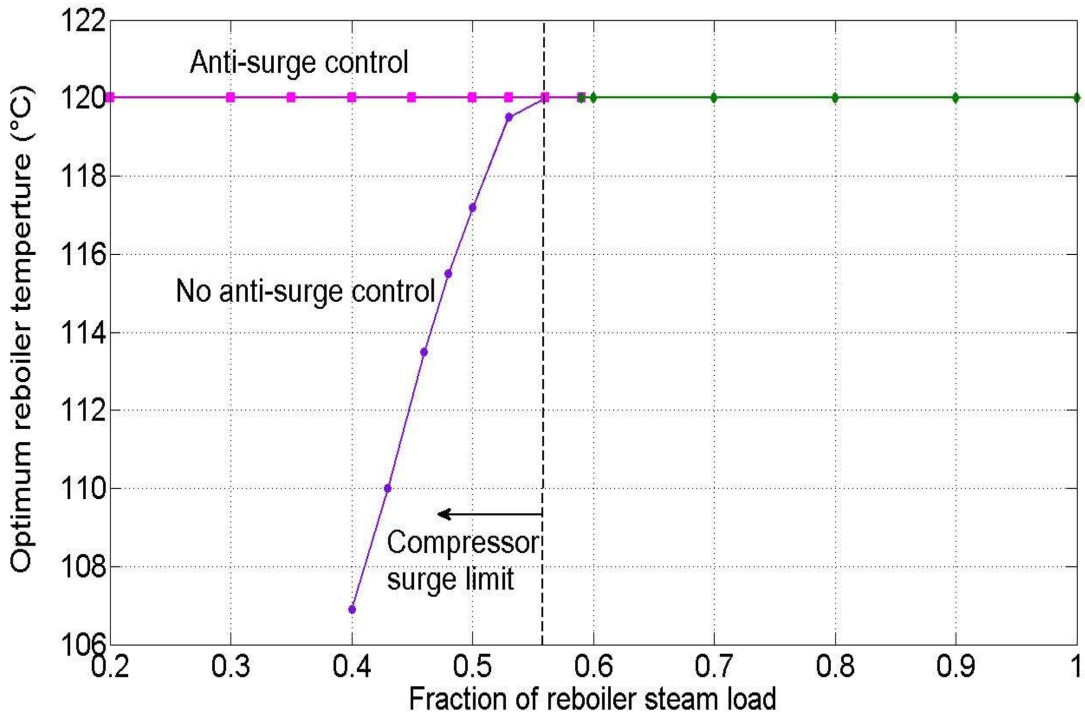

Figure 3.18: Optimization of reboiler steam rate reduction to minimize total equivalent work: optimum reboiler temperature vs. fractional reboiler steam rate by using ♦-compressor non-surge, ■- anti-surge control, and ●-not using anti-surge control.

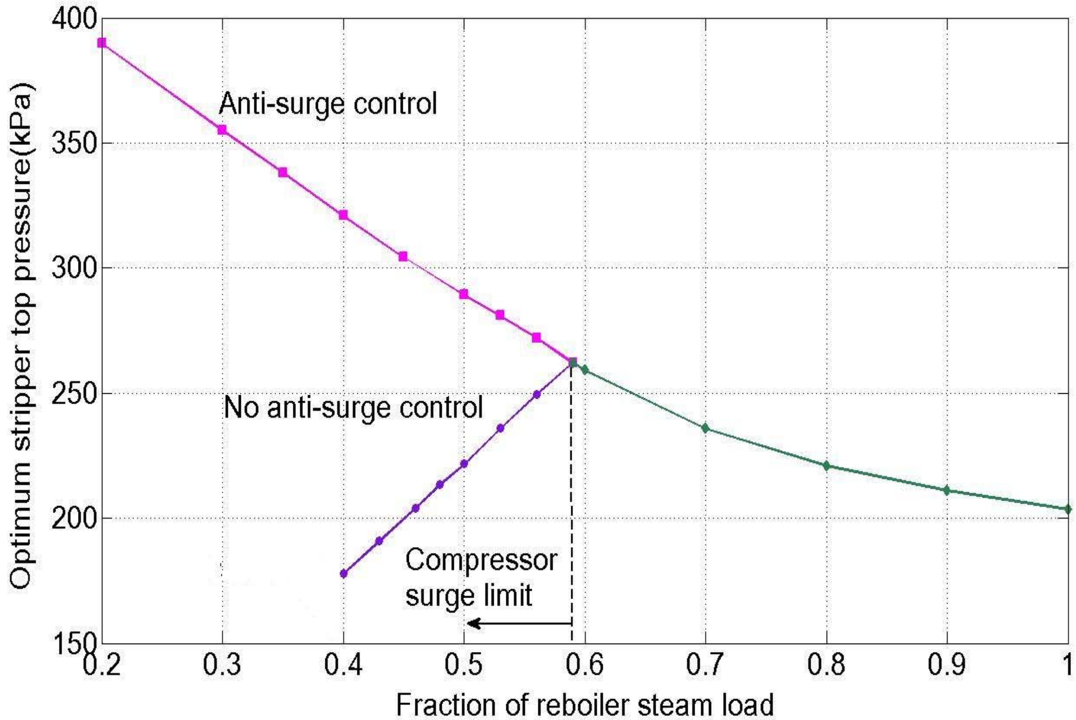

Figure 3.19: Optimization of reboiler steam rate reduction: optimum stripper top pressure vs. reboiler steam rate by using ♦- for compressor non-surge region, ■- for compressor surge region using anti-surge control, and ●- for compressor surge region not using anti-surge control.

Figure 3.19 shows how stripper top pressure varies with load reduction in surge and non-surge regions. In the non-surge region, pressure goes up as load decreases, although the reboiler temperature is constant. Anti-surge control on the compressor lets the pressure in the stripper increase with load reduction such that at 20% load, the stripper pressure is about two times greater than its initial design value. Therefore, there would be an additional capital cost associated with the stripper column, because of the greater pressure.

As the reboiler steam load is reduced, anti-surge control on the compressor that lets the pressure go up without causing surge leads to increased lean loading and decreased optimum solvent rate. (Figures 3.20 and 3.21).

As already shown in Figure 3.16, optimum solvent rate minimizing total lost work increases with steam rate reduction. However, increasing the stripper pressure at the same time does not allow the rich pump (stripper upstream pump) to handle the change of solvent rate desired. For reboiler steam load lower than 70%, the optimum solvent rate is greater than the maximum flow in the rich pump at the specific stripper pressure for each load. Therefore, using the anti-surge control strategy, although the lean loading increases, the optimum solvent rate set by rich pump maximum flow decreases with steam load (Figure 3.21). In conclusion, it is likely to further reduce lost work during partial steam load operation (for 30% or more reduction in steam rate) by initially designing an oversized rich solution pump to handle the liquid while the stripper becomes over-pressurized.

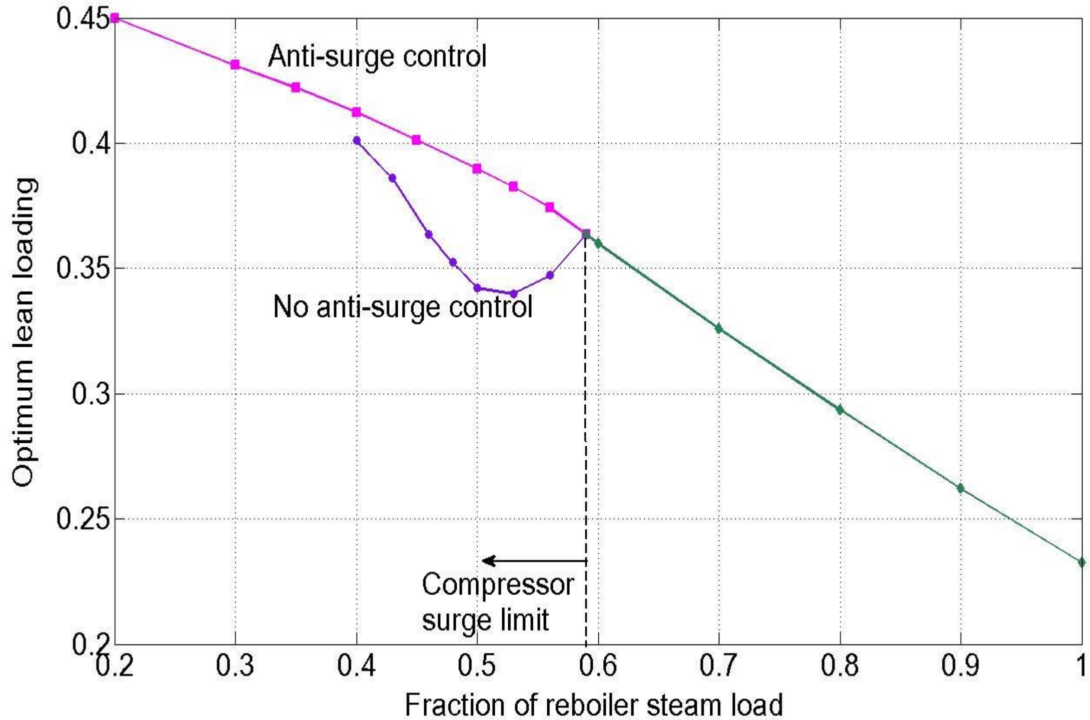

Figure 3.20: Optimization of reboiler steam rate reduction: optimum lean loading vs. fractional reboiler steam rate by using ♦- for compressor non-surge region, ■- for compressor surge region using anti-surge control, and ●- for compressor surge region not using anti-surge control.

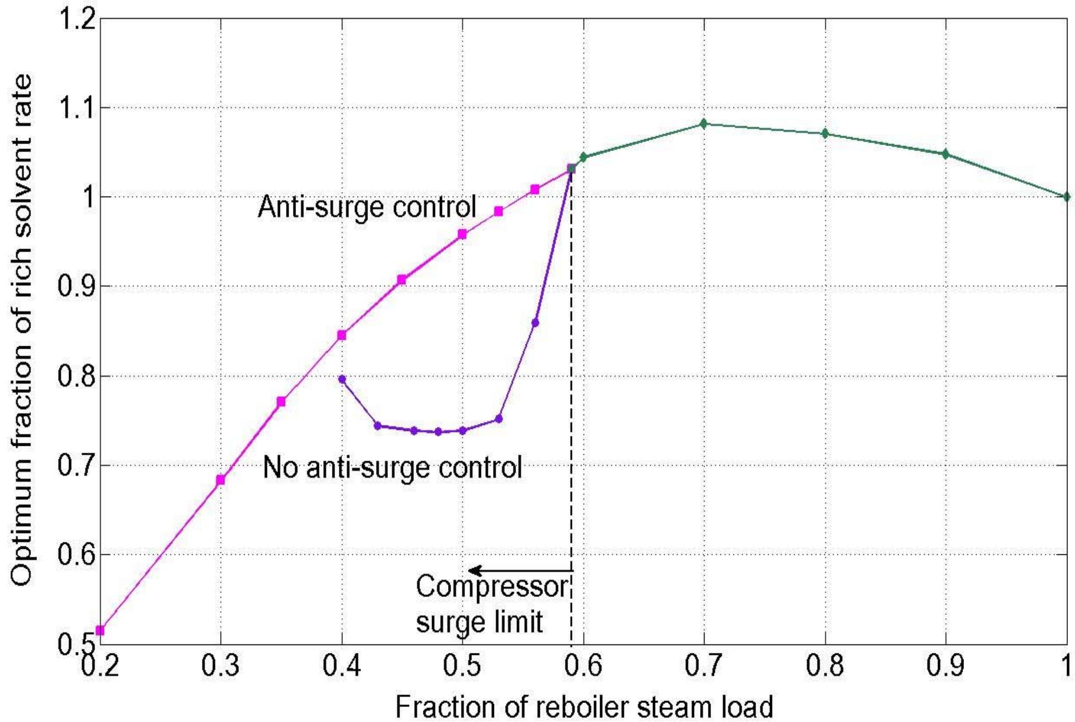

Figure 3.21: Optimization of reboiler steam rate reduction: rich solvent rate vs. reboiler steam rate by using ♦- for compressor non-surge region, ■- for compressor surge region using anti-surge control, and ●- for compressor surge region not using anti-surge control.

Figure 3.22 shows how the total equivalent work varies at optimum points with steam load reduction in both non-surge and surge regions. In the non-surge area it decreases with steam load mainly due to increasing suction pressure of the compressor. It still decreases with load in surge areas when anti-surge control is activated because of increasing stripper pressure. The second surge control strategy that loses the advantage of high reboiler steam pressure leads to increasing equivalent work. CO_2 removal is reduced linearly with steam rate and the surge control strategy chosen does not influence it significantly (Figure 3.23).

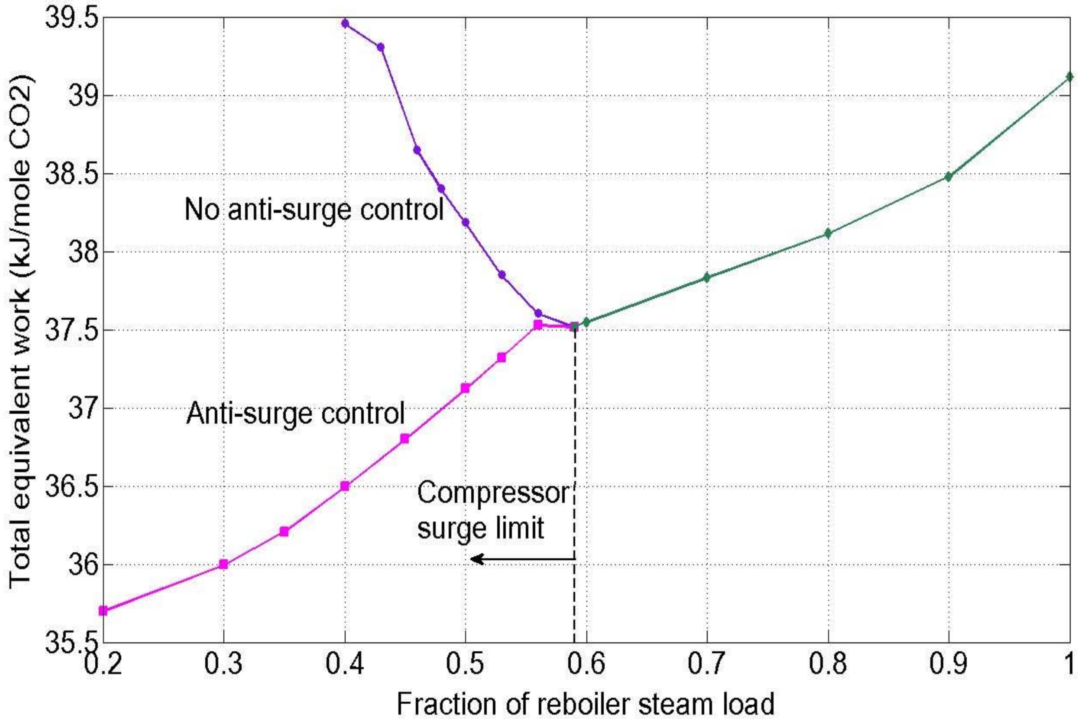

Figure 3.22: Optimization of reboiler steam rate reduction : minimized total equivalent work vs. reboiler steam rate by using ♦- for compressor non-surge region, ■- for compressor surge region using anti-surge control, and ●- for compressor surge region not using anti-surge control.

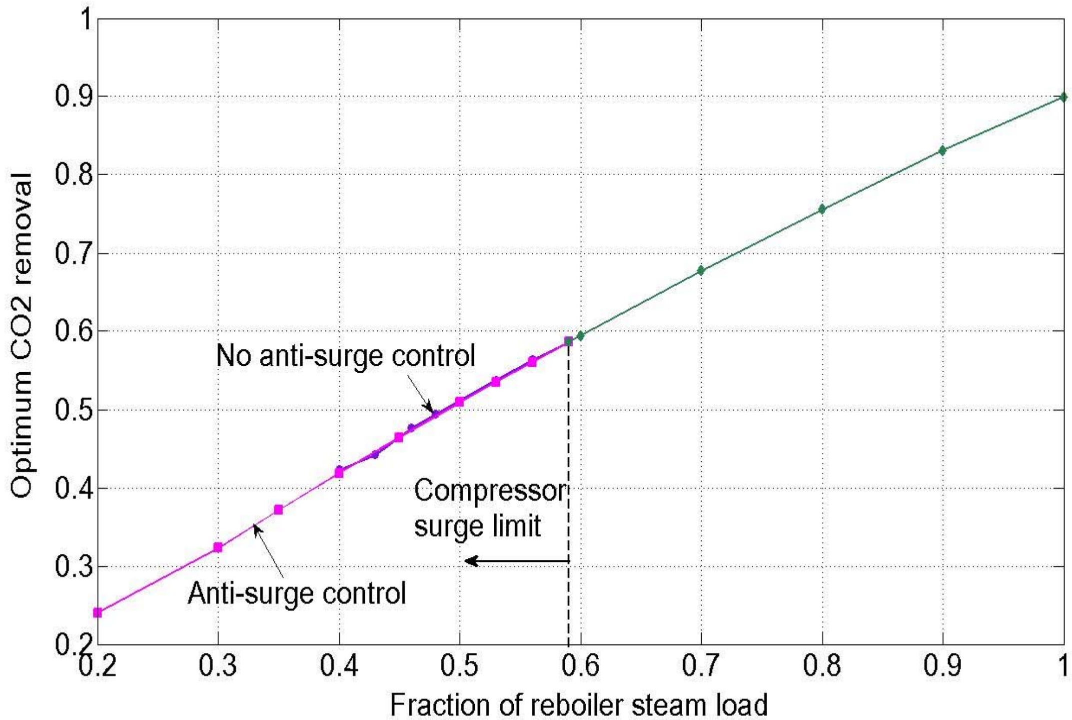

Figure 3.23: Reboiler steam rate reduction scenario demonstrates optimum CO_2 removal vs. fractional reboiler steam rate by ♦- for compressor non-surge region, ■- for compressor surge region using anti-surge control, and ●- for compressor surge region not using anti-surge control.

Comparing these two surge control options with respect to lost work and removal, it is concluded that although anti-surge control introduces additional mechanical energy for recompressing recycled gas during surging, it still causes less lost work relative to the alternative, because it takes advantage of the increased extracted steam pressure that occurs in this operational scenario and operates the reboiler and stripper at optimum temperature and pressure.

2.5. SUMMARY AND CONCLUSIONS

Chapter 3 employs the fully integrated model to simulate and optimize two main operational scenarios occurring in capture plants: power plant load reduction and partial reboiler steam load operation. The optimization minimizes total lost work at the final steady state condition by adjusting compressor speed and liquid circulation rate as optimization variables. The following are the summary of practical conclusions derived from the steady state analyses and optimization:

1. Changing the compressor speed and liquid rate is limited by following operational constraints :
    a. The compressor speed should not exceed the maximum allowable speed, which is set at 120% of rated speed.
    b. Reboiler temperature should not exceed 120 °C to prevent thermal degradation of the MEA solution.
    c. Either the reboiler temperature constraint or the compressor surge limit determines the minimum compressor speed, which varies with the load change for each load reduction scenario.
    d. Liquid circulation rate can vary in a limited range, whose minimum value is set by the compressor surge limit and maximum value is set either by solvent pump (lean or rich pump) maximum flow condition or compressor surge limit.
2. Analyzing and optimizing MEA plant operation in response to power plant load reduction provides the following conclusions:
    a. Increasing compressor speed that decreases reboiler temperature and pressure results in extracting more steam for the reboiler and consequently removes more CO_2.

b. For a specific CO_2 removal, there is a compressor speed and a solvent rate that minimizes total equivalent work. Therefore, a variable speed compressor is advantageous for optimal operations.
c. Based on equivalent work minimization in the presence of constraints associated with pumps, compressor, and solvent thermal degradation, the MEA plant initially designed for 90% removal can remove up to 94% of inlet CO_2 by increasing the compressor speed up to 120% of the rated speed.
d. For low load operation such as 40% load, the compressor-operating curve reaches surge limit and changing speed and solvent rate does not push it away from this undesired region.
e. Recycling gas through surging stages, a practice typically implemented by anti-surge control on the compressor package, is the only way to prevent the compressor from surging during low power plant load operation.
f. No general simple rule was derived for optimally controlling the flow rates for a wide range of load change. Installing ratio control between the CO_2 rate in rich solution and the steam rate could be a strategy that can keep the plant close to optimum during partial load operation. However, more reduction in power plant load results in more deviation of ratio control strategy from the optimum path,
g. Controlling lean loading at a set point that varies in proportion to the removal is another strategy that controls the plant close to the optimum.

3. Analyzing and optimizing MEA plant operation in response to reboiler steam load reduction provides the following conclusions:

a. Minimal lost work would be maintained if the reboiler temperature is controlled at 120 °C (the maximum temperature to prevent MEA thermal degradation) by adjusting the solvent rate and compressor speed as long as compressor operational limits permit.
b. At a reboiler load lower than 60%, where the compressor starts to surge, a surge control strategy should be applied. Two surge control strategies are identified and compared:
    i. Anti-surge control on the compressor package.
    ii. Adjusting compressor speed and solvent rate to save compressor from surging.
c. Anti-surge control has more advantages with respect to operation and minimum lost work and would be preferable during partial reboiler steam load operation. The following is a summary of reasons for this statement:
    i. Although there is additional energy loss associated with anti-surge control because of recompressing recycled gas, the total lost work is still lower than the adjustment strategy since it lets the reboiler run at 120 °C and the CO_2 compressor compresses the gas at higher suction pressure and consequently lower compression ratio.
    ii. Anti-surge control strategy has the capability of operating the plant at a wider range of steam load (20–100%) while the adjustment strategy could not operate the plant below a 40% load.
    iii. The only disadvantage of anti-surge control is the increase in capital cost for the stripper column, because it pressurizes the stripper gradually as the steam rate is reduced. For example, at

20% load the optimal stripper pressure is twice the full load pressure.

iv. Anti-surge control has the potential for even further reduction in lost work for low steam load cases. By over-sizing the rich pump it would be able to pump rich solution to the pressurized stripper before getting to its maximum flow and circulate the liquid at its optimum rate.

