SPRING ’16

06-665 PROCESS SYSTEM MODELING

PROJECT REPORT ON

OPTIMIZATION OF PROFIT FOR MANUFACTURE OF ASPIRIN

By

TEAM #5

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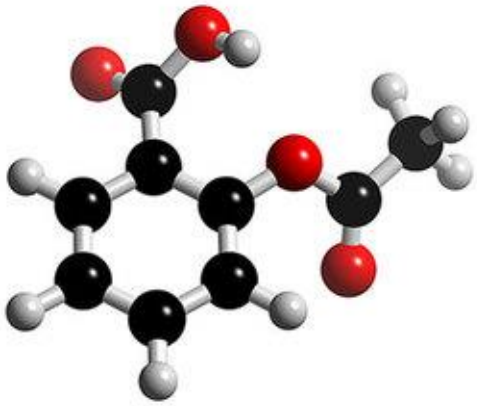

KEYWORDS: Aspen Simulation, Acetylation, Continuous Crystallization, Temperature Control, Optimization

ABSTRACT

Computing capacity allow us to design better quality of products, now that we can mathematically model a manufacturing process and optimize it by using a variety of software. In 1930s when Bayer's patent of acetyl salicylic acid ran out, it became a generic drug. This caused a variety of scientists to work on and optimize the manufacturing process. A comprehensive solution was provided to increase the profit of Aspirin production process.

A mathematical model of the process to optimize in GAMS, the manufacturing process along with its simulation in Aspen. In this project we will be considering the manufacture of Aspirin by acetylation of Salicylic Acid using Acetic Anhydride with Toluene as catalyst. The optimization is done in two ways, first by considering the actual manufacturing process and second by considering the simulated model in Aspen. We have also implemented control aspect in our project in order to control the reactor temperature. Finally we got great results with profit of about $160,000 per batch, which is almost 40% of the amount invested for reactants.

Contents

1 Introduction

Aspirin is one of the safest and least expensive pain relievers available in market. Today, Americans alone consume 16,000 tons of Aspirin tablets a year, equaling 80 million pills. Currently the drug is available in several dosage forms in various concentrations from 0.0021 ounces to 0.00227 ounces (60 to 650 milligrams), but the drug is most widely used in tablet form. Other forms include capsules, caplets, suppositories and liquid elixir[1] . Aspirin is used in the treatment of a number of conditions, including fever, pain, rheumatic fever, rheumatoid arthritis, pericarditis. Lower doses of aspirin have also shown to reduce the risk of death from a heart attack, or lower the risk of stroke in some cases[2] . Almost every medicine has some side effects if taken without consultation from family physician or a medical practitioner. Heavy doses of Aspirin may cause bleeding in stomach and intestine. Taking unadvised doses of Aspirin may cause thinning of blood below the recommended amount and affect the natural healing of damaged blood vessels and increase the risk of bleeding in the brain.

In this work, we have simulated the manufacturing process of Aspirin (acetylsalicylic acid) in Aspen[3] and optimized the simulated flowsheet for maximum profit. All the price of material have been cited or approximated (with reasons for approximation). There were a few difficulties faced during the simulation in Aspen, due to limited knowledge on complex flowsheets. The optimization was done in two different directions for this project. First, we concentrated on the Aspen simulated flowsheet and optimized the profit. Second, we optimized the profit using the actual flowsheet as described below. Both the optimizations have been done using General Algebraic Modeling System (GAMS).[4] We have also included a control analysis on temperature control for the batch reactor used in the manufacture of Aspirin[5] .

2 Problem Statement

2.1 Chemistry

In this project, we will optimize profit from sale of Aspirin manufactured in a batch reactor. The reaction into consideration is actylation of Salicylic Acid using Acetic Anhydride with toluene as catalyst. The reaction is given as :

$$OHC_6H_4COOH + (CH_3CO)_2O \rightarrow CH_3COOC_6H_4COOH + CH_3COOH$$

where OHC_6H_4COOH is salicylic Acid, $(CH_3CO)_2O$ is Acetic Anhydride, $CH_3COOC_6H_4COOH$ is Acetyl Salicylic Acid (Aspirin) and CH_3COOH is Acetic Acid

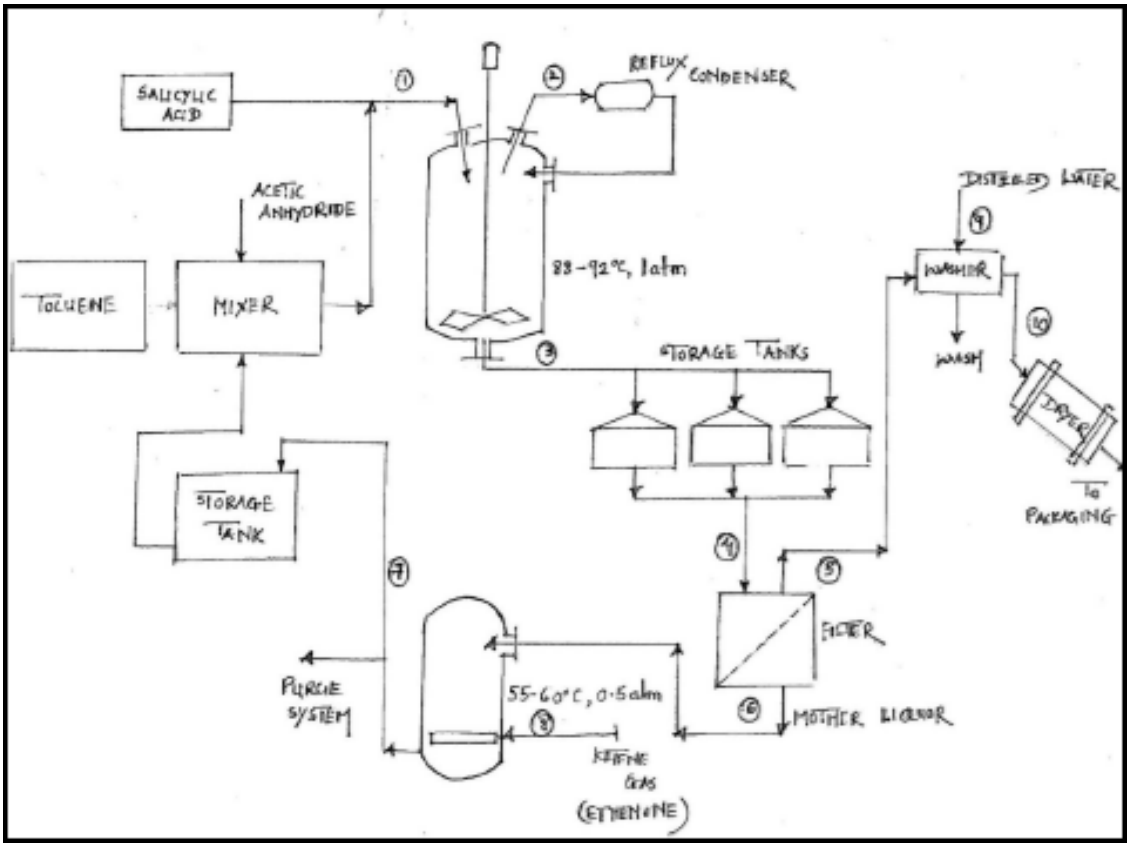

Figure 1: Manufacturing Process Flowsheet

Figure 1 represents a detailed flowsheet of manufacture of Aspirin using a batch reactor.[6]

2.2 Aspen Simulation

The process is simulated as described in the reference literature.[6] The input flows and process conditions in equipment are set as given in the reference. The goal of this simulation is to reproduce the results of the reference. Values calculated for flows and unspecified parameters will be used as initial guesses to solve the optimization problem in GAMS. Refer Figure 2 for Aspen simulated flowsheet.