Chapter Four: Design of an effective multi-loop system with storage tanks to improve control performance

This chapter implements the plant wide control procedure to determine efficient control structures in operating CO_2 capture. A fully integrated model created in Aspen custom modeler® is employed to simulate various operational scenarios: power plant load reduction, reboiler steam load reduction and foaming in the columns. This work identifies the best control configuration by its ability to reject disturbances and track the targeted set points, the quality of dynamic responses and safe operation of equipment in response to a wide range of changes in disturbances.

The second part of this chapter focuses on the effects of liquid residence time in the lean and rich tank on the dynamic performance of capture in response to the possible disturbances. Frequency analysis approach is employed to illustrate how changing the hold up time influences the quality of dynamic responses: response time and dampening oscillations.

4.1 INTRODUCTION

The technology of absorption/stripping process with aqueous amine solution is an energy intensive process. Much has been done to enhance the steady state absorption and energy performance in the conceptual design phase. In addition to optimizing the process configuration and solvent selection, energy can also be saved by understanding the dynamics of this process and exploring effective control configurations for transitional conditions.

However, there are very few studies focusing on dynamics and control of the capture plant. Load variation, start up, and shut down, the common disturbances affecting the operation of CO_2 capture, have been investigated in previous studies. (Kvamsdal et al. 2009, Ziaii et al. 2009, Lawal et al. 2010).

Schach et al. (2011) presented an optimal control structure designed by using self-optimized control for an MEA plant to operate at constant removal with minimal energy demand over 40–100% power plant load change. Those works that studied the power plant load variation scenario made step changes just in flue gas inlet condition. They did not consider the variation of total steam rate in the power cycle as a consequence of load variation. This is an important effect because it affects the operation of stripping and compression when reboiler steam is extracted from the power turbines. The operation of the CO_2 compressor during dynamic conditions also plays an important role in minimizing energy consumption. Previous studies have not included compressor performance.

This study integrates the dynamic model of the absorber and stripper, and combines the capture plant with a steady state model of steam turbines to account for all the interactions. In addition, by incorporating practical performance models for pumps and the variable speed CO_2 compressor, the model accounts for the operational boundaries created by compressor and pump limitations. This work is unique since it uses a fully integrated model to simulate unsteady-state operations and examines the dynamic performance of a variety of control structures.

This chapter includes two main parts. The first part presents a comprehensive plant wide control procedure to develop a multi-loop control structure that can efficiently control the plant during transitional operations. Power plant load variation, reboiler load change and foaming in the columns are the dynamic operations considered to evaluate the suggested control configurations.

Storage tanks are typically designed for different control purposes such as smoothing the responses and rejecting the disturbances where the established control structure cannot bring further improvement. Based on the control role that they play in a specific process, they are called with different names such as surge tank, buffer tank, and neutralizer (Faanes and Skogestad , 2000).

According to Luyben (1993), considering control performance when the tanks and reactors are designed is very important especially for recycle systems due to the trade off existing between design and control. However tank sizing is typically by rule of thumb rather than based on dynamics and control targets.

The second part of this chapter illustrates the effects of liquid residence time in lean and rich storage tanks on the dynamic performance in response to different disturbances by using frequency analysis.

4.2 DESIGN BASIS

This study simulates the dynamic operational scenarios using a process flow sheet created in ACM®. Figure 4.1 illustrates this flow sheet including the available valves for control purposes.

The following are inlet conditions and design specifications for the equipment:

- Gas rate and composition: 5.48 kmol/s , 13% CO_2
- Electric rate: 100 MW
- Absorber packing height: 15 m
- Stripper packing height: 10 m
- CO_2 removal with 30 wt % MEA: 90%
- Lean loading 0.233 mole CO_2/mole MEA
- Reboiler temperature: 120 °C

- CO_2 discharge pressure compressor: 150 bar
- Extracted reboiler steam = 30% total power cycle steam rate
- Steam turbine initial design condition (Lucquiaud (2010)):

$$P_{HP}^{in} = 290 \text{ bar}, \quad P_{IP}^{in} = 60 \text{ bar}, \quad P_{LP}^{in} = 2.65 \text{ bar}, \quad P_{LP}^{out} = 0.04 \text{ bar}$$

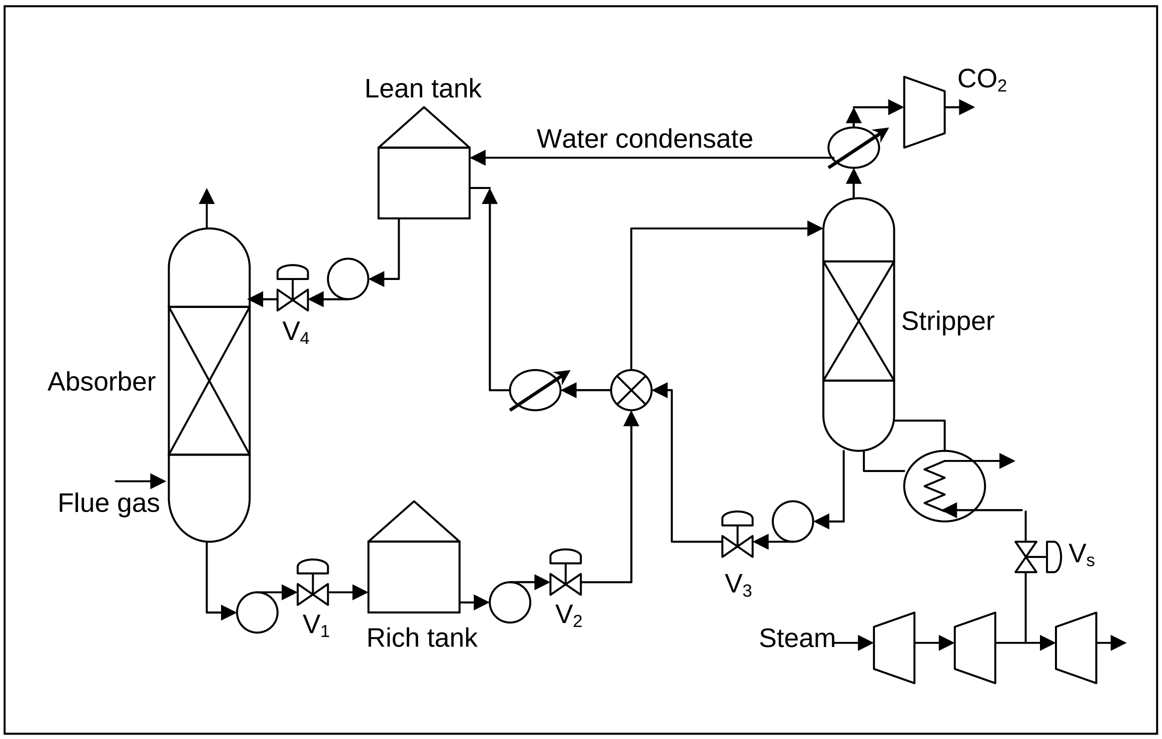

Figure 4.1: Process flow diagram of absorption/ stripping

4.3 DESIGN OF CONTROL SYSTEM

Amine absorption/stripping is a complex process with respect to control due to the liquid recycle and heat integration between the absorber and the regenerator. A systematic strategy is required to develop a viable control structure working satisfactorily over desirable operating conditions. This work employs the plant wide hierarchical design procedure presented by Seborg et al. (2004) to develop control structure alternatives and evaluate their performance in response to identified disturbances. In this work, it is assumed that a multi-loop control approach is sufficient for our control objectives and a multi-variable control system is not necessary. In section 4.3.3, the degree of interactions among control loops for different structures and pairing is evaluated and eventually the validity of that assumption is investigated.

4.3.1 Specifying control objectives

For operation of CO_2 capture in power plants, we are not required to satisfy any strict production rate or quality specifications. The most important objective in this energy intensive plant is to minimize energy consumption when the plant is operated at various operating loads. Therefore, a real time optimization should be performed based on current markets to optimize operating conditions. The responsibility of the control system is to bring the plant to the optimal condition smoothly and quickly when a disturbance is imposed. Safe operation of equipment such as the pumps and the CO_2 compressor should be addressed in control system design. To operate pumps safely the upstream level must be controlled to prevent cavitation and running dry. Compressor surge is also an unwanted condition that should be avoided by implementing a proper control strategy such as anti-surge control (discussed in detail in chapter 3).

The stripper pressure should be controlled with minimum oscillation to protect the overhead CO_2 compressor. To minimize thermal degradation of the solvent the reboiler temperature must be kept below the allowable value, 120 °C for MEA. In summary, the following objectives will be considered for the next steps where the control configurations are developed and evaluated.

1. Control the plant at optimum set points with a smooth and fast response during abnormal conditions.
2. Minimum oscillation in the inlet condition of the CO_2 compressor.
3. Level control on inventories
4. Keep $T_{Reboiler} \leq 120$ °C as much as possible during transition time

4.3.2 Top-down Analysis and bottom-up design

This section identifies potential controlled and manipulated variables and proposes applicable control structures based on a preliminary steady state analysis. Then it describes the sources of the most important disturbances and abnormal conditions that are likely to occur in the capture process.

Liquid levels in the inventories, absorber and stripper sumps and lean and rich storage tanks are process variables that should be controlled within a practical range. Other than liquid levels, the other controlled variables are not known yet and the task of this work is to identify the potential controlled variables among measurable process variables and then choose the best ones than can fulfill the control objectives discussed in section 4.3.1. Table 4.1 lists the available manipulating variables and potential control variables with the location of the measurement and/or the source of an inferential measurement.

Table 4.1: Potential manipulated and controlled variables for CO_2 capture plant

Process variables	**Location/symbol**
Liquid level, CV	Absorber sump, H_A
Liquid level, CV	Stripper sump, H_S
Liquid level, CV	Lean tank, H_L
Liquid level, CV	Rich tank, H_R
Flow rate, CV	Reboiler extracted steam , F_s
Flow rate, CV	Absorber sump effluent liquid, F_1
Flow rate, CV	Rich tank effluent liquid, F_2
Flow rate, CV	Stripper sump effluent liquid, F_3
Flow rate, CV	Lean tank effluent liquid, F_4
Lean loading(x_{CO2}/x_{MEA}), CV	Stripper sump effluent, Lldg (Inferred by density or temperature)
Rich loading(x_{CO2}/x_{MEA}), CV	Absorber sump effluent, Rldg (Inferred by density or temperature)
Pressure, CV	Top of the stripper, P_{top}
Temperature, CV	Reboiler, T_{Reb}
CO_2 removal, CV	CO_2 composition and gas rate are measured at absorber inlet and outlet gas streams, Rem
Compressor speed, MV	CO_2 compressor, speed
Control valve position, MV	Extracted steam valve, V_s
Control valve position, MV	Absorber sump downstream valve, V_1
Control valve position, MV	Rich tank downstream valve, V_2
Control valve position, MV	Stripper sump downstream valve, V_3
Control valve position, MV	Lean tank downstream valve, V_4

In order to minimize oxidative degradation in the absorber sump, thermal degradation in the stripper sump, and to meet hydraulic requirements in the reboiler, the sumps are fitted with level controls manipulating downstream valves (V_1 and V_3), which have the most direct influence on the controlled variables. Based on simulation, adjustment of solvent circulation rate is a strategy driving the plant to the optimum condition during a transitional operation. Therefore, one of the liquid valves (V_2 and V_4) is used for this purpose and the other is employed to control the levels in tanks. The following are two alternatives for controlling tank level by one valve:

1. Control the level of one tank by its downstream valve and let the level in the other tank vary freely.
2. Control the ratio of the level of tanks by one of downsteam liquid valves.

By accommodating the inventories with level controls, three manipulating variables remain to control the plant at desired operating condition: compressor speed, steam valve (V_s) and liquid valve (CV_2 or CV_4). To set up a multi loop SISO control system we need to choose three controlled variables among the ones listed in Table 4.1. A preliminary steady state relative gain array analysis (RGA) is performed on different sets of CVs by perturbing the MVs. As a result, five control configurations are found effective; however, some of them show higher degree of loop interactions. Table 4.2 summarizes the different structures of major control loops (excluding liquid level control loops) along with their computed relative gain array and MV-CV paring. The configurations are different in terms of controlled variables and pairing. Based on this analysis, F_L-Lldg-P and F_L-T-P configurations appear as the least and most interactive systems respectively. RGA can provide guidance for sensitivity and process interactions; however, dynamic simulations should check the results of this method. Section 4.3.4

presents the simulation results and investigates the validity of the RGA results on control performance of the proposed structures.

Table 4.2: Control system structures for MEA plant

Configuration name	**RGA (MV-CV pairing)**
F_L-F_S-P	$\begin{array}{c} \\ F_1 \\ F_s \\ P \end{array} \begin{array}{c} \begin{array}{ccc} V_2 & V_s & \text{speed} \end{array} \\ \begin{bmatrix} \underline{1.0846} & -0.0001 & -0.0845 \\ -0.0094 & \underline{0.6732} & 0.3362 \\ -0.0752 & 0.3270 & \underline{0.7483} \end{bmatrix} \end{array}$
F_L-T-P	$\begin{array}{c} \\ F_1 \\ T \\ P \end{array} \begin{array}{c} \begin{array}{ccc} V_2 & V_s & \text{speed} \end{array} \\ \begin{bmatrix} \underline{1.0031} & -0.1451 & 0.1420 \\ -0.0101 & \underline{2.5789} & -1.5687 \\ -0.0070 & -1.4337 & \underline{2.4267} \end{bmatrix} \end{array}$
F_L-Lldg-P	$\begin{array}{c} \\ F_1 \\ \text{Lldg} \\ P \end{array} \begin{array}{c} \begin{array}{ccc} V_2 & V_s & \text{speed} \end{array} \\ \begin{bmatrix} \underline{1.0073} & -0.2004 & 0.1930 \\ -0.0155 & \underline{1.0512} & 0.0002 \\ 0.0081 & 0.1852 & \underline{0.8067} \end{bmatrix} \end{array}$
Rldg-Lldg-P	$\begin{array}{c} \\ \text{Rldg} \\ \text{Lldg} \\ P \end{array} \begin{array}{c} \begin{array}{ccc} V_4 & V_s & \text{speed} \end{array} \\ \begin{bmatrix} \underline{0.6361} & 0.1695 & 0.1944 \\ 0.3557 & \underline{0.6441} & 0.0002 \\ 0.0082 & 0.1864 & \underline{0.8055} \end{bmatrix} \end{array}$
T-Rem-P	$\begin{array}{c} \\ T \\ \text{Rem} \\ P \end{array} \begin{array}{c} \begin{array}{ccc} V_4 & V_s & \text{speed} \end{array} \\ \begin{bmatrix} \underline{0.8972} & 0.0259 & 0.0769 \\ -0.0010 & \underline{0.8057} & 0.1952 \\ 0.1037 & 0.1684 & \underline{0.7279} \end{bmatrix} \end{array}$

This study incorporates following transitional scenarios as major disturbances influencing the operation of the capture:

1. Reboiler partial load operation: Due to the daily variation of electricity demand and pricing, it would be beneficial if all or part of the steam used in CO_2 capture is brought back to the power cycle and consequently increase electricity generation during the price peaks (Ziaii et al., 2009). This partial load operation is simulated by reducing the steam flow rate with the extracted steam valve.
2. Power plant load reduction: Power plants operating at variable load have two effects on the operation of the capture system: the flue gas flow rate varies and the extraction steam temperature and pressure change. This work simulates this scenario by making proportional step changes in both flue gas rate and power cycle total steam rate. According to previous studies by Kvamsdal et al. (2009) and Lawal et al. (2010), any change in inlet gas composition is neglected.
3. Foaming in the columns: Foaming in amine solution plants is one of the leading causes of plant upsets. It refers to the expansion of liquid due to passage of vapor and results in liquid buildup on the packing in the bed. Accumulating liquid in one of the columns leads to reduced liquid holdup in other inventories and endangers the operation of downstream pumps. Due to sudden change in holdup the performance of absorption and/or stripping might be also affected. This work simulates this condition by including a factor in the hydraulic model of the absorber and the stripper; then evaluates the ability of proposed control structures to maintain the capture performance and safety in response to this abnormal condition.

Level ratio control (LRC) on storage tanks is an alternative that replaces a conventional one tank level control to balance the liquid holdup between the lean and rich tanks. This strategy will be evaluated in terms of dynamic performance.

Cascade control is one of the advanced control strategies that can provide improved performance over single loop control, especially control loops that manipulate the variable being exposed to upstream disturbances. In our case study we manipulate steam rate and solvent circulation rate, which are likely to vary because of possible disturbances. Therefore, we examined the potential of applying this strategy for control structures, which manipulate the steam valve and liquid valve for controlling other process variables instead of direct flow rate control. The structures fitted with cascade control are as follows:

1. F_L-T-P : T control loop is cascaded with FC
2. F_L-Lldg-P: Lldg control loop is cascaded with FC
3. Rldg-Lldg-P : both Lldg and Rldg control loops are cascaded with FC
4. T-Rem-P : Both T and removal control loops are cascaded with FC

Table 4.3 provides the list of control configurations evaluated in response to discussed dynamic scenarios. This table also includes the modifications (LRC and cascade control) applied for basic version of each structure.

4.3.3 Validation of proposed control structures

The dynamic performance of the proposed control structures is evaluated in response to previously defined disturbances and abnormal conditions. For absorber and stripper foaming the dynamic results are generated for a 10% step change in the packing bed liquid holdup and maintaining control of the loops at their initial set points via PI controllers.

For partial load operation, besides looking at small changes in inputs we also consider a wide range of conditions; that is, 80% and 60% reduction in reboiler and power plant load respectively. In all cases of partial load operation, the liquid levels are controlled at their initial set points tightly with PI controllers while the other controlled variables utilize PI controller at the optimum set points where the lost work is minimized. For power plant load reduction it is also assumed that the control objective is to maintain the removal at its initial design value (90%) as the power plant load varies along with minimizing lost work at the new state. The details of the steady state optimization are discussed in Chapter #3.

The tuning parameters of PI controllers are calculated by using ITAE correlations with a back and forth procedure, a common strategy for MIMO system, to maximize the performance of each loop while other closed control loops are in service.

The simulations of dynamic scenarios with small changes in the magnitude of inputs have shown that all configurations are able to control the liquid levels in acceptable ranges without any problem associated with pump operation. For operation over a narrow range of conditions, figures show stripper response because this variable can represent the overall performance of the plant such as response time and smoothness of dynamics and determine if compressor is operating safely during dynamic scenarios. The following section presents a discussion of dynamic behavior of the control structure in response to the introduced disturbances.

4.3.3.1 Reboiler steam rate reduction

For this scenario, replacing level control on one of the tanks by level ratio control for both tanks has shown no significant change on dynamic response of the stripper pressure for all structures (see Figures 4.2 and 4.3) excluding T-Rem-P in which LRC improves the pressure response by eliminating the oscillations (Figure 4.4).

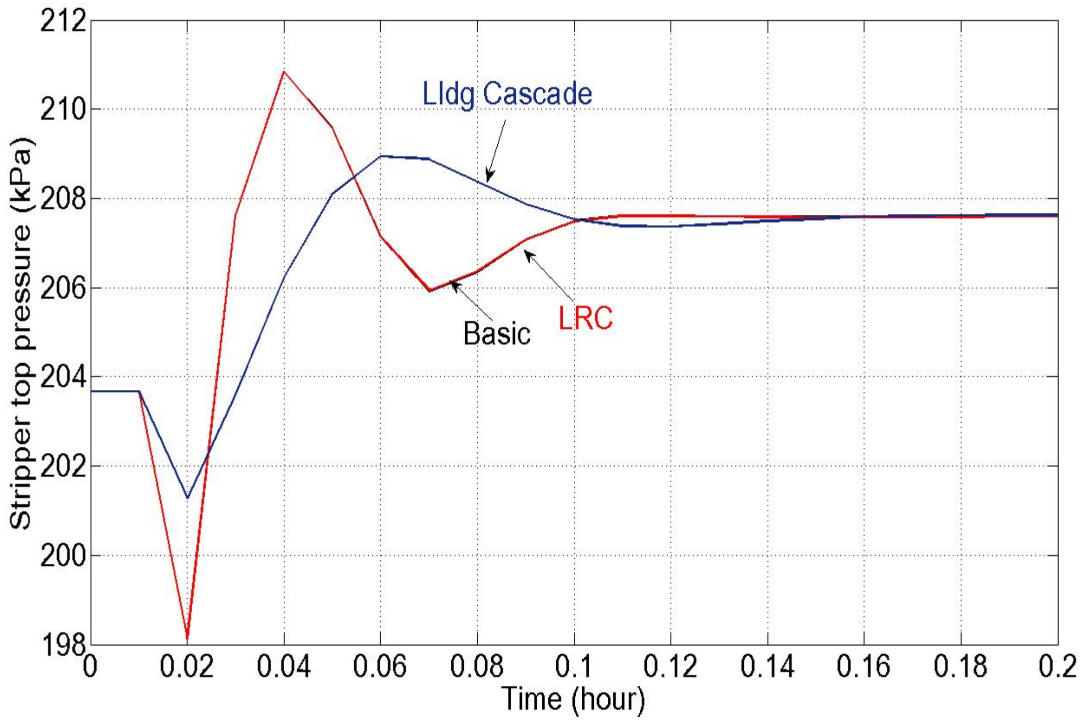

Figure 4.2: Stripper top pressure response in reboiler load reduction (-5% step change), in the presence of FL-Lldg-P control structure with modifications listed in table 4.4. Set points of LC loops are set at initial values and set points of FC, TC and PC loops are set at new optimum values.