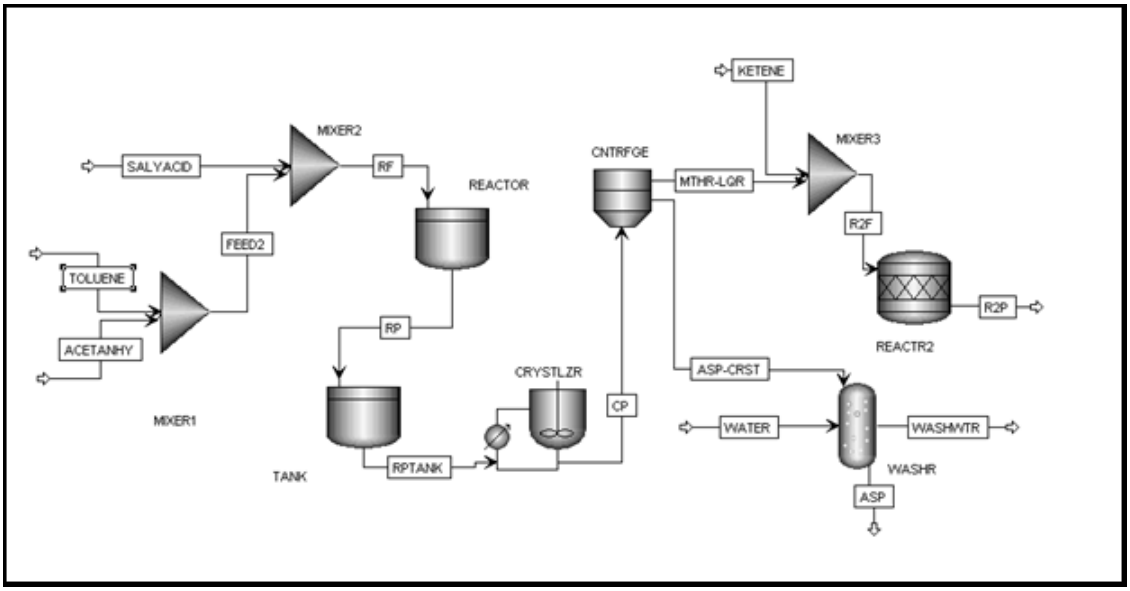

Figure 2: Manufacturing Process Flowsheet

2.3 Optimization based Aspen Simulation

We explored the optimization of a sample Aspirin production system to maximize profit and minimize operating costs. The basic idea is to use mathematical models to calculate the yeild, purity, conversion and utility cost, then these models were formulatd into a Non-Linear-Programming (NLP) optimization problem. The batch reactor was initally optimized and was then incorporated into the whole system. The optimization problem was solved using GAMS given the production requirement and some other constraints. All the values of properties were taken from National Institute of Standards and Technology (NIST).

2.4 System Wide Optimization

In this part of optimization we maximized the profit, taking the entire flowsheet (refer Figure 1) into consideration. From the initial work done in this topic,[6] we have taken into consideration the following:

- Exit concentration of Aspirin
- Performance of Ketene Reactor
- Simultaneous Production of Acetic Acid

All the values have been referred from Perry's Handbook.[7]

2.5 Temperature control

Reactor Temperature plays a significant role in the crystallization process. Temperature with residence time together would apparently affect the particle size distribution of the process, and thus the product quality.[8] For Aspirin's production process in this text, the optimum reaction temperature was determined to be above to be 60°C, which should be maintained during the 20 hour batch reaction process.
The reaction we chose is the acetylation of Salicylic Acid using Acetic Anhydride with Toluene as catalyst. The reaction itself is an endothermic reaction and thus the reaction's temperature will continually decrease during the process. Thus, it is essential to implement a control system in order to maintain a stable temperature around 60 °C.