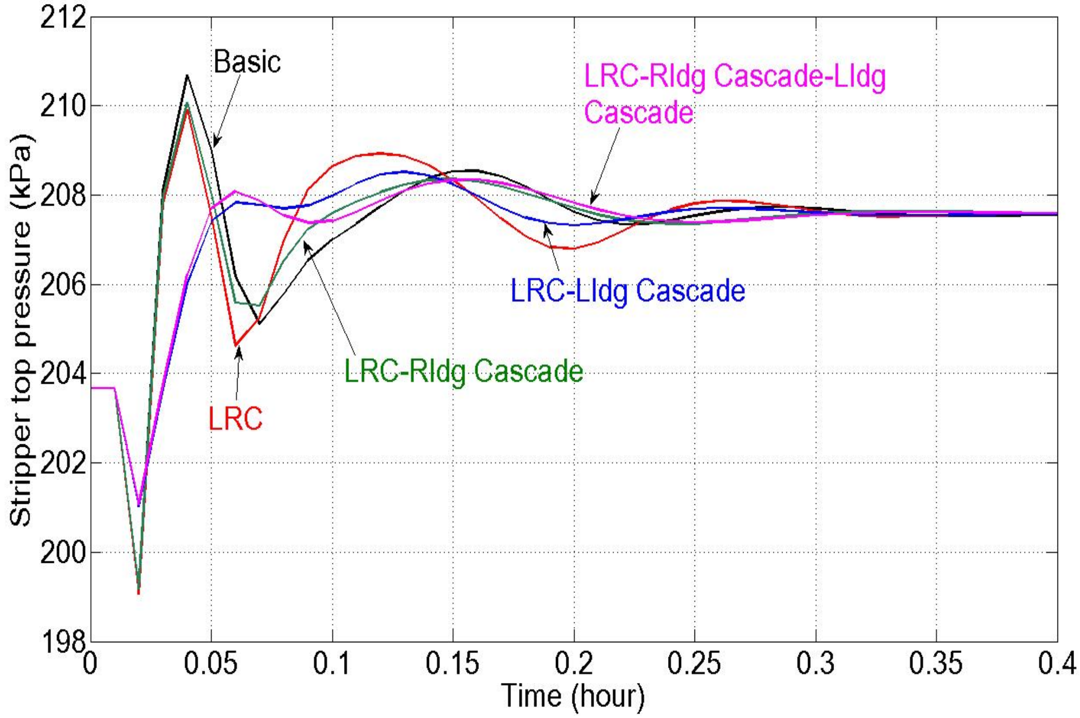

Figure 4.3: Stripper top pressure response in reboiler load reduction (-5% step change), in the presence of Rldg-Lldg-P control structure with modifications listed in table 4.4. Set points of LC loops are set at initial values and set points of RldgC, LldgC and PC loops are set at new optimum values.

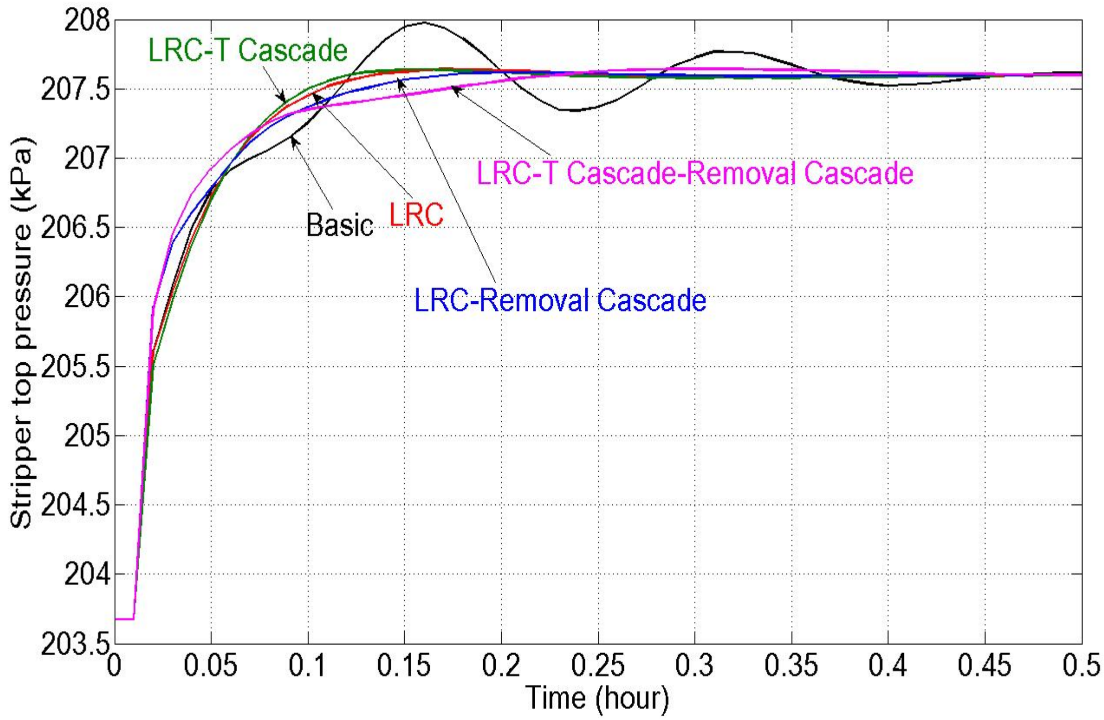

Figure 4.4: Stripper top pressure response in reboiler load reduction (-5% step change), in the presence of T-Rem-P control structure with modifications listed in table 4.4. Set points of LC loops are set at initial values and set points of TC, RemC and PC loops are set at new optimum values.

Based on the results, loading control either directly or indirectly performed in structures called F_L-Lldg-P, Rldg-Lldg-P and T-Rem-P would introduce some oscillations in the responses (Figures 4.3 and 4.4).

Cascade control is found as an enhanced strategy to improve the dynamics in the cases having oscillatory responses, such as F_L-Lldg-P and Rldg-Lldg-P. With T-Rem-P using LRC the oscillations are already damped, so cascade control on either TC loop or RemC loop not only provides an improvement in quality control but increases the response time. F_L-T-P does not show oscillatory behavior and so fitting the TC loop with cascade control does not change the response.

Figure 4.5 compares the pressure response for all the control structures subject to steam rate reduction. Although F_L-Lldg-P and Rldg-Lldg-P configurations were fitted by cascade control, their responses are not as smooth and fast as the response of F_L-F_s-P and F_L-T-P. For this scenario, the control configurations can be ranked as follows:

1. F_L-T(cascade)-P
2. F_L-F_s-P
3. T-Rem-P
4. F_L-Lldg(cascade)-P
5. Rldg(cascade)-Lldg(cascade)-P

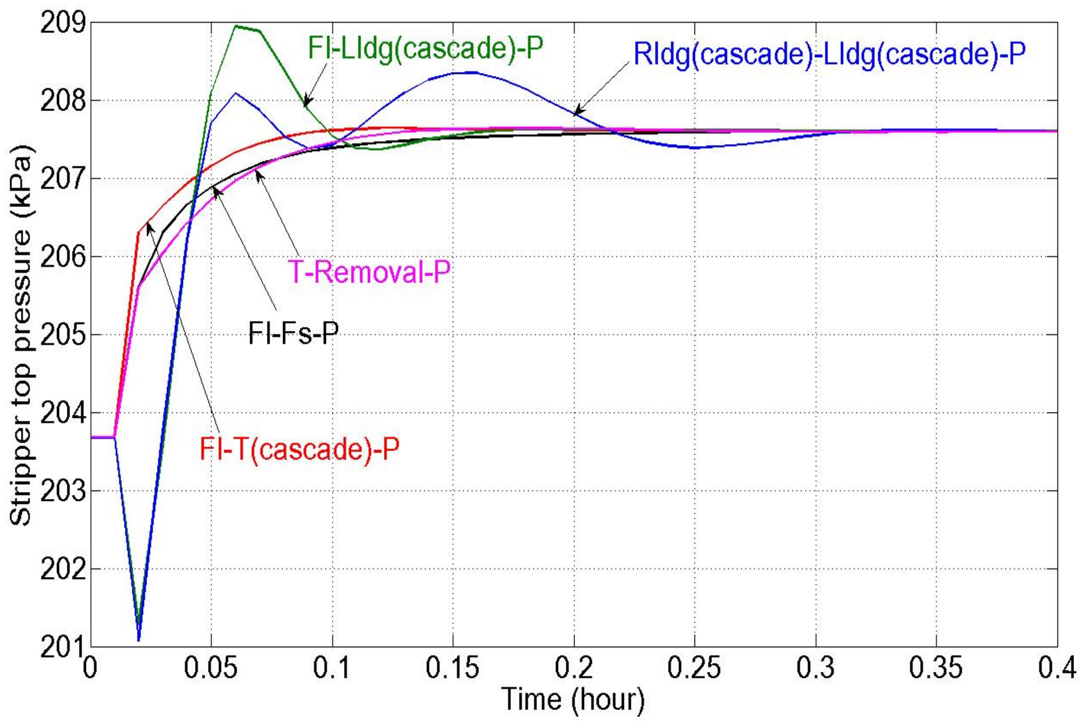

Figure 4.5: Comparison of control structures in terms of stripper top pressure response in reboiler load reduction (-5% step change). LRC is considered for lean and rich tanks. Set points of LC and LRC loops are set at initial values and set points of other control loops are set at new optimum values.

4.3.3.2 Power plant load reduction

The effects of power plant load reduction on the capture operation is simulated with various control structures by considering the dynamic performance with -10% step changes in both flue gas rate and power cycle steam rate.

This study shows that replacing level control by level ratio control has no significant positive or negative effects on dynamic responses in all the configurations. Controlling the rich and lean loading by liquid valve position and steam valve position leads to sustained oscillations that make the plant unstable. Cascading rich loading control loop with a flow control on the liquid valve could substantially damp the oscillation and stabilize the system. Cascade control on the lean loading has no effect on the response (Figure 4.6)

The basic version of T-Rem-P structure with or without level ratio control exhibits a dampened response. Cascading either a temperature or a removal control loop with a flow controller makes the response worse and when both loops are cascaded with flow controllers, the system becomes unstable with sustained oscillation(Figure 4.7). This case is an example of a system in which cascade control has adverse effects on dynamic performance.

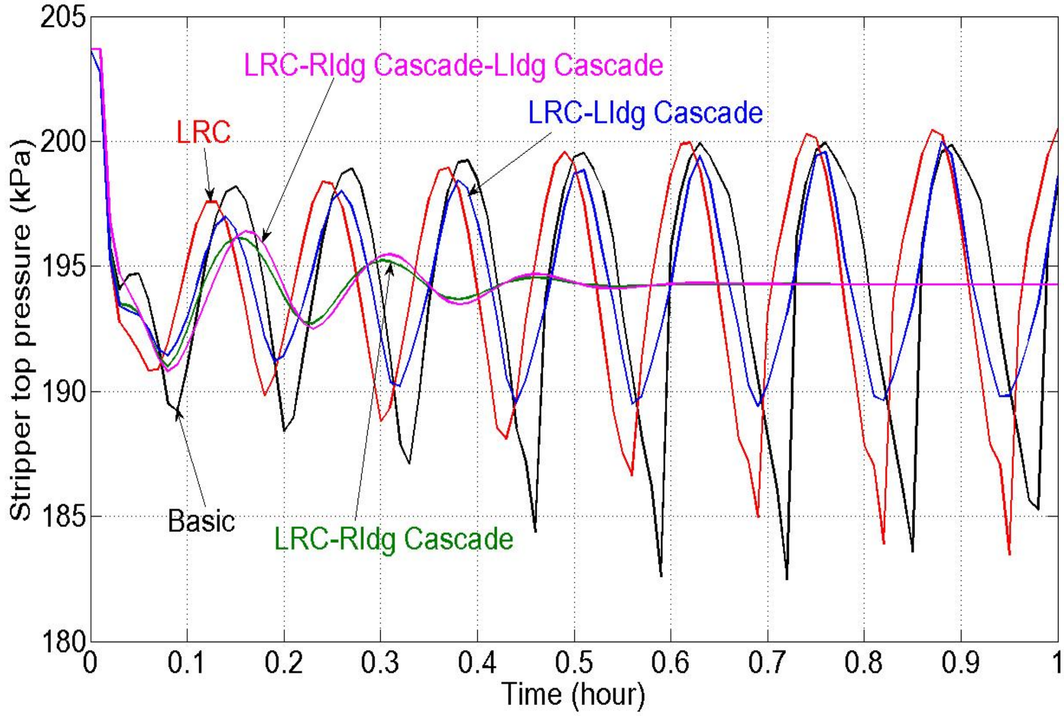

Figure 4.6: Stripper top pressure response in power plant load reduction (-10% step change), in the presence of Rldg-Lldg-P control structure with modifications listed in table 4.4. Set points of LC loops are set at initial values and set points of RldgC, LldgC and PC loops are set at new optimum values that keep the CO_2 removal at 90% removal.

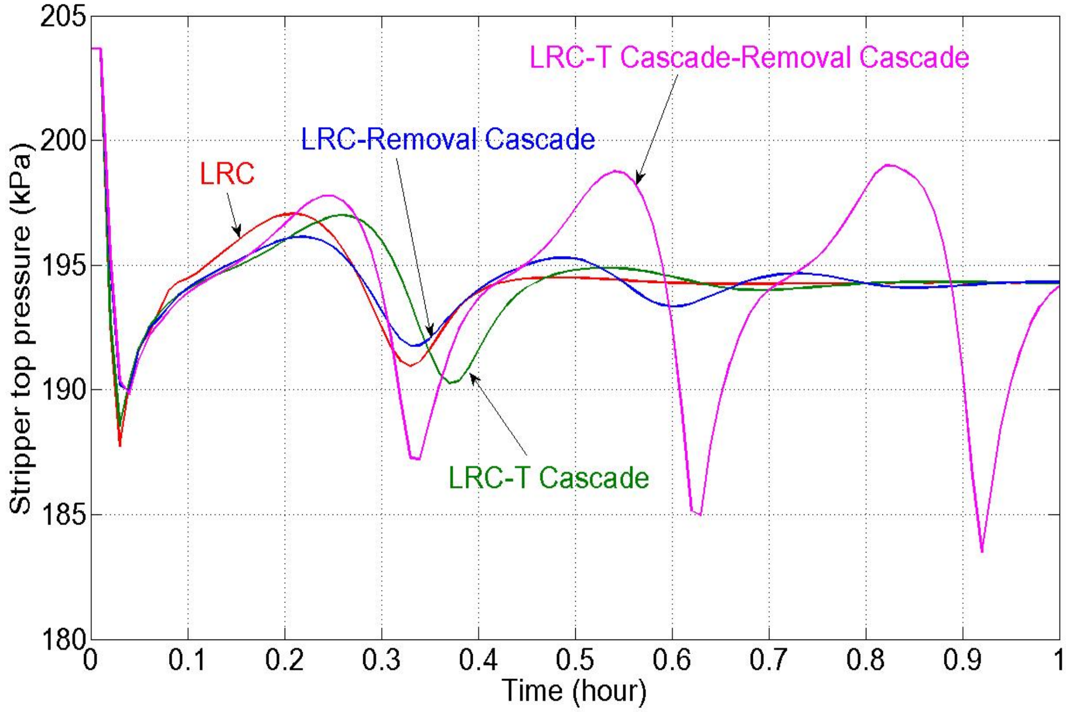

Figure 4.7: Stripper top pressure response in power plant load reduction (-10% step change), in the presence of T-Rem-P control structure with modifications listed in table 4.4. Set points of LC loops are set at initial values and set points of RldgC, LldgC and PC loops are set at new optimum values that keep the CO_2 removal at 90% removal.

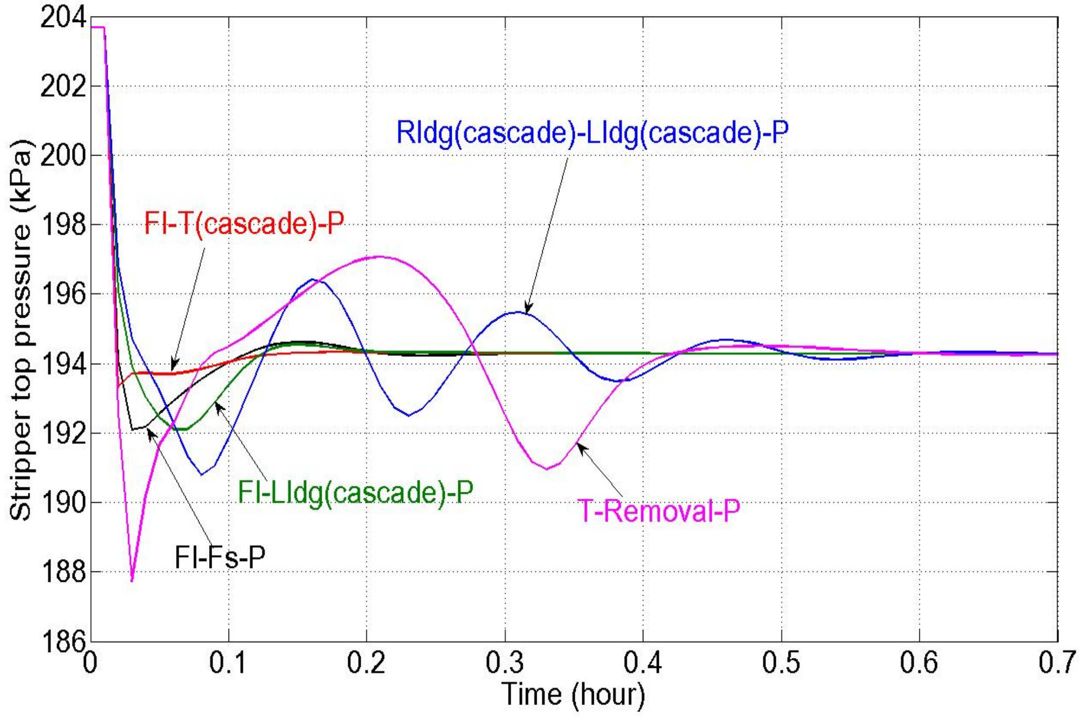

Figure 4.8: Comparison of control structures in terms of stripper top pressure response in power plant load reduction (-10% step change). Set points of LC loops are set at initial values and set points of other control loops are set at new optimum values that keep the CO_2 removal at 90% removal.

According to Figure 4.8, by comparing the pressure responses provided by the most effective version of control configurations to the partial load operation of power plant, we can rank them in terms of smoothness and minimum settling time as follows:

1. F_L-T(cascade)-P
2. F_L-F_s-P
3. F_L-Lldg(cascade)-P
4. Rldg(cascade)-Lldg-P
5. T-Rem-P

RGA is a well-known method to pair the variables. However this steady-state analysis shows this method is not always reliable to compare structure with respect to the dynamic behavior during the transition time. Dynamic simulation shows that F_L-Lldg-P is more interactive than F_L-Lldg-P while RGA predicts that F_L-Lldg-P is a less interactive system than F_L-T-P since the diagonal elements are much closer to 1 (Table 4.3).

Table 4.3: Evaluated basic control configurations with modifications

Configuration	Alternatives
F_L-F_S-P	Basic, Basic+LRC
F_L-T-P	Basic, Basic+LRC, Basic+LRC+T cascaded
F_L-Lldg-P	Basic, Basic+LRC, Basic+LRC+Lldg cascaded
Rldg-Lldg-P	Basic, Basic+LRC, Basic+LRC+Lldg cascaded, Basic+LRC+Rldgcascaded, Basic+LRC+Rldg cascaded+ Lldg cascaded
T-Rem-P	Basic, Basic+LRC, Basic+LRC+T cascaded, Basic+LRC+Rem cascaded, Basic+LRC+T cascaded+ Rem cascaded

4.3.3.3 Absorber foaming scenario

According to the outputs of simulating absorber foaming, level ratio control provides a remarkable improvement on dynamics especially for Rldg-Lldg-P in which the response is very oscillatory and for T-Rem-P where unstable sustained oscillation is observed. Applying LRC results in stabilizing and damping the oscillations (Figures 4.9 and 4.10).

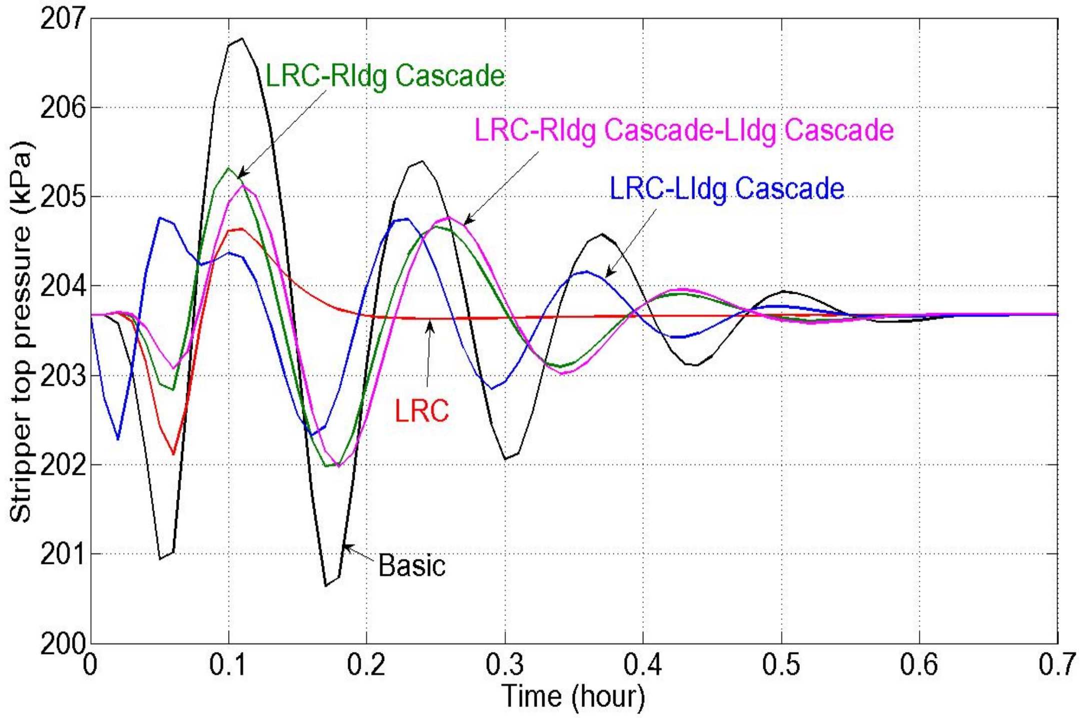

Figure 4.9: Stripper top pressure response to absorber foaming (10% step change), in the presence of Rldg-Lldg-P with modifications listed in table 4.4. Set points of all control loops are set at initial values.

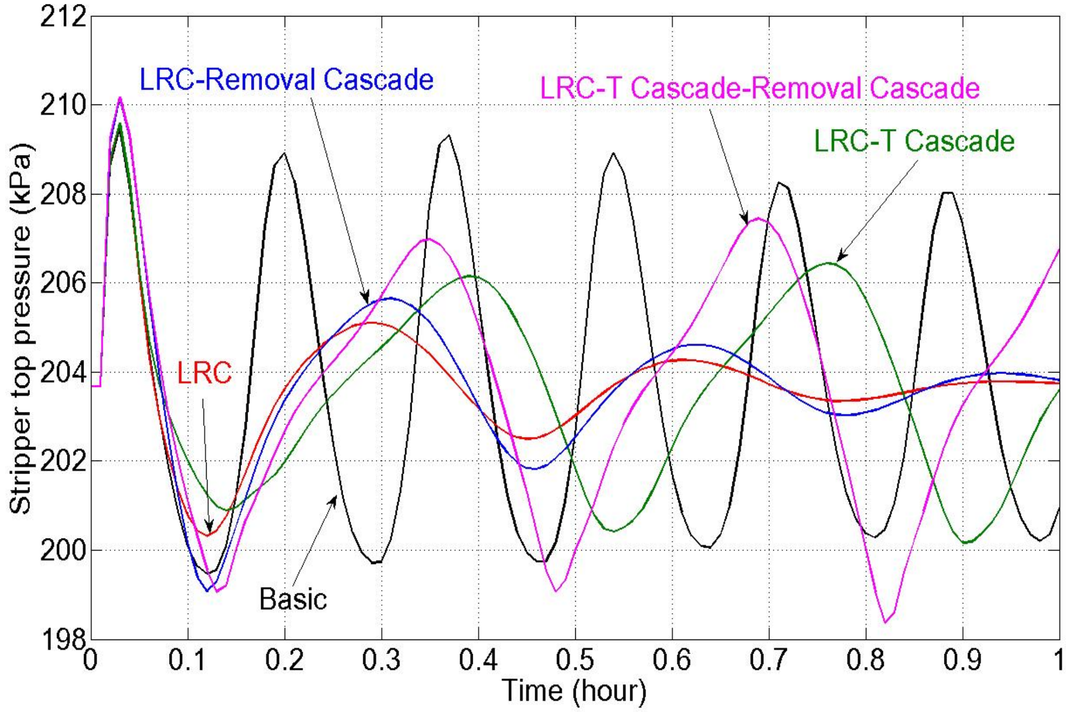

Figure 4.10: Stripper top pressure response in absorber foaming (10% step change), in the presence of T-Rem-P control structure with modifications listed in table 4.4. Set points of all control loops are set at initial values.

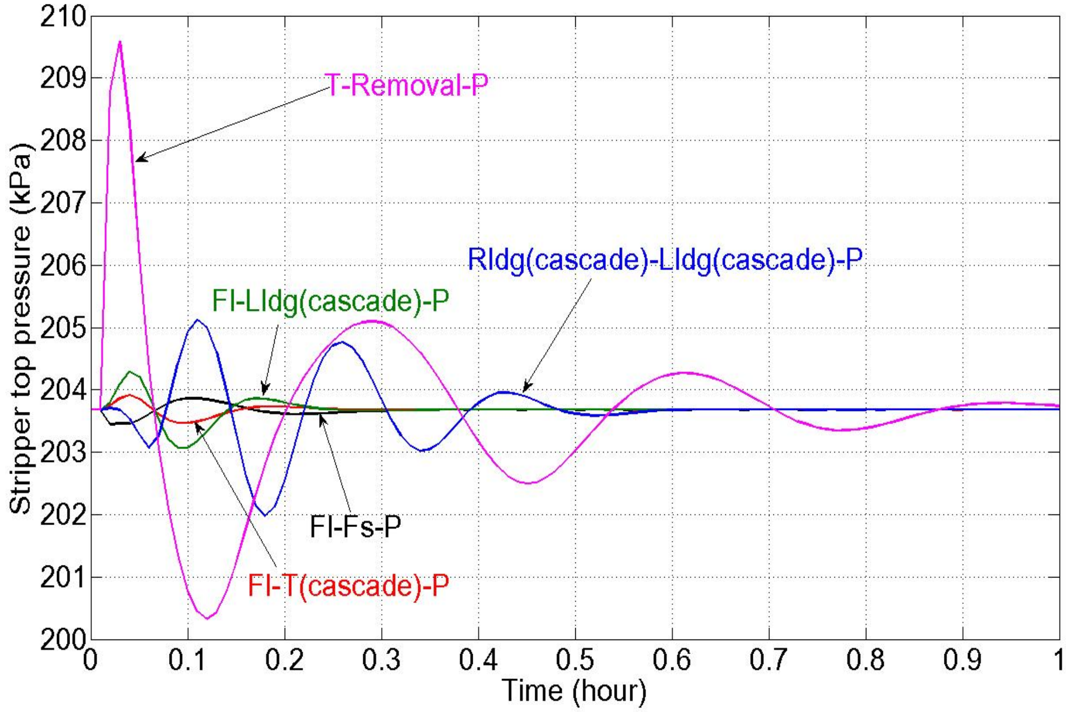

Figure 4.11: Response of control structures as stripper top pressure response to absorber foaming (10% step change). Set points of all control loops are set at initial values.

Cascade control is not an effective strategy for those control structures to reject the foaming disturbance. Furthermore it makes the responses worse by introducing damped or sustained oscillations.

The comparison of the control structures (figure 4.11) offers the following ranking in terms of smoothness and minimum settling time of pressure response:

1. F_L-T(cascade)-P
2. F_L-F_s-P
3. F_L-Lldg(cascade)-P
4. Rldg(cascade)-Lldg(cascade)-P
5. T-Rem-P

4.3.3.4 Stripper foaming scenario

As with absorber foaming, with stripper foaming, level ratio control is an effective strategy to damp the oscillation and stabilize Rldg-Lldg-P and T-Rem-P structures respectively. Cascade control has an adverse effect on the response in T-Rem-P. (Figures 4.12 and 4.13)

Figure 4.14 illustrates that F_L-F_s-P and F_L-T (cascade)-P can reject this disturbance quickly and smoothly while the other configurations show large overshoots and inverse responses.

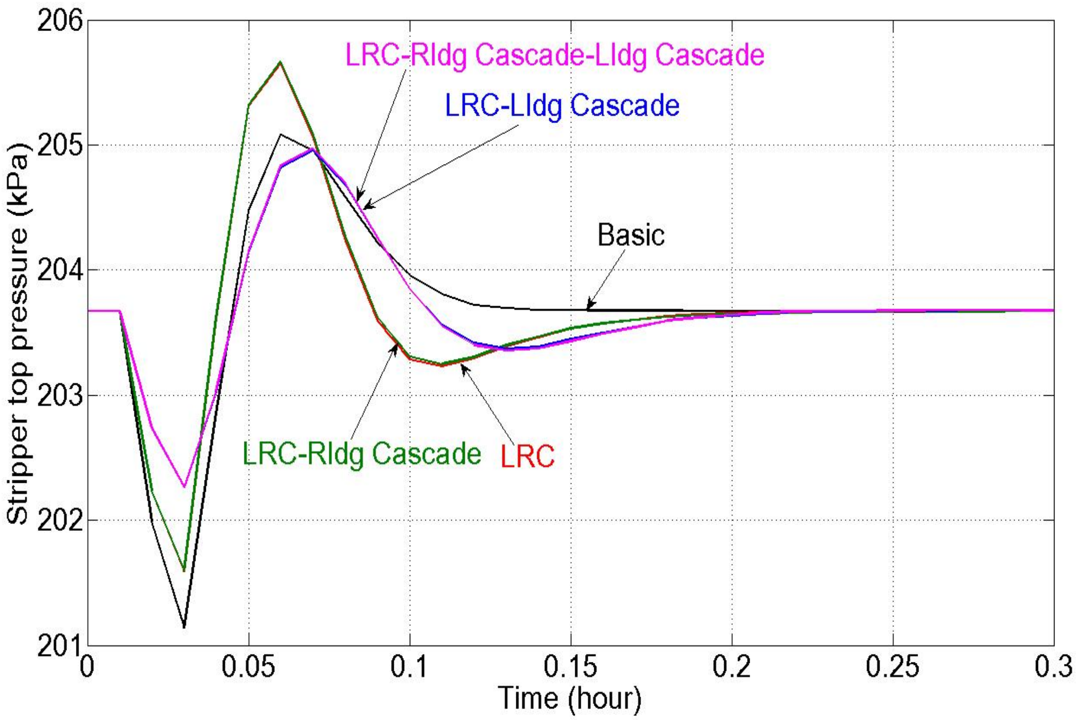

Figure 4.12: Stripper top pressure response to stripper foaming (10% step change), for Rldg-Lldg-P with modifications listed in table 4.4. Set points of all control loops are set at initial values.

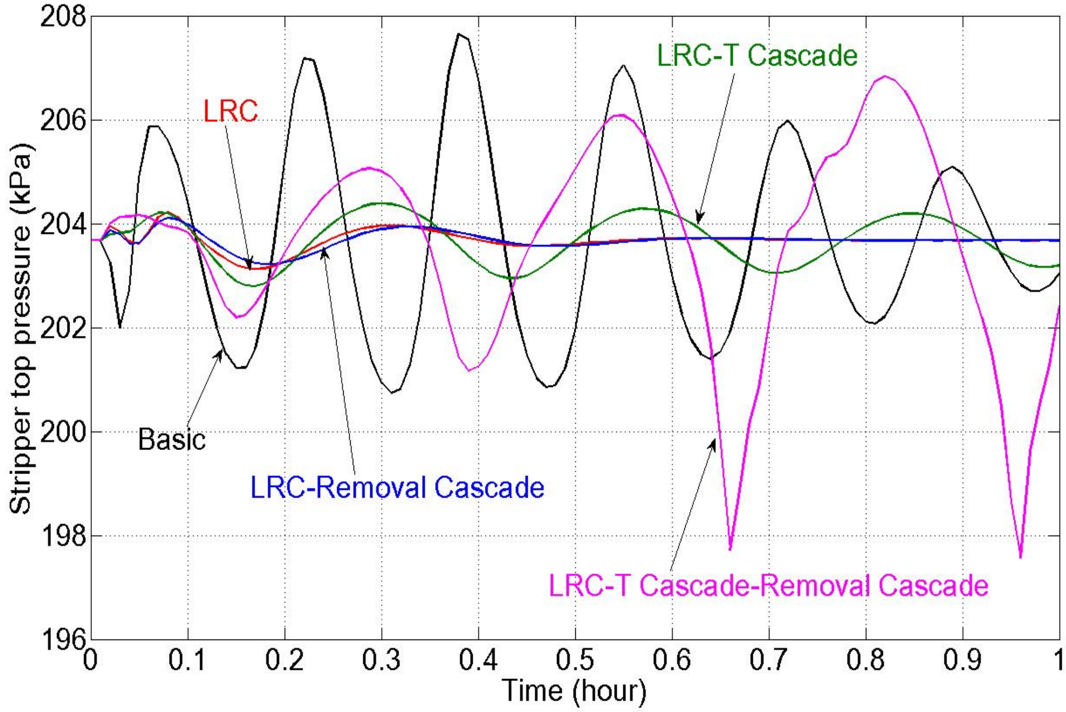

Figure 4.13: Stripper top pressure response to stripper foaming (10% step change), using T-Rem-P with modifications listed in table 4.4. Set points of all control loops are set at initial values.

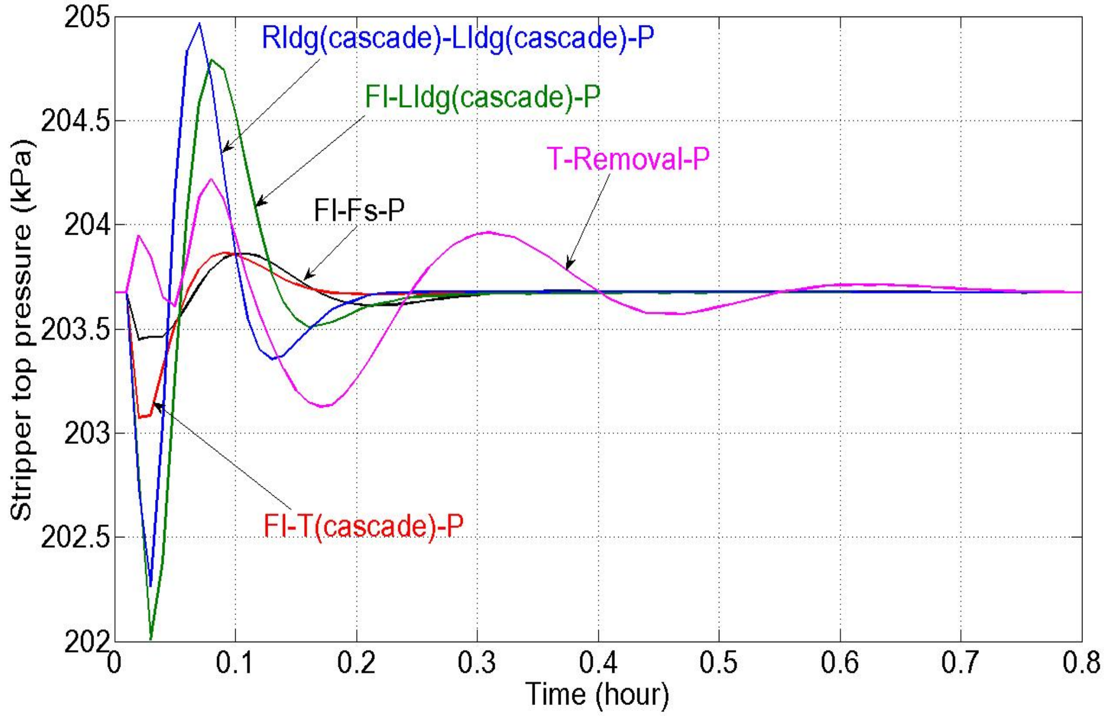

Figure 4.14: Comparison of control structures in terms of stripper top pressure response in stripper foaming (10% step change). Set points of all control loops are set at initial values.

4.3.3.5 Partial load operations over a wide range of operating conditions

This part of study is focused on dynamic performance evaluation over a wide range of operating conditions when the capture plant is run in one of the two partial load operations. For this study, we selected two control configurations among the ones discussed previously:

1. F_L-T (cascade)-P ; because of its best dynamic performance among all the structures for rejecting disturbances and bringing the plant to the targeted set points for all scenarios
2. Rldg(cascade)-Lldg(cascade)-P; because it is a highly interactive system that produces oscillatory responses; however, it was successful in set point tracking and disturbance rejection

It should be noted that the storage tanks are fitted with the level ratio control loop. The objective is to examine those configurations in terms of the ability of controlling the capture at new operating conditions and running the pumps and compressor safely in response to the following cases:

1. Partial load operation of reboiler ; simulated in 2 phases :

phase 1 : Ramping steam rate from 100% to 20% load in 30 min at time=0

phase 2 : Ramping steam rate from 20% to 100% load in 30 min at time=60 min

2. Partial load operation of power plant; simulated in 2 phases :

phase 1 : Ramping flue gas rate and power cycle steam rate simultaneously from 100% to 40% load in 10 min at time=0

phase 2 : Ramping flue gas rate and power cycle steam rate simultaneously from 40% to 100% load in 10 min at time=60 min

Similar to the previous simulations of operation over a narrow range, this work selected the set points of level control loops at the initial design values while the other control loop set points are set at optimal values that have already been obtained by an off-line steady state optimization. Therefore, in current simulations the set points vary with time as the load changes. The optimization minimized the total lost work of CO_2 capture at new steady state condition for both load reduction operations. For power plant load reduction, an additional optimization constraint was considered, which was maintaining CO_2 removal at the initial design value (90%). Table 4.4 provides those optimum conditions at various loads for both scenarios.

Table 4.4: Optimum control loop set points that minimize total lost work at reduced loads

Load	**100%**	**90%**	**80%**	**70%**	**60%**	**50%**	**40%**	**30%**	**20%**
Reboiler load reduction									
Rich solvent rate (kmol/s)	17.46	18.46	18.93	18.77	17.98	16.56	14.51	11.82	9.77
T_{Reb} (°C)	120	120	120	120	120	120	120	120	120
P_{Stripp} (kPa)	203.65	209.97	221.43	238.11	259.99	287.08	319.37	356.88	399.59
Rich loading	0.5689	0.5745	0.5790	0.5831	0.5878	0.5940	0.6023	0.6138	0.6293
Lean loading	0.2292	0.2642	0.2974	0.3286	0.3579	0.3853	0.4107	0.4343	0.4559
Power plant load reduction (Reduction of flue gas rate and power cycle steam rate)									
Rich solvent rate (kmol/s)	17.462	15.715	13.969	12.223	10.477	8.731	6.9848		
T_{Reb} (°C)	120	118.39	116.38	113.89	110.78	106.86	101.71		
P_{Stripp} (kPa)	203.67	194.62	183.2	169.31	152.89	133.75	111.44		
Rich loading	0.5688	0.5736	0.5788	0.5844	0.5904	0.5966	0.6030		
Lean loading	0.2326	0.2372	0.2423	0.2477	0.2534	0.2594	0.2656		

According to the simulation outputs, both configurations have the ability to deal with 80% load change in the reboiler steam and maintain the stability of capture plant. The controlled variables (solvent rate, stripper pressure, lean and rich loading)show nice and smooth set point tracking during forward and reverse phases of this operation.

A few controlled variables are not being controlled effectively. Reboiler temperature is one of the variables that show non-smooth dynamic behavior with relatively large transitional deviations from the set point. This situation is more noticeable for Rldg(cascaded)-Lldg(cascaded)-P where this variable is not controlled directly (Figure 4.15).

Liquid levels in the tanks are also not controlled well. As shown in Figure 4.16, the ratio of levels shows a large drop after 0.5 hour which can result in operational problems such as cavitation and running dry the lean tank downstream pump.