3 Literature Survey

In this project all values of the different properties were taken either from Perry's Handbook [7] or from trusted online source like National Institute of Standards and Technology (NIST). [9] The following properties required in the modeling of the process:

Table 1: Properties Values from Perry's Handbook

Compound	Cost ($/Kg)	Heat Capacity (J/mol.K)	Variable assigned
Salicylic Acid	83.488	161	x_1
Acetic Anhydride	30.13	168.2	x_2
Aspirin	133.17	227	x_3
Acetic Acid	0.64	139.7	x_4
Toluene	4.7	155.96	x_5
Conversion			x_6
Heating Water	0.02	75.6	x_7

The following is the manufacturing procedure of Aspirin by acetylation of Salicylic Acid [10] (Refer Figure 1)

1. A glass- lined reactor of 1500 gallons capacity, fitted with a water cooled reflux condenser, thermometers with automatic temperature registers and an efficient agitator, is employed.
2. To start the process, a mother liquor is made by dissolving 510 kg of acetic anhydride (15 moles) with 1,200 kg of toluene. To this mother liquor, 1,382 kg salicylic acid (10 moles)is added
3. The reaction mixture is heated under an efficient reflux condenser, to 88°-92°C and maintained within this temperature range for 20 hours.
4. The vapors formed during the process is condensed with the help of condenser so that there will be no loss of reactants and also for better productivity.
5. The reaction mixture is now transferred to aluminum cooling tanks, and is allowed to cool slowly, to a terminal temperature of 15°-25°C (room temperature).
6. The acetylsalicylic acid precipitates as large, regular crystals. The mother liquor is now filtered or centrifuged from the precipitated acetylsalicylic acid and the filter cake is pressed or centrifuged as free of mother liquor as possible
7. The crystals are washed with distilled water until completely free of acetic acid, pressed or centrifuged as dry as possible and the filter cake is then dried in a current of warm air at a temperature of 6O °-7O °C.
8. The filtrate from this first batch will comprise a solution of 180 to 270 kg of unprecipitated acetylsalicylic acid(1.0 to 1.5 moles),510 kg of acetic anhydride(5.0 moles), 600 kg of acetic acid (10 moles)(obtained as a by-product in the acetylation step) and 1,200 kg of diluent toluene.
9. Into this filtrate, at a temperature of 15 °to 25 °C, ketene gas is now passed through a sparger tube or diffuser plate, with good agitation, until a weight increase of 420.5 kg of ketene (10 moles) occurs.
10. The reaction mixture will now contain 180- 270 kg of unprecipitated acetylsalicylic acid and 1,532 acetic anhydride (15 moles) with toluene. This mother liquor is recycled to the first step of the process for reaction with another batch of salicylic acid. On recirculating the mother liquor, the yield of pure acetylsalicylic acid is increased substantially from 1,780 to 1,795 kg per batch.

4 Mathematical Model

4.1 Optimization based on Aspen Model

4.1.1 Objective function

The objective function of this process is the profit per batch or per day. The profit can be calculated by (value of product) - (value of feed) - (utility cost).

4.1.2 Constraints

Conversion:
The minimum conversion required is 80%. So for the batch reactor, the mathematical model can be formulated as follow:

$$C_7H_6O_3 + C_4H_6O_3 \rightarrow C_9H_8O_4 + C_2H_4O_2$$

$$\Delta G_f^o = \sum \alpha_i \times G_{i,f}^o$$

$$ln(k^o) = \frac{\Delta G_f^o}{R \times T}$$

At temperature of 60 deg C,

$$ln(\frac{k_1}{k_2}) = (\frac{-\Delta H}{R}(\frac{1}{T_1} - \frac{1}{T_2}))$$

We can calculate the equilibrium constant is 334.17, so the equilibrium conversion is 0.948.
Energy Balance
The energy balance across the batch reaction is given by:
(Heat Input by reactants) - (Heat Output by products) + (Heat of Reaction) = (Heat input by heating water)

$$\sum m_i \times C_{p,i} \times (T_{in}) - \sum m_i \times C_{p,i} \times (T_{out}) + \Delta H = m_{water} * C_{water} * \Delta T$$

Stoichiometry and feed ratio
To improve the equilibrium conversion of salicylic acid, the feeding acetic anhydride was set to be 50% mole excess. And the solvent toluene used was 86.6% to the mass flow of salicylic acid.
Reaction Rate
According to the rate law of the reaction, the first order reaction conversion can be expressed as

$$Conversion = 1 - \exp(-k \times t)$$

4.1.3 Mathematical expression

For the optimization model, the variables are expressed as following table:

Table 2: Variables Definition of Components

Components	Variable	Cost Variable	Mole Weight	Heat Capacity
Salicylic Acid	x1	a	M1	C1
Acetic Anhydride	x2	b	M2	C2
Aspirin	x3	c	M3	C3
Acetic Acid	x4	d	M4	C4
Toluene	x5	e	M5	C5
Conversion	conv			
Water	xw	f	Mw	C6
Reaction time	t			

The optimization problems can be stated as:
max:

$$x_3 \times c + x_4 \times d - x_1 \times a - x_2 \times b - x_w \times f) \times 24 \times 60/t$$

s.t.

$$x_1 + x_2 + x_5 \leqslant 1000$$

$$x_2 = x_1/M_1 \times M_2 * 1.5$$

$$x_3 = x_1/M_1 \times conv \times M_3$$

$$x_4 = x_1/M_1 \times cons \times M_4$$

$$x_5 = 0.868 \times x_1$$

$$x_w \times C_6/Mw \times (T_{out} - T_{in}) = -\sum C_{in}x_{in} + \sum C_{out}x_{out} + \Delta H \times conv$$

$$0.8 \leqslant Conv \leqslant 0.948$$

$$x_3/t \times 60 * 24 \geqslant 3526.4$$

4.2 System wide optimization

Table 3: Variables Definition of Components

Components	Variable	Cost Variable	Mole Weight	Heat Capacity
Salicylic Acid	x1	a	M1	Cp_1
Acetic Anhydride	x2	b	M2	Co_2
Aspirin	x3	c	M3	Cp_3
Acetic Acid	x4	d	M4	Cp_4
Toluene	x5	e	M5	Cp_5
Conversion	x6			Cp_w
Water	x7	f		Cp_6

4.2.1 Objective function

Maximize(Profit): (product value) - (feed) - (energy cost)
Now,

$$Product = \text{(product generated)} + \text{(unreacted reactants processed and fed back)}$$

Therefore, unreacted reactants processed and fed back (considering the performance of the batch reactor [6]):

$$\text{Salicylic Acid} = (1 - x_6) - x_1$$

$$\text{Acetic Anhydride} = 1.11 * x_4 + (0.99 - 0.6603 * x_6) * x_2$$

$$\text{Toluene} = 0.98 * x_5$$

Therefore,

$$\text{Product Value is} = c * x_3 + (1 - x_6) * x_1 * c + 1.11 * x_4 * d + 0.98 * x_5 * e + (0.99 - 0.663 * x_6) * x_2 * b$$

$$\text{Feed} = x_1 * a + x_2 * b + x_5 * e$$

$$\text{Utility Cost(Heating Water)} = x_7 * f$$

4.2.2 Constraints

Maximum Reactor Capacity The basis considered for this project is 10,000Kg capacity of the reactor, which includes the recycle coming from the ketene reactor
Energy Balance
Given by,

$$\text{(Heat in)} - \text{(Heat out)} + \text{(Heat of Reaction)} = \text{(Heat by steam)}$$

From the manufacturing process provided, we can get the following information as the basis for the process
Aspirin Target
The target value of Aspirin should be greater than 3526.7 Kg.
Acetic Acid Production
Considering all the values of reactants and the reaction mechanics, the simultaneous Acetic Acid will be greater than 1174.422Kg
Ketene Reactor
Ketene Reactor mechanism and performance has been initial work[6]
Performance of the Reactor
The Acetic Anhydride to Acetic Acid ratio is 2.86
Performance of the reactor
It is found that just the batch reactor's conversion is 0.8, so we limit the overall conversion between 0.8 to 1
According to Stoichiometry proportions
the solvent toluene used was 86.6% to the mass flow of salicylic acid:
Input for Salicylic Acid
From the manufacturing process described above and the basis taken for the calculations, we get amount of Salicylic Acid in input should be greater than 2702.53 Kg
We also have to consider the conservation of mass in the constraints.