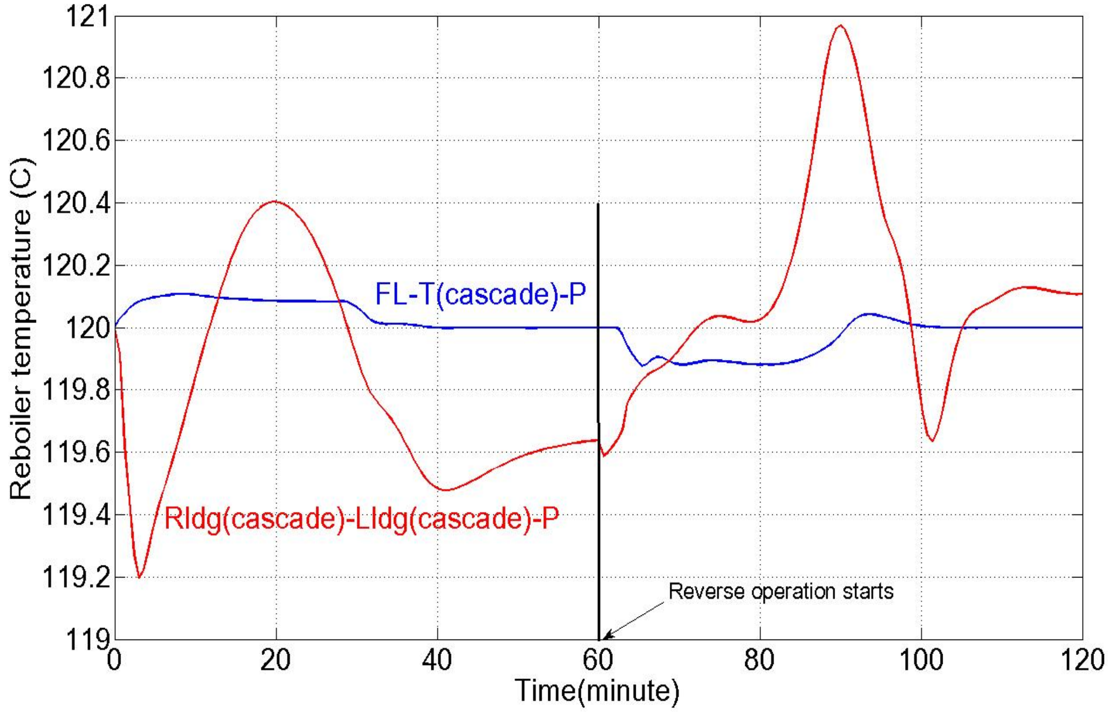

Figure 4.15: Reboiler temperature responses to the ramp change of reboiler steam load from 100% to 20% applied at time=0 and reverse change applied at time=60 minute. The responses are given for F_L-T (cascade)-P and Rldg(cascade)- Lldg (cascade)-P control configurations.

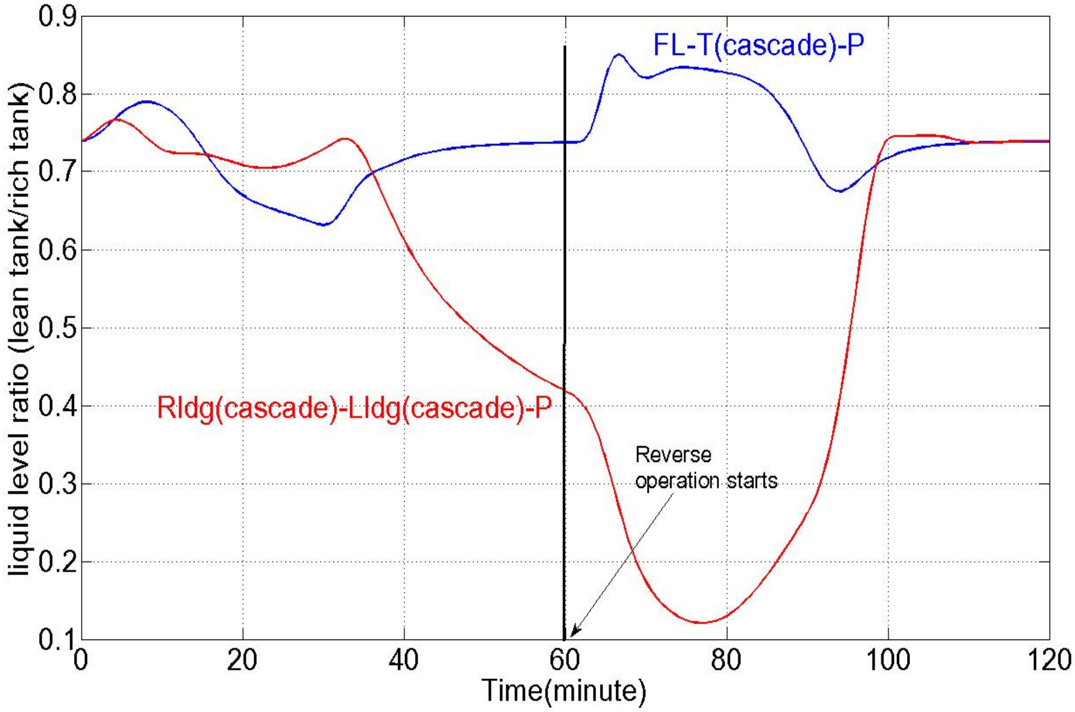

Figure 4.16: The responses of liquid level ratio of storage tanks to the ramp change of reboiler steam load from 100% to 20% applied at time=0 and reverse change applied at time=60 minute. The responses are given for F_L-T (cascade)-P and Rldg(cascade)- Lldg (cascade)-P control configurations.

Simulation of the large change in power plant load (60%) shows that FL-T(cascade)-P perfectly controls the capture at the desired set points with smooth and fast responses for both forward and reverse operations. Rldg(cascaded)-Lldg(cascaded)-P is not a successful structure for control nor does it stabilize the plant condition.

As shown in Figure 4.17, this configuration forces the stripper pressure to follow the set point initially but just after finishing the input ramp, unstable oscillations are appearing in the whole system, which results in some operational problems such as saturation of liquid valves and eventually failure of the simulation. That is why Figure 4.17 does not show the complete response of stripper pressure for this configuration.

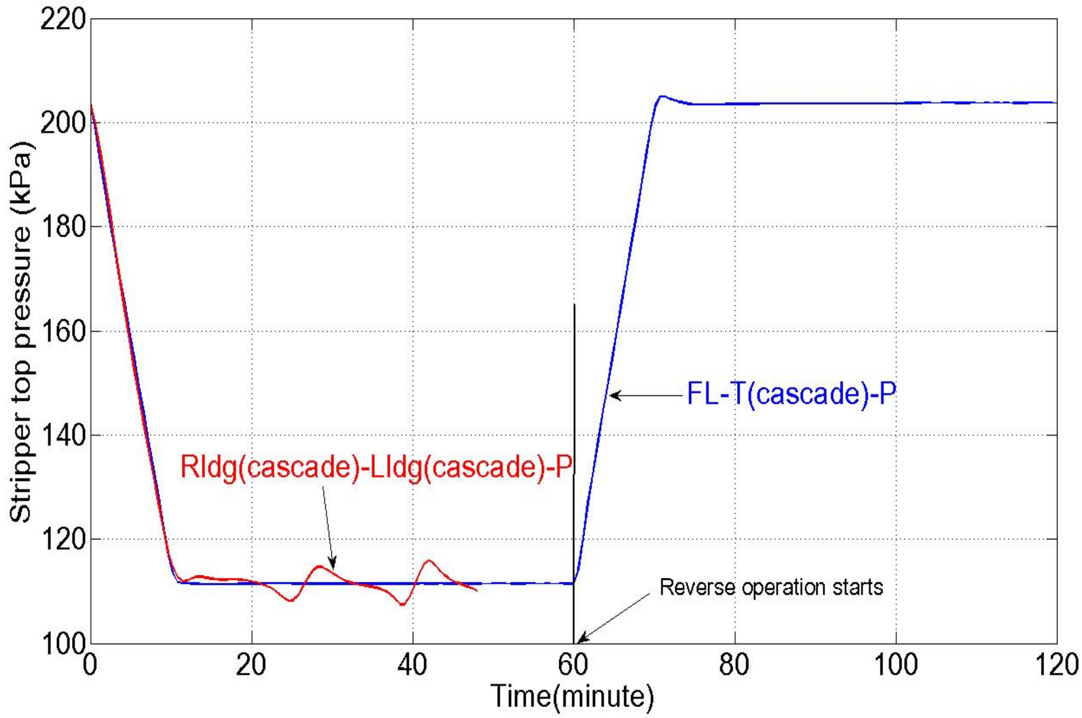

Figure 4.17: The response of stripper top pressure to the ramp change of power plant load from 100% to 40% applied at time=0 and reverse change applied at time=60 minute. The responses are given for F_L-T (cascade)-P and Rldg(cascade)- Lldg (cascade)-P control configurations.

Obviously, FL-T (cascade)-P shows a good performance in controlling capture for large changes in operating condition. It is able to bring the plant to the new operating condition in less than five minutes, which is relatively short for such a system in which the total liquid residence time is about 11 minutes.

4.4 INFLUENCE OF STORAGE TANKS HOLD UP TIME ON DYNAMICS

The objective of this work is to provide a systematic approach to investigate the influence of the residence time in the lean and rich tank on the quality of dynamics in response to a few types of disturbances. In frequency response analysis, which is used to analyze this dynamic system, we apply a sinusoidal input and sketch a graph showing the output response characteristics versus frequency of the input signal.

Stripper top pressure is selected as the output because it represents the compressor operation and reflects the whole system dynamic behavior. The variation of flue gas rate, total steam rate in power cycle, and absorber and stripper bed liquid holdups are considered as disturbances for this analysis. The plant is fully controlled by the FL-T(cascade)-P configuration (shown in Figure 4.18), proved as the most effective control structure among the evaluated ones , at initial set points for all control loops. The simulation is run for each disturbance at a specific input frequency and then the magnitude of the pressure oscillation is calculated relative to the design value in percent.

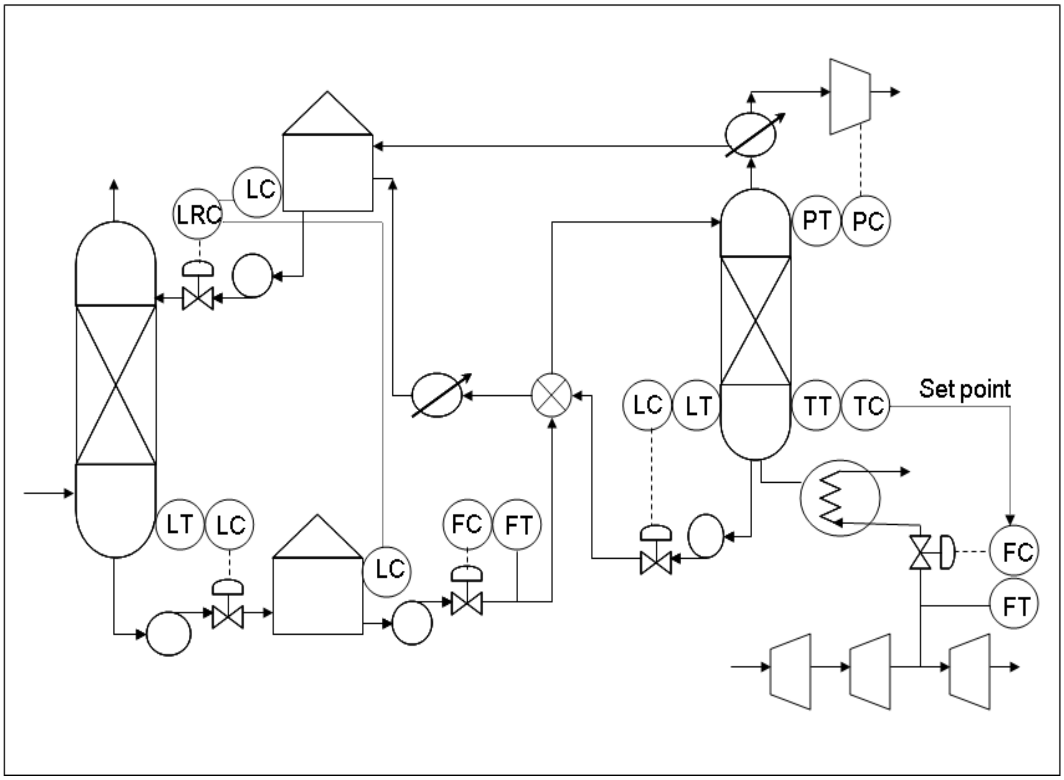

Figure 4.18: Process flow diagram with F_L-T (cascade)-P control configuration

The liquid residence time in absorber sump, stripper sump, absorber bed and stripper bed are initialized at 2, 2, 2 and 1 minutes respectively and they do not change significantly as disturbances are applied. The liquid residence time in the storage tanks is varied to see the effects on the magnitude of the oscillations.

Figure 4.19 represents the frequency response to the flue gas rate sinusoidal change. As seen for all cases of hold up time in the tanks, there is a critical frequency (ω_c) where the maximum magnitude is located. Based on the simulations it is found that the critical frequency represents the response time of the system to the related input. Since the frequency is the inverse of time, the higher critical frequency is equivalent to the faster response of the system. Therefore, this graph can provide two important dynamic characteristics: the response time and the magnitude of output change.

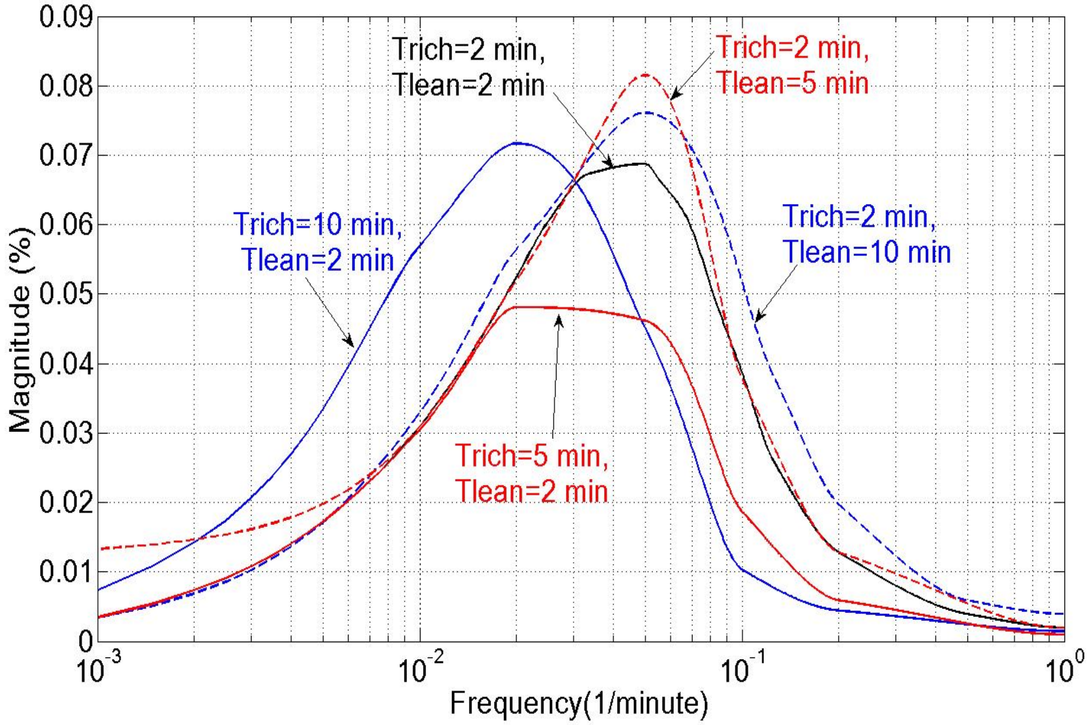

Figure 4.19: Frequency response of the stripper top pressure to ±10% sinusoidal signal in the flue gas rate for different sets of lean and rich tank hold up times. The initial liquid hold up time in other inventories are as follows: $\tau_{absorber}$= 2 min, $\tau_{stripper}$= 1 min, $\tau_{absorber\text{-}sump}$= 2 min, $\tau_{stripper\text{-}sump}$= 2 min.

As seen in figure 4.19, increasing the τ of the lean tank reduces the response time while at the same time it increase the magnitude of the oscillation, an undesired effect. Increasing the τ of the lean tank gives more sluggish responses, however, there is an optimum rich tank holdup between 2 and 10 minute that minimizes the magnitude. Figure 4.20, showing the dynamic response of the pressure to -10% step change in the flue gas rate, confirms the above discussed results. As observed, a 5-minute holdup in the rich tank shows the minimum magnitude for the inverse response and 10-minute hold up in the lean tank provides the fastest response.

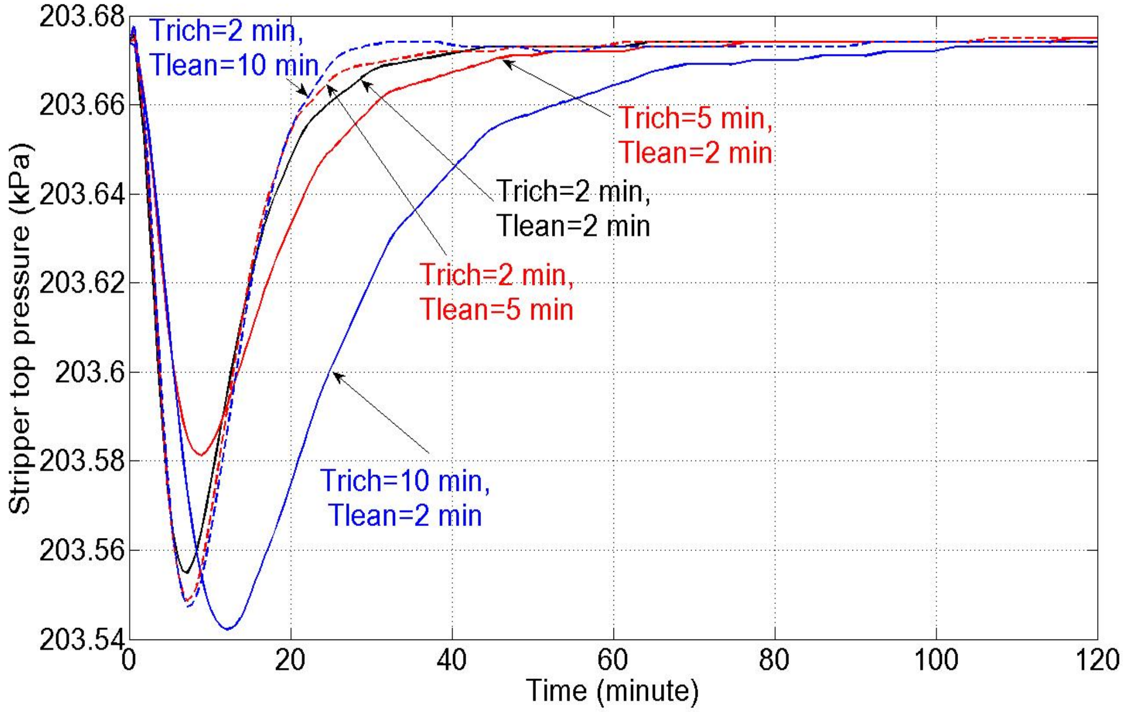

Figure 4.20: The comparison of the effects of initial liquid hold up time in the lean and rich tanks on the stripper top pressure in response to -10% step change in the flue gas rate. The responses are given for F_L-T (cascade)-P. The initial liquid hold up time in other inventories is: $\tau_{absorber}$= 2min, $\tau_{stripper}$= 1min, $\tau_{absorber\text{-}sump}$= 2min, $\tau_{stripper\text{-}sump}$= 2min.

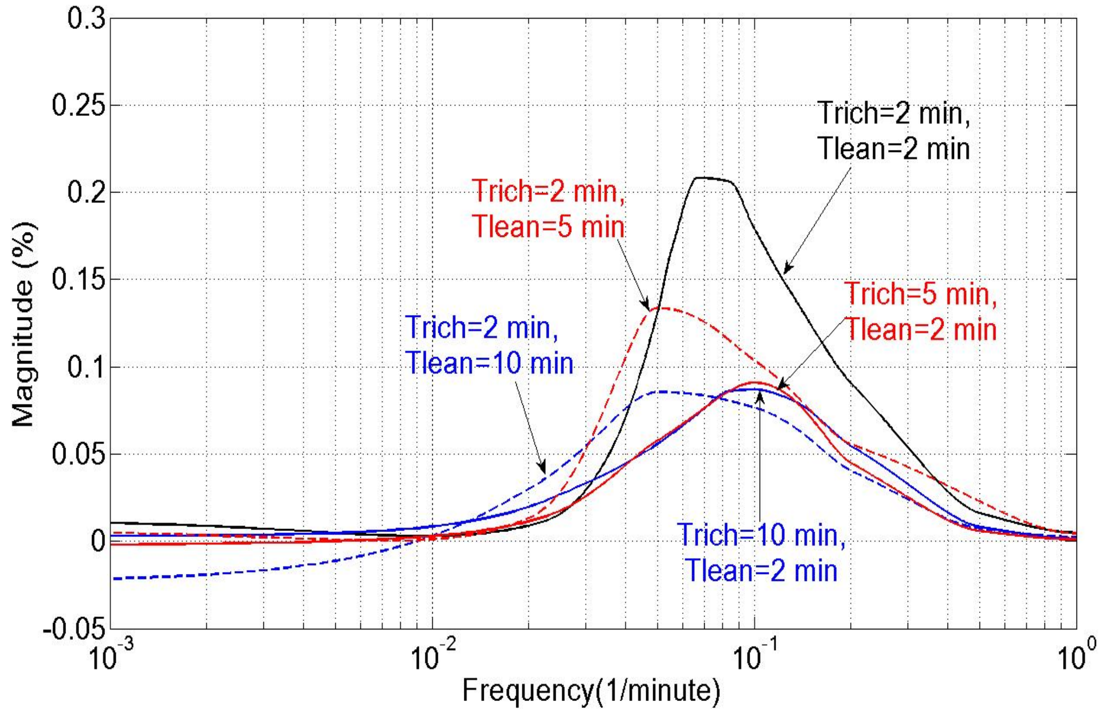

Figure 4.21: Frequency response of the stripper top pressure to ±10% sinusoidal signal of the liquid hold up on the absorber packing bed for different sets of lean and rich tank hold up times. The initial liquid hold up time in other inventories are as follows: $\tau_{absorber}$= 2min, $\tau_{stripper}$= 1min, $\tau_{absorber\text{-}sump}$= 2min, $\tau_{tripper\text{-}sump}$= 2min.

The change in the absorber bed liquid hold up (foaming) is the other disturbance in which the associated frequency response is calculated and shown in Figure 4.21. Similar to the flue gas rate change, changing residence time of the tanks influences the dynamics both in magnitude and response time. In contrast to the flue gas rate, increasing τ of the lean tank increases the response time while increasing τ of the rich tank makes the response faster. As observed in this figure, increasing the residence time in both tanks reduces the magnitude; however, for the rich tank increasing the time from 5 to 10 minutes does not have any benefit but adds an additional amine inventory cost. The step response shown in Figure 4.22 confirms outcomes of frequency response.

Frequency analysis has shown that holdup time in storage tanks does not have a significant impact on dynamics when the plant is subjected to the power cycle steam rate change or stripper foaming.

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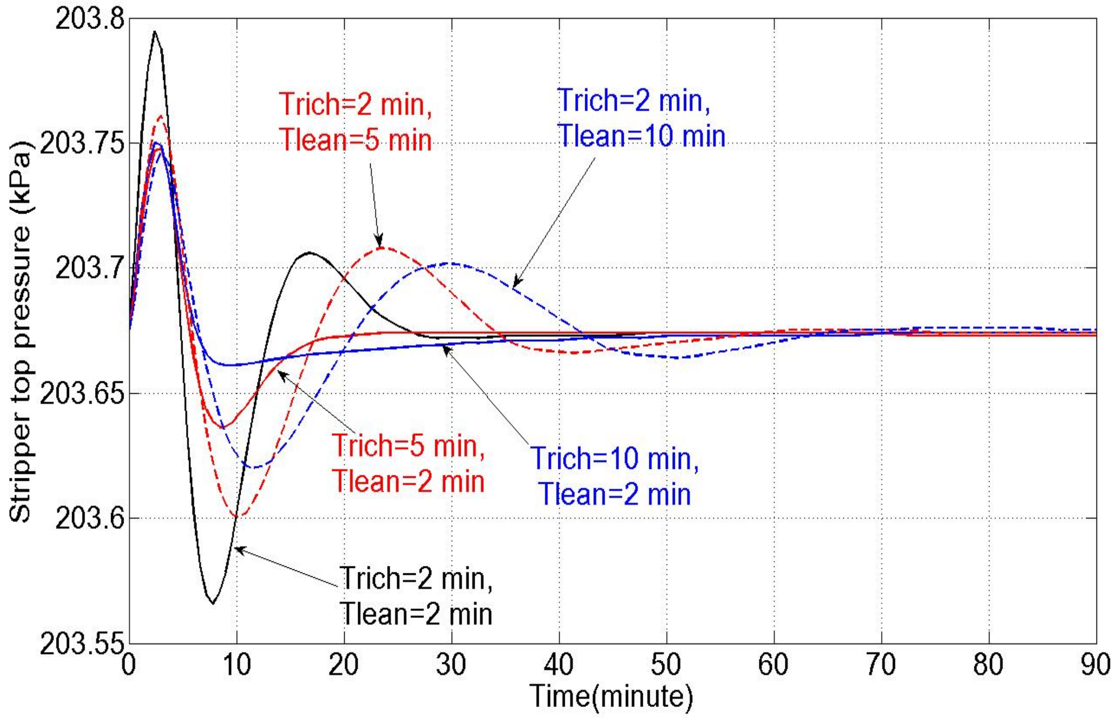

Figure 4.22: The comparison of the effects of initial liquid hold up time in the lean and rich tanks on the stripper top pressure in response to -10% step change in the absorber bed hold up. The responses are given for F_L-T (cascade)-P control configuration. The initial liquid hold up time in other inventories are as follows: $\tau_{absorber}$= 2min, $\tau_{stripper}$= 1min, $\tau_{absorber\text{-}sump}$= 2min, $\tau_{stripper\text{-}sump}$= 2min.

4.5 CONCLUSIONS

Chapter 4 is divided into two parts. The first part applies a plant-wide control procedure to develop an effective multi-loop control structure, which shows a degree of satisfactory performance in rejecting disturbances, load changes and set point tracking. The dynamic scenarios considered for this study, namely, load variation and foaming in columns, make this control problem challenging since they involve a combination of disturbance rejection and set point tracking at the same time.

In the second part of this chapter, frequency analysis is used to investigate the effects of holdup in storage tanks on dynamic performances. The frequency plots provide important dynamic performance information related to the response time and the magnitude of deviation from the target. The following lists the conclusions drawn from the results presented in chapter 4:

1. The most effective control structure is to control the solvent rate by the liquid valve, the reboiler temperature by the steam valve and the stripper pressure by the compressor speed. This configuration provides the smoothest and fastest response for disturbances in a narrow range of conditions. It also shows a degree of satisfactory performance to deal with large load variations: 80% reduction in reboiler load and 60% reduction in power plant load. In both scenarios, the configuration not only handles the large changes in inputs but also keeps the plant at optimal conditions by handling large changes in the set points of solvent rate and stripper pressure. The simulation of large load variations illustrates that this control structure can bring the plant to the new condition in about five minutes after finishing the input ramp.
2. Replacing the conventional level control on one of the lean or rich tanks by a level ratio control not only keeps the liquid holdup in balance in the tanks but also plays an important role in dampening oscillations for the column foaming scenarios.
3. Oscillatory responses appearing for the structures that control the loading of CO_2 represent some degree of interactions. Therefore, controlling rich or lean

loading or any combination such as CO_2 removal is not a proper strategy specifically when the plant has to be operated within wide ranges of operation.

4. Cascade control shows some degree of improvement on dynamic performances. Cascading CO_2 loading control loops with the flow controller is found as an enhanced strategy for dampening the oscillations in response to the load changes. However, this technique does not do a good job when foaming happens in one of the columns.
5. Advanced multi-variable systems may not be necessary. This study shows that if the considered disturbances are the dominant scenarios happening in the capture plant, establishing a multi-loop control system with F_L-T (cascade)-P configuration with level ratio control on the storage tanks shows a degree of satisfactory performance, robustness and safe operation that would avoid the costs of developing an advanced multivariable system.
6. For estimating the residence time in tanks based on stripper pressure response, dominant disturbances are the ones that directly influence the absorber performance such as foaming and flue gas rate variation. This behavior occurs because the stripper pressure is sensitive to the rich loading which is affected by those disturbances.
7. There exists an optimum initial residence time in lean and rich tanks. Increasing the holdup time is not always helpful to damp the oscillations and rejecting the disturbances. It may increase either the magnitude of overshoot and inverse responses or the response time of the plant
8. Based on the results, 5-minute holdup time for both tanks can be a reasonable number to fulfill the targets. This number is recommended by handbooks as a rule of thumb.

Chapter Five: Summary, conclusions, and recommendations

This chapter summarizes the main contributions of the research described in this dissertation and offers recommendations for future work.

5.1. SUMMARY AND CONCLUSIONS

A rigorous dynamic model of absorption/stripping process using MEA was developed and combined with an approximate model of power cycle steam turbines and CO_2 multi-stage compressor in Aspen Custom Modeler. The dynamic models developed for the absorber and the stripper are based on a rate-based approach using the film theory for liquid and vapor phases. They take into account the impact of equilibrium reactions (for the stripper) and kinetic reactions (for the absorber) on the mass transfer, thermodynamic non-idealities, and hydraulics of the structured packing.

Chapter 2 presents the details of the model including thermodynamic and rate model, physical properties, hydraulic calculations along the packing, and mass and energy balances in the column segments. It also describes the numerical problems encountered during model development and convergence. I have found that the model can be converged easier if I run the model in the steady state mode firstly and start with one segment of each column in the flow sheet and then gradually increase the number of segments. After both columns are converged separately, I inserted the other components and eventually close the absorption/stripping loop. To switch to the dynamic mode, all the steady state specifications should be replaced by dynamic ones. To make the convergence feasible and easier for columns, a proper initial guess should be selected for each unknown variable. For example, we can use inlet stream conditions as an initial guess for those variables inside the equipment.

Chapter 3 employs the fully integrated model to simulate and optimize two main operational scenarios occurring in capture plants: power plant load reduction and partial reboiler steam load operation. The optimization minimizes total lost work at the final steady state condition by adjusting compressor speed and liquid circulation rate as optimization variables. The following are the summary of practical conclusions derived from the steady state analyses and optimization:

4. Changing the compressor speed and liquid rate is limited by following operational constraints :
    e. The compressor speed should not exceed the maximum allowable speed, which is set at 120% of rated speed.
    f. Reboiler temperature should not exceed 120 °C to prevent thermal degradation of the MEA solution.
    g. Either the reboiler temperature constraint or the compressor surge limit determines the minimum compressor speed, which varies with the load change for each load reduction scenario.
    h. Liquid circulation rate can vary in a limited range, whose minimum value is set by the compressor surge limit and maximum value is set either by solvent pump (lean or rich pump) maximum flow condition or compressor surge limit.
5. Analyzing and optimizing MEA plant operation in response to power plant load reduction provides the following conclusions:
    a. Increasing compressor speed that decreases reboiler temperature and pressure results in extracting more steam for the reboiler and consequently removes more CO_2.

b. For a specific CO_2 removal, there is a compressor speed and a solvent rate that minimizes total equivalent work. Therefore, a variable speed compressor is advantageous for optimal operations.
c. Based on equivalent work minimization in the presence of constraints associated with pumps, compressor, and solvent thermal degradation, the MEA plant initially designed for 90% removal can remove up to 94% of inlet CO_2 by increasing the compressor speed up to 120% of the rated speed.
d. For low load operation such as 40% load, the compressor-operating curve reaches surge limit and changing speed and solvent rate does not push it away from this undesired region.
e. Recycling gas through surging stages, a practice typically implemented by anti-surge control on the compressor package, is the only way to prevent the compressor from surging during low power plant load operation.
f. No general simple rule was derived for optimally controlling the flow rates for a wide range of load change. Installing ratio control between the CO_2 rate in rich solution and the steam rate could be a strategy that can keep the plant close to optimum during partial load operation. However, more reduction in power plant load results in more deviation of ratio control strategy from the optimum path,
g. Controlling lean loading at a set point that varies in proportion to the removal is another strategy that controls the plant close to the optimum.

6. Analyzing and optimizing MEA plant operation in response to reboiler steam load reduction provides the following conclusions:

a. Minimal lost work would be maintained if the reboiler temperature is controlled at 120 °C (the maximum temperature to prevent MEA thermal degradation) by adjusting the solvent rate and compressor speed as long as compressor operational limits permit.
b. At a reboiler load lower than 60%, where the compressor starts to surge, a surge control strategy should be applied. Two surge control strategies are identified and compared:
    i. Anti-surge control on the compressor package.
    ii. Adjusting compressor speed and solvent rate to save compressor from surging.
c. Anti-surge control has more advantages with respect to operation and minimum lost work and would be preferable during partial reboiler steam load operation. The following is a summary of reasons for this statement:
    i. Although there is additional energy loss associated with anti-surge control because of recompressing recycled gas, the total lost work is still lower than the adjustment strategy since it lets the reboiler run at 120 °C and the CO_2 compressor compresses the gas at higher suction pressure and consequently lower compression ratio.
    ii. Anti-surge control strategy has the capability of operating the plant at a wider range of steam load (20–100%) while the adjustment strategy could not operate the plant below a 40% load.
    iii. The only disadvantage of anti-surge control is the increase in capital cost for the stripper column, because it pressurizes the stripper gradually as the steam rate is reduced. For example, at

20% load the optimal stripper pressure is twice the full load pressure.

iv. Anti-surge control has the potential for even further reduction in lost work for low steam load cases. By over-sizing the rich pump it would be able to pump rich solution to the pressurized stripper before getting to its maximum flow and circulate the liquid at its optimum rate.

Chapter 4 is divided into two parts. The first part applies a plant-wide control procedure to develop an effective multi-loop control structure, which shows a degree of satisfactory performance in rejecting disturbances, load changes and set point tracking. The dynamic scenarios considered for this study, namely, load variation and foaming in columns, make this control problem challenging since they involve a combination of disturbance rejection and set point tracking at the same time.

In the second part of this chapter, frequency analysis is used to investigate the effects of holdup in storage tanks on dynamic performances. The frequency plots provide important dynamic performance information related to the response time and the magnitude of deviation from the target. The following lists the conclusions drawn from the results presented in chapter 4:

7. The most effective control structure is to control the solvent rate by the liquid valve, the reboiler temperature by the steam valve and the stripper pressure by the compressor speed. This configuration provides the smoothest and fastest response for disturbances in a narrow range of conditions. It also shows a degree of satisfactory performance to deal with large load variations: 80% reduction in reboiler load and 60% reduction in power plant load. In both scenarios, the configuration not only handles the large changes in inputs but also keeps the plant

at optimal conditions by handling large changes in the set points of solvent rate and stripper pressure. The simulation of large load variations illustrates that this control structure can bring the plant to the new condition in about five minutes after finishing the input ramp.

8. Replacing the conventional level control on one of the lean or rich tanks by a level ratio control not only keeps the liquid holdup in balance in the tanks but also plays an important role in dampening oscillations for the column foaming scenarios.
9. Oscillatory responses appearing for the structures that control the loading of CO_2 represent some degree of interactions. Therefore, controlling rich or lean loading or any combination such as CO_2 removal is not a proper strategy specifically when the plant has to be operated within wide ranges of operation.
10. Cascade control shows some degree of improvement on dynamic performances. Cascading CO_2 loading control loops with the flow controller is found as an enhanced strategy for dampening the oscillations in response to the load changes. However, this technique does not do a good job when foaming happens in one of the columns.
11. Advanced multi-variable systems may not be necessary. This study shows that if the considered disturbances are the dominant scenarios happening in the capture plant, establishing a multi-loop control system with F_L-T (cascade)-P configuration with level ratio control on the storage tanks shows a degree of satisfactory performance, robustness and safe operation that would avoid the costs of developing an advanced multivariable system.
12. For estimating the residence time in tanks based on stripper pressure response, dominant disturbances are the ones that directly influence the absorber

performance such as foaming and flue gas rate variation. This behavior occurs because the stripper pressure is sensitive to the rich loading which is affected by those disturbances.

13. There exists an optimum initial residence time in lean and rich tanks. Increasing the holdup time is not always helpful to damp the oscillations and rejecting the disturbances. It may increase either the magnitude of overshoot and inverse responses or the response time of the plant
14. Based on the results, 5-minute holdup time for both tanks can be a reasonable number to fulfill the targets. This number is recommended by handbooks as a rule of thumb.

5.2. RECOMMENDATIONS

For future research that expands the technical work presented in this dissertation, the following recommendations are offered:

1. It would be more practical if the dynamic model of post combustion capture is integrated with a more accurate model of coal-fired power plant. By doing so the operation of the capture and power plant can be optimized simultaneously and compatible control systems can be developed for both power plant and downstream CO_2 capture plant.
2. Replacing the steam valve on the extracted steam by a let down steam turbine can improve the steady state energy efficiency of the capture plant. In the case of feasibility of driving the CO_2 compressor by a let down steam turbine, complexity is added to the system that results in a more challenging control problem.
3. Converting standard absorption/stripping to advanced regeneration configurations such as the double matrix stripper or intercooled absorber have been proved as

promising schemes regarding steady state energy minimization. However, the dynamics and control of those configurations have not been studied yet. Controlling such complicated systems could be the subject of further PhD research.

4. Implementing advanced multi-variable control systems such as MPC may bring some improvement on the dynamic performance of the capture plant. However, applying this technique on such a complicated model may not be feasible. It requires model simplifications such as developing an approximated linear system based on step responses of the existing model.
5. It is recommended to continue working on storage tanks holdup by carrying out a large number of simulations, and establishing a proper objective function for optimizing the holdup and eventually finding a unique relationship among optimal storage tank holdups with other inventories holdup.

Appendix A: Details of results for the capture plant in response to the power plant load reduction

Scenario :

Step1 : 60% load reduction (100% to 40%) starting at time=0 (ramping over 10 minutes)

Step2 : 60% load increase (40% to 100%) starting at time=1(ramping over 10 minutes)

Time	Reboiler. Lean ldg	Reboiler. P	Reboiler. T	SV.in_f. F	Absorber. Rich ldg	top_column .P	Absorber. removal
Hour		kPa	°C	kmol/s		kPa	
0	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
0.01	0.2331	204.199	119.193	1.84404	0.56844	198.531	0.90818
0.02	0.235	197.617	118.13	1.72565	0.56725	192.488	0.91955
0.03	0.23796	191.248	117.061	1.61198	0.56545	186.678	0.93082
0.04	0.24162	185.07	115.988	1.50044	0.56335	181.056	0.94055
0.05	0.24583	179.097	114.915	1.38974	0.56127	175.622	0.94815
0.06	0.25051	173.325	113.841	1.28047	0.55956	170.353	0.95346
0.07	0.25559	167.712	112.758	1.17685	0.55855	165.181	0.95661
0.08	0.2609	162.193	111.663	1.08504	0.55853	160.019	0.95779
0.09	0.2662	156.719	110.557	1.00827	0.55965	154.813	0.95725
0.1	0.27116	151.267	109.448	0.94502	0.56182	149.558	0.95536
0.11	0.27553	145.834	108.339	0.89202	0.56478	144.266	0.95254
0.12	0.27904	140.418	107.234	0.84745	0.56824	138.948	0.94925
0.13	0.28165	135.018	106.131	0.80873	0.57182	133.615	0.9461
0.14	0.28331	129.636	105.03	0.77557	0.57527	128.273	0.94357
0.15	0.28398	124.281	103.926	0.74866	0.57841	122.932	0.9421
0.16	0.28384	118.96	102.814	0.72752	0.58124	117.597	0.9417
0.17	0.28293	113.724	101.693	0.71449	0.58374	112.332	0.94233
0.18	0.2818	112.773	101.545	0.79945	0.5867	111.549	0.93372
0.19	0.28008	112.84	101.666	0.81101	0.59069	111.559	0.91582
0.2	0.27805	112.835	101.743	0.80942	0.59536	111.518	0.88925
0.21	0.276	112.795	101.787	0.80239	0.60013	111.464	0.85979
0.22	0.27405	112.736	101.807	0.79165	0.60444	111.412	0.83637
0.23	0.2723	112.67	101.81	0.7786	0.60778	111.368	0.82513
0.24	0.27078	112.607	101.803	0.7648	0.60996	111.338	0.82527
0.25	0.26953	112.555	101.789	0.75159	0.61094	111.322	0.83263
0.26	0.26854	112.517	101.773	0.73997	0.61092	111.321	0.84259
0.27	0.26778	112.493	101.757	0.73053	0.61021	111.33	0.85203

0.28	0.26724	112.481	101.743	0.72341	0.60912	111.346	0.85945
0.29	0.26687	112.479	101.731	0.7186	0.60798	111.367	0.86434
0.3	0.26664	112.484	101.721	0.71583	0.60704	111.389	0.86688
0.31	0.26653	112.494	101.714	0.71478	0.60644	111.412	0.86775
0.32	0.2665	112.506	101.709	0.71494	0.60615	111.433	0.86798
0.33	0.26651	112.518	101.706	0.71601	0.60607	111.451	0.86828
0.34	0.26656	112.53	101.704	0.7177	0.6061	111.466	0.86908
0.35	0.26662	112.542	101.703	0.71982	0.60614	111.478	0.87049
0.36	0.26668	112.551	101.703	0.72219	0.60613	111.486	0.87244
0.37	0.26673	112.558	101.703	0.72462	0.60602	111.49	0.87465
0.38	0.26677	112.562	101.703	0.72699	0.60586	111.492	0.87684
0.39	0.2668	112.565	101.704	0.72925	0.60566	111.492	0.87894
0.4	0.2668	112.566	101.705	0.73126	0.60544	111.49	0.88071
0.41	0.26681	112.567	101.706	0.73319	0.60522	111.488	0.88239
0.42	0.26678	112.566	101.707	0.73474	0.60503	111.485	0.88366
0.43	0.26676	112.565	101.708	0.73628	0.60484	111.482	0.88491
0.44	0.26673	112.564	101.709	0.73741	0.6047	111.479	0.88583
0.45	0.26669	112.562	101.71	0.73855	0.60456	111.476	0.88676
0.46	0.26665	112.561	101.71	0.73948	0.60445	111.472	0.88756
0.47	0.2666	112.559	101.711	0.74026	0.60436	111.47	0.88827
0.48	0.26656	112.558	101.711	0.74104	0.60427	111.468	0.88898
0.49	0.26652	112.556	101.712	0.74179	0.60418	111.466	0.88967
0.5	0.26648	112.555	101.712	0.74232	0.60412	111.464	0.8902
0.51	0.26644	112.554	101.712	0.74285	0.60406	111.462	0.89073
0.52	0.2664	112.553	101.712	0.74337	0.604	111.461	0.89126
0.53	0.26636	112.553	101.712	0.7439	0.60393	111.46	0.89179
0.54	0.26632	112.552	101.712	0.74443	0.60387	111.458	0.89232
0.55	0.26629	112.551	101.712	0.74479	0.60383	111.457	0.89268
0.56	0.26626	112.55	101.713	0.74514	0.60379	111.457	0.89302
0.57	0.26624	112.55	101.713	0.74548	0.60375	111.456	0.89336
0.58	0.26621	112.55	101.713	0.74583	0.60372	111.455	0.89369
0.59	0.26618	112.549	101.713	0.74617	0.60368	111.455	0.89403
0.6	0.26615	112.549	101.713	0.74651	0.60364	111.454	0.89437
0.61	0.26612	112.549	101.713	0.74686	0.6036	111.453	0.89471
0.62	0.26609	112.548	101.713	0.74719	0.60356	111.453	0.89505
0.63	0.26608	112.548	101.713	0.7474	0.60354	111.452	0.89525
0.64	0.26606	112.548	101.713	0.74761	0.60352	111.452	0.89545
0.65	0.26604	112.547	101.713	0.74782	0.6035	111.451	0.89565
0.66	0.26602	112.547	101.713	0.74802	0.60348	111.451	0.89586
0.67	0.266	112.547	101.713	0.74823	0.60346	111.45	0.89606
0.68	0.26598	112.547	101.713	0.74844	0.60343	111.45	0.89626
0.69	0.26597	112.547	101.713	0.74864	0.60341	111.45	0.89646

0.7	0.26595	112.547	101.713	0.74885	0.60339	111.45	0.89666
0.71	0.26593	112.547	101.713	0.74906	0.60337	111.449	0.89686
0.72	0.26592	112.546	101.713	0.74921	0.60335	111.449	0.89702
0.73	0.26591	112.546	101.713	0.74932	0.60334	111.449	0.89713
0.74	0.2659	112.546	101.713	0.74942	0.60333	111.449	0.89724
0.75	0.26589	112.546	101.713	0.74952	0.60332	111.448	0.89735
0.76	0.26587	112.546	101.713	0.74963	0.60331	111.448	0.89746
0.77	0.26586	112.546	101.713	0.74973	0.6033	111.448	0.89756
0.78	0.26585	112.546	101.713	0.74983	0.60329	111.448	0.89767
0.79	0.26584	112.546	101.713	0.74994	0.60328	111.448	0.89778
0.8	0.26583	112.546	101.713	0.75004	0.60326	111.447	0.89789
0.81	0.26582	112.546	101.713	0.75014	0.60325	111.447	0.898
0.82	0.26581	112.546	101.713	0.75024	0.60324	111.447	0.89811
0.83	0.2658	112.546	101.713	0.75035	0.60323	111.447	0.89822
0.84	0.26579	112.545	101.713	0.75045	0.60322	111.447	0.89833
0.85	0.26579	112.545	101.713	0.75049	0.60321	111.447	0.89838
0.86	0.26578	112.545	101.714	0.75054	0.60321	111.447	0.89843
0.87	0.26578	112.545	101.714	0.75058	0.6032	111.447	0.89848
0.88	0.26578	112.545	101.714	0.75062	0.6032	111.447	0.89853
0.89	0.26577	112.545	101.714	0.75066	0.60319	111.446	0.89859
0.9	0.26577	112.545	101.714	0.7507	0.60319	111.446	0.89864
0.91	0.26576	112.545	101.714	0.75074	0.60319	111.446	0.89869
0.92	0.26576	112.545	101.714	0.75078	0.60318	111.446	0.89874
0.93	0.26575	112.545	101.714	0.75082	0.60318	111.446	0.89879
0.94	0.26575	112.545	101.714	0.75086	0.60317	111.446	0.89884
0.95	0.26574	112.545	101.714	0.7509	0.60317	111.446	0.89889
0.96	0.26574	112.545	101.714	0.75094	0.60316	111.446	0.89894
0.97	0.26574	112.545	101.714	0.75098	0.60316	111.446	0.89899
0.98	0.26573	112.545	101.714	0.75102	0.60315	111.446	0.89904
0.99	0.26573	112.545	101.714	0.75106	0.60315	111.446	0.89909
1	0.26567	112.545	101.714	0.75155	0.60307	111.444	0.89994
1.01	0.26567	112.545	101.714	0.75155	0.60307	111.445	0.89994
1.02	0.26644	122.677	104.044	0.88613	0.60421	121.753	0.8596
1.03	0.26729	127.724	105.073	0.84465	0.60598	126.898	0.82927
1.04	0.26977	133.184	106.041	0.86306	0.60774	132.398	0.81017
1.05	0.27382	138.899	106.991	0.92807	0.60874	138.074	0.80491
1.06	0.27872	144.666	107.962	1.02826	0.60833	143.722	0.80865
1.07	0.28318	150.371	108.971	1.14201	0.60629	149.245	0.81438
1.08	0.28623	156.031	110.011	1.25862	0.60303	154.674	0.81764
1.09	0.28743	161.701	111.076	1.37199	0.59922	160.078	0.81638
1.1	0.28682	167.43	112.156	1.48031	0.59576	165.521	0.81049
1.11	0.28482	173.232	113.24	1.58438	0.59314	171.02	0.80175

1.12	0.28179	179.105	114.325	1.68628	0.59138	176.574	0.79231
1.13	0.27793	185.059	115.404	1.78838	0.59021	182.177	0.78436
1.14	0.27349	191.089	116.478	1.89239	0.58926	187.816	0.77875
1.15	0.26856	197.193	117.548	1.99934	0.58831	193.479	0.7756
1.16	0.26318	203.371	118.613	2.11	0.58725	199.154	0.77465
1.17	0.25747	209.195	119.61	2.20919	0.58607	204.414	0.7763
1.18	0.25194	210.72	119.95	2.14781	0.58457	205.425	0.78833
1.19	0.24752	210.392	119.971	2.13325	0.58254	204.909	0.80462
1.2	0.24402	210.12	119.982	2.12843	0.58025	204.492	0.82063
1.21	0.24119	209.892	119.989	2.12466	0.57802	204.147	0.83494
1.22	0.23889	209.704	119.994	2.1214	0.57604	203.869	0.84711
1.23	0.23704	209.56	119.998	2.11814	0.57442	203.662	0.85711
1.24	0.23558	209.461	120.002	2.11461	0.57319	203.523	0.86512
1.25	0.23443	209.399	120.005	2.1107	0.57227	203.439	0.87158
1.26	0.23354	209.365	120.007	2.10647	0.5716	203.397	0.87685
1.27	0.23288	209.354	120.01	2.10203	0.57111	203.386	0.88116
1.28	0.23243	209.359	120.011	2.09754	0.57076	203.397	0.88461
1.29	0.23208	209.37	120.012	2.09315	0.57046	203.415	0.88768
1.3	0.23184	209.385	120.012	2.0889	0.5702	203.439	0.89031
1.31	0.2317	209.4	120.011	2.08501	0.56997	203.463	0.8925
1.32	0.2316	209.415	120.011	2.08124	0.56974	203.487	0.89455
1.33	0.23157	209.427	120.011	2.07809	0.56953	203.506	0.89608
1.34	0.23155	209.439	120.01	2.07498	0.56933	203.525	0.89758
1.35	0.23157	209.447	120.01	2.07247	0.56916	203.539	0.89863
1.36	0.2316	209.454	120.009	2.07013	0.569	203.552	0.89956
1.37	0.23163	209.462	120.008	2.06782	0.56884	203.565	0.90047
1.38	0.23169	209.466	120.008	2.06622	0.56875	203.574	0.9009
1.39	0.23174	209.47	120.007	2.06463	0.56866	203.582	0.90132
1.4	0.23179	209.474	120.007	2.06303	0.56857	203.591	0.90175
1.41	0.23184	209.478	120.006	2.06171	0.56851	203.599	0.90202
1.42	0.2319	209.481	120.005	2.06071	0.56848	203.605	0.90211
1.43	0.23195	209.483	120.005	2.05971	0.56845	203.612	0.9022
1.44	0.232	209.486	120.004	2.05871	0.56842	203.618	0.9023
1.45	0.23205	209.488	120.004	2.05773	0.56839	203.624	0.90238
1.46	0.23209	209.491	120.003	2.05718	0.5684	203.628	0.90231
1.47	0.23213	209.493	120.003	2.05663	0.56841	203.632	0.90225
1.48	0.23218	209.495	120.003	2.05607	0.56842	203.636	0.90218
1.49	0.23222	209.496	120.003	2.05552	0.56842	203.64	0.90212
1.5	0.23226	209.498	120.002	2.05496	0.56843	203.644	0.90206
1.51	0.23229	209.499	120.002	2.05455	0.56844	203.648	0.90198
1.52	0.23232	209.501	120.002	2.0543	0.56846	203.651	0.90188
1.53	0.23234	209.502	120.002	2.05404	0.56847	203.653	0.90179

1.54	0.23237	209.502	120.002	2.05379	0.56849	203.655	0.9017
1.55	0.23239	209.503	120.002	2.05354	0.5685	203.657	0.9016
1.56	0.23242	209.504	120.001	2.05328	0.56852	203.659	0.90151
1.57	0.23244	209.504	120.001	2.05303	0.56854	203.661	0.90142
1.58	0.23247	209.505	120.001	2.0528	0.56855	203.663	0.90133
1.59	0.23248	209.506	120.001	2.05271	0.56857	203.665	0.90126
1.6	0.23249	209.507	120.001	2.05263	0.56858	203.665	0.9012
1.61	0.2325	209.507	120.001	2.05254	0.56859	203.666	0.90113
1.62	0.23251	209.508	120.001	2.05246	0.56861	203.667	0.90107
1.63	0.23252	209.508	120.001	2.05237	0.56862	203.667	0.901
1.64	0.23253	209.508	120.001	2.05228	0.56863	203.668	0.90094
1.65	0.23255	209.508	120.001	2.0522	0.56865	203.669	0.90087
1.66	0.23256	209.508	120.001	2.05211	0.56866	203.669	0.90081
1.67	0.23257	209.508	120.001	2.05203	0.56867	203.67	0.90074
1.68	0.23258	209.509	120.001	2.05194	0.56868	203.671	0.90068
1.69	0.23258	209.509	120.001	2.05192	0.56869	203.671	0.90065
1.7	0.23259	209.509	120.001	2.05191	0.5687	203.672	0.90062
1.71	0.23259	209.509	120.001	2.05189	0.5687	203.673	0.90059
1.72	0.23259	209.509	120.001	2.05187	0.56871	203.673	0.90056
1.73	0.2326	209.51	120	2.05186	0.56871	203.673	0.90053
1.74	0.2326	209.51	120	2.05184	0.56872	203.673	0.9005
1.75	0.2326	209.51	120	2.05182	0.56873	203.673	0.90047
1.76	0.23261	209.51	120	2.0518	0.56873	203.673	0.90044
1.77	0.23261	209.51	120	2.05179	0.56874	203.673	0.90042
1.78	0.23261	209.51	120	2.05177	0.56875	203.673	0.90039
1.79	0.23262	209.51	120	2.05175	0.56875	203.673	0.90036
1.8	0.23262	209.51	120	2.05174	0.56876	203.673	0.90033
1.81	0.23262	209.51	120	2.05173	0.56876	203.674	0.9003
1.82	0.23263	209.51	120	2.05171	0.56877	203.674	0.90027
1.83	0.23263	209.51	120	2.0517	0.56878	203.674	0.90024
1.84	0.23263	209.51	120	2.05169	0.56878	203.674	0.90024
1.85	0.23263	209.51	120	2.05169	0.56878	203.674	0.90023
1.86	0.23263	209.51	120	2.05169	0.56878	203.674	0.90022
1.87	0.23263	209.51	120	2.05169	0.56878	203.674	0.90021
1.88	0.23263	209.51	120	2.05169	0.56879	203.674	0.9002
1.89	0.23263	209.51	120	2.05169	0.56879	203.674	0.9002
1.9	0.23263	209.51	120	2.05169	0.56879	203.674	0.90019
1.91	0.23263	209.51	120	2.05169	0.56879	203.674	0.90018
1.92	0.23263	209.51	120	2.05169	0.56879	203.674	0.90017
1.93	0.23263	209.51	120	2.05169	0.5688	203.675	0.90016
1.94	0.23263	209.51	120	2.05169	0.5688	203.675	0.90016
1.95	0.23263	209.51	120	2.05169	0.5688	203.675	0.90015

1.96	0.23263	209.51	120	2.05169	0.5688	203.675	0.90014
1.97	0.23264	209.51	120	2.05169	0.5688	203.675	0.90013
1.98	0.23264	209.51	120	2.05169	0.5688	203.675	0.90012
1.99	0.23264	209.51	120	2.05169	0.56881	203.675	0.90012
2	0.23264	209.51	120	2.05169	0.56881	203.675	0.90011
2.01	0.23264	209.51	120	2.05168	0.56881	203.675	0.9001
2.02	0.23264	209.51	120	2.05168	0.56881	203.675	0.90009
2.03	0.23264	209.51	120	2.05168	0.56881	203.675	0.90008
2.04	0.23264	209.51	120	2.05168	0.56882	203.675	0.90008
2.05	0.23264	209.51	120	2.05168	0.56882	203.675	0.90007
2.06	0.23264	209.51	120	2.05168	0.56882	203.675	0.90006
2.07	0.23264	209.51	120	2.05168	0.56882	203.675	0.90006
2.08	0.23264	209.51	120	2.05168	0.56882	203.675	0.90006
2.09	0.23264	209.51	120	2.05168	0.56882	203.675	0.90006
2.1	0.23264	209.51	120	2.05168	0.56882	203.675	0.90005
2.11	0.23264	209.51	120	2.05168	0.56882	203.675	0.90005
2.12	0.23264	209.51	120	2.05168	0.56882	203.675	0.90005
2.13	0.23264	209.51	120	2.05168	0.56882	203.675	0.90005
2.14	0.23264	209.51	120	2.05168	0.56882	203.675	0.90005
2.15	0.23264	209.51	120	2.05168	0.56882	203.675	0.90005
2.16	0.23264	209.51	120	2.05168	0.56882	203.675	0.90005
2.17	0.23264	209.51	120	2.05168	0.56882	203.675	0.90004
2.18	0.23264	209.51	120	2.05168	0.56883	203.675	0.90004
2.19	0.23264	209.51	120	2.05168	0.56883	203.675	0.90004
2.2	0.23264	209.51	120	2.05168	0.56883	203.675	0.90004
2.21	0.23264	209.51	120	2.05168	0.56883	203.675	0.90004
2.22	0.23264	209.51	120	2.05168	0.56883	203.675	0.90004
2.23	0.23264	209.51	120	2.05168	0.56883	203.675	0.90004
2.24	0.23264	209.51	120	2.05168	0.56883	203.675	0.90004
2.25	0.23264	209.51	120	2.05168	0.56883	203.675	0.90003
2.26	0.23264	209.51	120	2.05168	0.56883	203.675	0.90003
2.27	0.23264	209.51	120	2.05169	0.56883	203.674	0.90003
2.28	0.23264	209.51	120	2.05169	0.56883	203.674	0.90003
2.29	0.23264	209.51	120	2.05169	0.56883	203.674	0.90003
2.3	0.23264	209.51	120	2.05169	0.56883	203.674	0.90003
2.31	0.23264	209.51	120	2.05169	0.56883	203.674	0.90003
2.32	0.23264	209.51	120	2.05169	0.56883	203.674	0.90003
2.33	0.23264	209.51	120	2.05169	0.56883	203.674	0.90002
2.34	0.23264	209.51	120	2.05169	0.56883	203.674	0.90002
2.35	0.23264	209.51	120	2.05169	0.56883	203.674	0.90002
2.36	0.23264	209.51	120	2.05169	0.56883	203.674	0.90002
2.37	0.23264	209.51	120	2.05169	0.56883	203.674	0.90002

2.38	0.23264	209.51	120	2.05169	0.56883	203.674	0.90002
2.39	0.23264	209.51	120	2.05169	0.56883	203.674	0.90002
2.4	0.23264	209.51	120	2.05169	0.56883	203.674	0.90002
2.41	0.23264	209.51	120	2.05169	0.56883	203.674	0.90001
2.42	0.23264	209.51	120	2.05169	0.56883	203.674	0.90001
2.43	0.23264	209.51	120	2.05169	0.56883	203.674	0.90001
2.44	0.23264	209.51	120	2.05169	0.56883	203.674	0.90001
2.45	0.23264	209.51	120	2.05169	0.56883	203.674	0.90001
2.46	0.23264	209.51	120	2.05169	0.56883	203.674	0.90001
2.47	0.23264	209.51	120	2.05169	0.56883	203.674	0.90001
2.48	0.23264	209.51	120	2.05169	0.56883	203.674	0.90001
2.49	0.23264	209.509	120	2.05169	0.56883	203.674	0.90001
2.5	0.23264	209.509	120	2.05169	0.56883	203.674	0.90001
2.51	0.23264	209.509	120	2.05169	0.56883	203.674	0.90001
2.52	0.23264	209.509	120	2.05169	0.56884	203.674	0.90001
2.53	0.23264	209.509	120	2.05169	0.56884	203.674	0.90001
2.54	0.23264	209.509	120	2.05169	0.56884	203.674	0.90001
2.55	0.23264	209.509	120	2.05169	0.56884	203.674	0.90001
2.56	0.23264	209.509	120	2.05169	0.56884	203.674	0.90001
2.57	0.23264	209.509	120	2.05169	0.56884	203.674	0.90001
2.58	0.23264	209.509	120	2.05169	0.56884	203.674	0.90001
2.59	0.23264	209.509	120	2.05169	0.56884	203.674	0.90001
2.6	0.23264	209.509	120	2.05169	0.56884	203.674	0.90001
2.61	0.23264	209.509	120	2.05169	0.56884	203.674	0.90001
2.62	0.23264	209.509	120	2.05169	0.56884	203.674	0.90001
2.63	0.23264	209.509	120	2.0517	0.56884	203.674	0.90001
2.64	0.23264	209.509	120	2.0517	0.56884	203.674	0.90001
2.65	0.23264	209.509	120	2.0517	0.56884	203.674	0.90001
2.66	0.23264	209.509	120	2.0517	0.56884	203.674	0.90001
2.67	0.23264	209.509	120	2.0517	0.56884	203.674	0.90001
2.68	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.69	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.7	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.71	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.72	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.73	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.74	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.75	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.76	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.77	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.78	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.79	0.23264	209.509	120	2.0517	0.56884	203.674	0.9

2.8	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.81	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.82	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.83	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.84	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.85	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.86	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.87	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.88	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.89	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.9	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.91	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.92	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.93	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.94	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.95	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.96	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.97	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.98	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
2.99	0.23264	209.509	120	2.0517	0.56884	203.674	0.9
3	0.23264	209.509	120	2.0517	0.56884	203.674	0.9

Time	Absorber. level	Stripper. level	sump.level	Lean tank. level	Rich_tank. level	Reboiler. level
Hour	m	m	m	m	m	m
0	1.17923	1.53871	1.12167	1.24087	1.67833	3.07639
0.01	1.17867	1.52973	1.12238	1.23972	1.68189	3.07858
0.02	1.17531	1.50716	1.1238	1.23733	1.69763	3.08053
0.03	1.16716	1.47638	1.12469	1.23497	1.72971	3.07513
0.04	1.15314	1.4403	1.12407	1.23336	1.7781	3.06325
0.05	1.13217	1.40074	1.12128	1.23336	1.84138	3.04804
0.06	1.10351	1.3591	1.11604	1.23623	1.91649	3.03339
0.07	1.06739	1.31639	1.10867	1.24336	1.99863	3.02204
0.08	1.02515	1.27322	1.10018	1.25595	2.08207	3.01479
0.09	0.97936	1.22991	1.09208	1.27413	2.16082	3.01101
0.1	0.93302	1.18655	1.08566	1.29667	2.23063	3.00961
0.11	0.88832	1.14311	1.08144	1.32184	2.2902	3.00974
0.12	0.84686	1.09951	1.07958	1.34812	2.33914	3.0109
0.13	0.80837	1.05569	1.07934	1.37424	2.38091	3.01259

0.14	0.77231	1.01158	1.08027	1.39973	2.4177	3.01457
0.15	0.7377	0.96712	1.08191	1.42444	2.45195	3.01669
0.16	0.70346	0.9223	1.08387	1.44868	2.48557	3.0188
0.17	0.66884	0.87711	1.08593	1.47272	2.51957	3.02091
0.18	0.63386	0.84789	1.08789	1.49749	2.54674	3.02328
0.19	0.60134	0.83928	1.08969	1.5222	2.55955	3.02723
0.2	0.57544	0.83721	1.0914	1.5479	2.55775	3.03354
0.21	0.55931	0.83646	1.09331	1.57286	2.5417	3.03985
0.22	0.55421	0.83604	1.09562	1.59421	2.51371	3.04547
0.23	0.55966	0.83568	1.09848	1.60967	2.47761	3.0503
0.24	0.57248	0.83529	1.10188	1.61878	2.43888	3.05442
0.25	0.58847	0.83486	1.10562	1.62242	2.40275	3.0579
0.26	0.60345	0.83441	1.10935	1.62261	2.37306	3.06083
0.27	0.61464	0.83398	1.11271	1.62154	2.35142	3.0633
0.28	0.62109	0.83358	1.11542	1.62092	2.33738	3.06539
0.29	0.62295	0.83324	1.11735	1.62181	2.32956	3.06715
0.3	0.6215	0.83295	1.11852	1.62455	2.32567	3.06861
0.31	0.61849	0.8327	1.11908	1.62884	2.32328	3.06983
0.32	0.61563	0.83247	1.11932	1.63377	2.32052	3.07085
0.33	0.6138	0.83228	1.11944	1.63864	2.31665	3.0717
0.34	0.61326	0.8321	1.11955	1.64294	2.31169	3.07242
0.35	0.6139	0.83196	1.11974	1.6464	2.30598	3.07301
0.36	0.61535	0.83184	1.12	1.64899	2.30012	3.07351
0.37	0.61708	0.83176	1.1203	1.65085	2.29471	3.07393
0.38	0.61869	0.83171	1.1206	1.6523	2.28999	3.07428
0.39	0.6201	0.83167	1.12088	1.65347	2.28597	3.07458
0.4	0.62103	0.83167	1.1211	1.65453	2.28287	3.07482
0.41	0.62184	0.83166	1.1213	1.65555	2.28005	3.07506
0.42	0.62221	0.83168	1.12141	1.65656	2.27803	3.07524
0.43	0.62256	0.83169	1.12152	1.65756	2.27605	3.07541
0.44	0.62272	0.8317	1.12157	1.6585	2.27456	3.07553
0.45	0.62289	0.83171	1.12161	1.65943	2.27306	3.07564
0.46	0.62305	0.83173	1.12164	1.66024	2.27177	3.07575
0.47	0.6232	0.83174	1.12166	1.66097	2.27062	3.07583
0.48	0.62336	0.83175	1.12167	1.66169	2.26947	3.0759
0.49	0.62352	0.83176	1.12168	1.66238	2.26835	3.07598
0.5	0.62367	0.83177	1.12169	1.66284	2.26758	3.07601
0.51	0.62381	0.83177	1.1217	1.66329	2.2668	3.07605
0.52	0.62396	0.83177	1.1217	1.66374	2.26603	3.07609
0.53	0.62411	0.83177	1.12171	1.66419	2.26525	3.07612
0.54	0.62426	0.83178	1.12171	1.66465	2.26448	3.07616
0.55	0.62435	0.83178	1.12172	1.66491	2.26402	3.07619

0.56	0.62443	0.83178	1.12172	1.66515	2.2636	3.07621
0.57	0.62452	0.83178	1.12172	1.66539	2.26318	3.07622
0.58	0.6246	0.83179	1.12172	1.66563	2.26276	3.07623
0.59	0.62469	0.83179	1.12172	1.66587	2.26234	3.07625
0.6	0.62477	0.83179	1.12172	1.66611	2.26192	3.07626
0.61	0.62486	0.83179	1.12172	1.66635	2.26151	3.07628
0.62	0.62494	0.83179	1.12172	1.66659	2.26109	3.07629
0.63	0.62498	0.83179	1.12172	1.6667	2.26088	3.0763
0.64	0.62503	0.8318	1.12171	1.66682	2.26067	3.07632
0.65	0.62507	0.8318	1.12171	1.66693	2.26046	3.07632
0.66	0.62511	0.8318	1.12171	1.66705	2.26025	3.07632
0.67	0.62515	0.8318	1.12171	1.66717	2.26004	3.07633
0.68	0.62519	0.8318	1.12171	1.66728	2.25983	3.07633
0.69	0.62523	0.8318	1.12171	1.6674	2.25962	3.07633
0.7	0.62527	0.8318	1.12171	1.66751	2.2594	3.07634
0.71	0.62531	0.8318	1.12171	1.66763	2.25919	3.07634
0.72	0.62534	0.83181	1.12171	1.66771	2.25904	3.07635
0.73	0.62536	0.83181	1.1217	1.66775	2.25894	3.07635
0.74	0.62538	0.83181	1.1217	1.6678	2.25885	3.07635
0.75	0.6254	0.83181	1.1217	1.66784	2.25875	3.07636
0.76	0.62542	0.83181	1.1217	1.66789	2.25865	3.07636
0.77	0.62543	0.83181	1.1217	1.66793	2.25856	3.07636
0.78	0.62545	0.83181	1.1217	1.66798	2.25846	3.07637
0.79	0.62547	0.83182	1.1217	1.66802	2.25836	3.07637
0.8	0.62549	0.83182	1.1217	1.66807	2.25827	3.07637
0.81	0.62551	0.83182	1.12169	1.66811	2.25817	3.07637
0.82	0.62553	0.83182	1.12169	1.66816	2.25808	3.07637
0.83	0.62554	0.83182	1.12169	1.6682	2.25798	3.07637
0.84	0.62556	0.83182	1.12169	1.66825	2.25788	3.07637
0.85	0.62557	0.83182	1.12169	1.66826	2.25784	3.07637
0.86	0.62558	0.83183	1.12169	1.66827	2.2578	3.07637
0.87	0.62559	0.83183	1.12169	1.66829	2.25776	3.07638
0.88	0.62559	0.83183	1.12169	1.6683	2.25772	3.07638
0.89	0.6256	0.83183	1.12168	1.66831	2.25768	3.07638
0.9	0.62561	0.83183	1.12168	1.66832	2.25764	3.07638
0.91	0.62561	0.83183	1.12168	1.66833	2.2576	3.07638
0.92	0.62562	0.83183	1.12168	1.66834	2.25756	3.07638
0.93	0.62563	0.83184	1.12168	1.66835	2.25752	3.07638
0.94	0.62564	0.83184	1.12168	1.66836	2.25749	3.07638
0.95	0.62564	0.83184	1.12168	1.66837	2.25745	3.07638
0.96	0.62565	0.83184	1.12168	1.66838	2.25741	3.07638
0.97	0.62566	0.83184	1.12168	1.6684	2.25737	3.07638

0.98	0.62566	0.83184	1.12168	1.66841	2.25733	3.07638
0.99	0.62567	0.83184	1.12168	1.66842	2.25729	3.07638
1	0.62579	0.83189	1.12167	1.66841	2.25664	3.07639
1.01	0.63277	0.88509	1.12157	1.66665	2.22404	3.07903
1.02	0.64896	0.9268	1.1217	1.66307	2.1834	3.08415
1.03	0.67876	0.96856	1.12248	1.65518	2.12738	3.08939
1.04	0.72103	1.01024	1.12434	1.6401	2.06124	3.09396
1.05	0.77092	1.05203	1.12754	1.61721	1.99241	3.09797
1.06	0.82102	1.09378	1.13175	1.58922	1.92867	3.10167
1.07	0.86572	1.1352	1.13628	1.5598	1.87443	3.1052
1.08	0.90251	1.17611	1.14031	1.53209	1.83058	3.10862
1.09	0.93227	1.21637	1.14328	1.50792	1.79444	3.11205
1.1	0.95769	1.25583	1.145	1.48769	1.76194	3.11548
1.11	0.98231	1.29444	1.14586	1.4701	1.72893	3.11904
1.12	1.00812	1.33217	1.14641	1.45375	1.69347	3.1228
1.13	1.03547	1.36901	1.14711	1.43758	1.65565	3.12685
1.14	1.06387	1.40489	1.14817	1.42122	1.61628	3.13127
1.15	1.09251	1.43968	1.14964	1.40471	1.5764	3.13615
1.16	1.12085	1.47317	1.15145	1.38821	1.53679	3.14149
1.17	1.14687	1.49316	1.15429	1.37245	1.50559	3.14603
1.18	1.16774	1.50244	1.15783	1.35797	1.48823	3.14399
1.19	1.18215	1.50862	1.1611	1.34448	1.48471	3.13464
1.2	1.1909	1.51526	1.16338	1.33084	1.49052	3.12363
1.21	1.19424	1.52211	1.16376	1.31754	1.50388	3.11679
1.22	1.1936	1.52755	1.16177	1.30676	1.52222	3.11311
1.23	1.19107	1.53151	1.15792	1.29889	1.54225	3.11052
1.24	1.18782	1.53415	1.15271	1.29381	1.56181	3.10818
1.25	1.1848	1.53588	1.14705	1.29058	1.5794	3.10573
1.26	1.18241	1.53695	1.14158	1.28849	1.5943	3.1031
1.27	1.18078	1.53757	1.13667	1.28693	1.60645	3.10035
1.28	1.18001	1.53786	1.13273	1.28548	1.61559	3.09757
1.29	1.17987	1.53799	1.12981	1.28375	1.62238	3.0949
1.3	1.18004	1.53805	1.12754	1.28178	1.6279	3.09237
1.31	1.18047	1.53807	1.12598	1.2795	1.63217	3.09006
1.32	1.1809	1.53809	1.12498	1.27699	1.6357	3.0881
1.33	1.18134	1.53811	1.12424	1.27437	1.63889	3.0863
1.34	1.18163	1.53816	1.12374	1.2718	1.64178	3.08484
1.35	1.18182	1.5382	1.1234	1.26926	1.64448	3.08361
1.36	1.18201	1.53826	1.12306	1.26673	1.64718	3.08239
1.37	1.18196	1.53832	1.12286	1.26462	1.64949	3.08163
1.38	1.18192	1.53838	1.12266	1.26253	1.6518	3.08088
1.39	1.18187	1.53844	1.12246	1.26044	1.6541	3.08013

1.4	1.18174	1.53849	1.12231	1.25882	1.65596	3.07966
1.41	1.1816	1.53854	1.12217	1.25731	1.65772	3.07925
1.42	1.18146	1.53859	1.12203	1.2558	1.65948	3.07884
1.43	1.18132	1.53863	1.1219	1.2543	1.66123	3.07843
1.44	1.1812	1.53866	1.12183	1.25331	1.66241	3.07822
1.45	1.18109	1.53868	1.12176	1.25232	1.6636	3.07802
1.46	1.18097	1.5387	1.12169	1.25133	1.66478	3.07782
1.47	1.18085	1.53873	1.12162	1.25035	1.66596	3.07762
1.48	1.18073	1.53875	1.12156	1.24946	1.66702	3.07742
1.49	1.18065	1.53875	1.12154	1.24888	1.66773	3.07732
1.5	1.18057	1.53876	1.12152	1.2483	1.66844	3.07723
1.51	1.18049	1.53876	1.1215	1.24772	1.66915	3.07714
1.52	1.18041	1.53877	1.12148	1.24714	1.66987	3.07705
1.53	1.18033	1.53877	1.12147	1.24655	1.67058	3.07695
1.54	1.18025	1.53878	1.12145	1.24597	1.67129	3.07686
1.55	1.18021	1.53878	1.12145	1.24566	1.67169	3.07682
1.56	1.18016	1.53879	1.12145	1.24537	1.67207	3.07679
1.57	1.18011	1.53878	1.12146	1.24508	1.67245	3.07676
1.58	1.18006	1.53878	1.12146	1.24479	1.67283	3.07672
1.59	1.18001	1.53878	1.12146	1.2445	1.67321	3.07669
1.6	1.17997	1.53878	1.12147	1.24421	1.67358	3.07665
1.61	1.17992	1.53878	1.12147	1.24392	1.67396	3.07662
1.62	1.17987	1.53878	1.12148	1.24363	1.67434	3.07659
1.63	1.17982	1.53878	1.12148	1.24334	1.67472	3.07656
1.64	1.1798	1.53878	1.12149	1.24322	1.67489	3.07654
1.65	1.17978	1.53878	1.12149	1.2431	1.67506	3.07653
1.66	1.17975	1.53877	1.1215	1.24299	1.67522	3.07652
1.67	1.17973	1.53877	1.1215	1.24287	1.67538	3.07651
1.68	1.1797	1.53877	1.12151	1.24276	1.67555	3.07651
1.69	1.17968	1.53877	1.12151	1.24264	1.67571	3.0765
1.7	1.17965	1.53877	1.12152	1.24253	1.67587	3.07649
1.71	1.17963	1.53877	1.12152	1.24242	1.67603	3.07648
1.72	1.1796	1.53877	1.12153	1.2423	1.6762	3.07648
1.73	1.17958	1.53877	1.12153	1.24219	1.67636	3.07647
1.74	1.17955	1.53877	1.12154	1.24208	1.67652	3.07646
1.75	1.17953	1.53876	1.12154	1.24196	1.67669	3.07645
1.76	1.17951	1.53876	1.12155	1.24185	1.67685	3.07644
1.77	1.17949	1.53876	1.12155	1.24178	1.67694	3.07644
1.78	1.17948	1.53876	1.12156	1.24175	1.67699	3.07643
1.79	1.17947	1.53876	1.12156	1.24172	1.67704	3.07642
1.8	1.17946	1.53876	1.12157	1.24168	1.67709	3.07641
1.81	1.17946	1.53876	1.12157	1.24165	1.67714	3.07641

1.82	1.17945	1.53876	1.12157	1.24162	1.6772	3.07641
1.83	1.17944	1.53876	1.12158	1.24158	1.67725	3.07641
1.84	1.17943	1.53875	1.12158	1.24155	1.6773	3.07641
1.85	1.17942	1.53875	1.12158	1.24152	1.67735	3.07641
1.86	1.17941	1.53875	1.12158	1.24148	1.6774	3.07641
1.87	1.1794	1.53875	1.12159	1.24145	1.67745	3.07641
1.88	1.1794	1.53875	1.12159	1.24142	1.6775	3.07641
1.89	1.17939	1.53875	1.12159	1.24138	1.67755	3.07641
1.9	1.17938	1.53875	1.12159	1.24135	1.6776	3.07641
1.91	1.17937	1.53875	1.1216	1.24132	1.67765	3.0764
1.92	1.17936	1.53875	1.1216	1.24128	1.67771	3.0764
1.93	1.17935	1.53874	1.1216	1.24125	1.67776	3.0764
1.94	1.17934	1.53874	1.12161	1.24122	1.67781	3.0764
1.95	1.17933	1.53874	1.12161	1.24118	1.67786	3.0764
1.96	1.17933	1.53874	1.12161	1.24115	1.67791	3.0764
1.97	1.17932	1.53874	1.12161	1.24114	1.67793	3.0764
1.98	1.17931	1.53874	1.12162	1.24113	1.67794	3.0764
1.99	1.17931	1.53874	1.12162	1.24112	1.67795	3.0764
2	1.17931	1.53874	1.12162	1.24111	1.67796	3.0764
2.01	1.1793	1.53874	1.12163	1.24111	1.67798	3.0764
2.02	1.1793	1.53873	1.12163	1.2411	1.67799	3.0764
2.03	1.1793	1.53873	1.12163	1.24109	1.678	3.07639
2.04	1.1793	1.53873	1.12163	1.24109	1.67801	3.07639
2.05	1.1793	1.53873	1.12163	1.24108	1.67802	3.07639
2.06	1.17929	1.53873	1.12163	1.24107	1.67803	3.07639
2.07	1.17929	1.53873	1.12163	1.24107	1.67804	3.07639
2.08	1.17929	1.53873	1.12163	1.24106	1.67805	3.07639
2.09	1.17929	1.53873	1.12163	1.24105	1.67806	3.07639
2.1	1.17929	1.53873	1.12163	1.24104	1.67807	3.07639
2.11	1.17928	1.53873	1.12163	1.24104	1.67808	3.07639
2.12	1.17928	1.53872	1.12163	1.24103	1.67809	3.07639
2.13	1.17928	1.53872	1.12163	1.24102	1.6781	3.07639
2.14	1.17928	1.53872	1.12164	1.24102	1.67811	3.07639
2.15	1.17928	1.53872	1.12164	1.24101	1.67812	3.07638
2.16	1.17927	1.53872	1.12164	1.241	1.67813	3.07638
2.17	1.17927	1.53872	1.12164	1.241	1.67814	3.07638
2.18	1.17927	1.53872	1.12164	1.24099	1.67815	3.07638
2.19	1.17927	1.53872	1.12164	1.24098	1.67816	3.07638
2.2	1.17927	1.53872	1.12164	1.24098	1.67817	3.07638
2.21	1.17926	1.53872	1.12164	1.24097	1.67818	3.07638
2.22	1.17926	1.53872	1.12164	1.24096	1.67819	3.07638
2.23	1.17926	1.53872	1.12164	1.24096	1.6782	3.07638

2.24	1.17926	1.53872	1.12164	1.24095	1.67821	3.07638
2.25	1.17926	1.53872	1.12164	1.24094	1.67822	3.07638
2.26	1.17925	1.53872	1.12165	1.24094	1.67823	3.07638
2.27	1.17925	1.53872	1.12165	1.24093	1.67824	3.07638
2.28	1.17925	1.53872	1.12165	1.24092	1.67826	3.07638
2.29	1.17925	1.53872	1.12165	1.24092	1.67826	3.07638
2.3	1.17925	1.53872	1.12165	1.24092	1.67826	3.07638
2.31	1.17925	1.53872	1.12165	1.24092	1.67826	3.07638
2.32	1.17924	1.53872	1.12165	1.24092	1.67826	3.07638
2.33	1.17924	1.53872	1.12165	1.24092	1.67826	3.07638
2.34	1.17924	1.53872	1.12165	1.24092	1.67826	3.07638
2.35	1.17924	1.53872	1.12165	1.24092	1.67826	3.07638
2.36	1.17924	1.53872	1.12165	1.24091	1.67827	3.07638
2.37	1.17924	1.53872	1.12165	1.24091	1.67827	3.07638
2.38	1.17924	1.53872	1.12166	1.24091	1.67827	3.07638
2.39	1.17924	1.53872	1.12166	1.24091	1.67827	3.07638
2.4	1.17924	1.53871	1.12166	1.24091	1.67827	3.07638
2.41	1.17924	1.53871	1.12166	1.24091	1.67827	3.07638
2.42	1.17924	1.53871	1.12166	1.24091	1.67827	3.07638
2.43	1.17924	1.53871	1.12166	1.24091	1.67827	3.07638
2.44	1.17924	1.53871	1.12166	1.24091	1.67828	3.07638
2.45	1.17924	1.53871	1.12166	1.24091	1.67828	3.07638
2.46	1.17924	1.53871	1.12166	1.24091	1.67828	3.07638
2.47	1.17924	1.53871	1.12166	1.24091	1.67828	3.07638
2.48	1.17924	1.53871	1.12166	1.2409	1.67828	3.07638
2.49	1.17924	1.53871	1.12166	1.2409	1.67828	3.07638
2.5	1.17924	1.53871	1.12166	1.2409	1.67828	3.07638
2.51	1.17924	1.53871	1.12166	1.2409	1.67828	3.07638
2.52	1.17924	1.53871	1.12166	1.2409	1.67829	3.07638
2.53	1.17924	1.53871	1.12166	1.2409	1.67829	3.07638
2.54	1.17924	1.53871	1.12166	1.2409	1.67829	3.07638
2.55	1.17923	1.53871	1.12166	1.2409	1.67829	3.07638
2.56	1.17923	1.53871	1.12166	1.2409	1.67829	3.07638
2.57	1.17923	1.53871	1.12166	1.2409	1.67829	3.07638
2.58	1.17923	1.53871	1.12166	1.2409	1.67829	3.07638
2.59	1.17923	1.53871	1.12166	1.24089	1.67829	3.07638
2.6	1.17923	1.53871	1.12166	1.24089	1.6783	3.07638
2.61	1.17923	1.53871	1.12166	1.24089	1.6783	3.07638
2.62	1.17923	1.53871	1.12166	1.24089	1.6783	3.07638
2.63	1.17923	1.53871	1.12166	1.24089	1.6783	3.07638
2.64	1.17923	1.53871	1.12166	1.24089	1.6783	3.07638
2.65	1.17923	1.53871	1.12166	1.24089	1.6783	3.07638

2.66	1.17923	1.53871	1.12166	1.24089	1.6783	3.07638
2.67	1.17923	1.53871	1.12166	1.24089	1.6783	3.07638
2.68	1.17923	1.53871	1.12166	1.24089	1.67831	3.07638
2.69	1.17923	1.53871	1.12166	1.24089	1.67831	3.07638
2.7	1.17923	1.53871	1.12166	1.24088	1.67831	3.07638
2.71	1.17923	1.53871	1.12166	1.24088	1.67831	3.07638
2.72	1.17923	1.53871	1.12166	1.24088	1.67831	3.07638
2.73	1.17923	1.53871	1.12166	1.24088	1.67831	3.07638
2.74	1.17923	1.53871	1.12166	1.24088	1.67831	3.07638
2.75	1.17923	1.53871	1.12167	1.24088	1.67831	3.07638
2.76	1.17923	1.53871	1.12167	1.24088	1.67832	3.07638
2.77	1.17923	1.53871	1.12167	1.24088	1.67832	3.07638
2.78	1.17923	1.53871	1.12167	1.24088	1.67832	3.07638
2.79	1.17923	1.53871	1.12167	1.24088	1.67832	3.07638
2.8	1.17923	1.53871	1.12167	1.24088	1.67832	3.07638
2.81	1.17923	1.53871	1.12167	1.24088	1.67832	3.07638
2.82	1.17922	1.53871	1.12167	1.24087	1.67832	3.07638
2.83	1.17922	1.53871	1.12167	1.24087	1.67832	3.07638
2.84	1.17922	1.53871	1.12167	1.24087	1.67832	3.07638
2.85	1.17922	1.53871	1.12167	1.24087	1.67832	3.07638
2.86	1.17922	1.53871	1.12167	1.24087	1.67832	3.07638
2.87	1.17922	1.53871	1.12167	1.24087	1.67832	3.07638
2.88	1.17922	1.53871	1.12167	1.24087	1.67832	3.07638
2.89	1.17922	1.53871	1.12167	1.24087	1.67832	3.07638
2.9	1.17922	1.53871	1.12167	1.24087	1.67832	3.07638
2.91	1.17922	1.53871	1.12167	1.24087	1.67832	3.07638
2.92	1.17922	1.53871	1.12167	1.24087	1.67833	3.07638
2.93	1.17922	1.53871	1.12167	1.24087	1.67833	3.07638
2.94	1.17922	1.53871	1.12167	1.24087	1.67833	3.07638
2.95	1.17922	1.53871	1.12167	1.24087	1.67833	3.07638
2.96	1.17922	1.53871	1.12167	1.24087	1.67833	3.07638
2.97	1.17922	1.53871	1.12167	1.24087	1.67833	3.07638
2.98	1.17922	1.53871	1.12167	1.24087	1.67833	3.07638
2.99	1.17922	1.53871	1.12167	1.24087	1.67833	3.07638
3	1.17922	1.53871	1.12167	1.24087	1.67833	3.07638

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