4.2.3 Mathematical model

max:

$$(-x_6 * x_1 * a) + (c * x_3) + [(-0.01 - 0.6603 * x_6) * x_2 * b + (1.11 * x_4 * d)] + (-0.02 * x_5 e) - x_7 * f$$

st:

$$x_1 + x_4 + x_5 + ((1 - x_6) * x_2) + ((1 - 0.667 * x_6) * x_2) \leq 10000$$

$$\begin{aligned}(x_1 * Cp_1/M_1 + x_2 * Cp_2/M_1 + x_5 * Cp_5/M_5) * T_{in} - x_3 * Cp_3/M_3 + x_4 * Cp_4/M_4 + x_5 * Cp_5/M_5 + 0.1 * x_1 * Cp_1/M_1 \\ + 0.408 * x_2 * Cp_2/M_2) * T_{out} + \\ - \Delta H_r * k \\ * C_a(\frac{0.1 * x_1 * Cp_1/M_1 + 0.408 * x_2 * Cp_2/M_2 + x_3 + x_4 + x_5}{1.821}) \\ - x_7 * Cp_w/M_w * \Delta T = 0\end{aligned} \tag{1}$$

$$x_3 \geq 3526.7Kg$$

$$x_4 \geq 1174.422Kg$$

$$x_2 \geq 2.86 * x_4$$

$$0.8 \leq x_6 \leq 1$$

$$x_6 = 0.868 * x_1$$

$$x_6 * x_1 * 0.1802 - x_3 * 0.1318 = 0$$

$$x_1 \geq 2702.53$$

4.3 Temperature Control

Mass conservation can be neglected for batch process, thus only conservation of energy is taken into consideration

4.3.1 Conservation of Energy

$$\begin{aligned}\text{(rate of energy accumulation)} =&\text{(rate of energy in by convection)}\\ &-\text{(rate of energy out by convection)}\\ &+\text{(net rate of heat addition to the system from the surrounding)}\\ &+\text{(net rate of work performed on the system by the surroundings)}\end{aligned} \tag{2}$$

4.3.2 Total energy's expression

$$U_{tot} = U_{int} + U_{KE} + U_{PE} \tag{3}$$

For aspirin production process, changes in potential energy and kinetic energy is negligible compared to changes in internal energy. Similarly, the net rate of work can be neglected. Thus we can get the energy balance equation for our system.

4.3.3 Energy Balance

$$\frac{dU_{int}}{dt} = -\Delta(\omega\hat{H}) + Q \tag{4}$$

where is the enthalpy per unit mass, w is the mass flow rate, and Q is the rate of heat transfer to the system. The Δ operator denotes the difference between outlet conditions and inlet conditions of the flowing streams. For low pressure process, we have

$$\frac{dU_{int}}{dt} = \rho V C\frac{dT}{dt} \tag{5}$$

where C is the constant pressure heat capacity.
For enthalpy, we have

$$-\Delta(\omega\hat{H}) = \omega C(T_i - T) + (-\Delta H_R)VkC_A \tag{6}$$

where $\omega C(T_i - T)$ is the change of enthalpy due to flowing stream, thus we don't have this term for batch reactor. Based on equation of rate of heat transfer $Q = UA(T_c - T)$, 5 ,6 we can get our final differential equation for control:
Control Differential Equation:

$$\rho V C\frac{dT}{dt} = \omega C(T_i - T) + (-\Delta H_R)VkC_A + UA(T_c - T) \tag{7}$$

5 Methods

5.1 Aspen Simulation

Salicylic Acid and Acetic Anhydride are introduced into a reactor maintained at 60 C. Toluene is added as a diluent to prevent run away reaction and keep a check on the temperature and pressure in the reactor. This is a batch process with batch time 22 hours. Maximum conversion obtained is 94 percent. Products of the reactor are acetylsalicylic acid, which is aspirin, acetic acid, unreacted salicylic acid and acetic anhydride, and inert toluene.
The products are stored in a storage tank (label: TANK) and slowly introduced to a crystallizer. Acetylsalicylic acid is precipitated out as crystals. All of the desired product is obtained as crystals. To separate the crystals from the mixture, the crystallizer product is centrifuged. The mother liquor and crystals are

separated in the centrifuge.
The mother liquor consists of acetic acid, toluene, acetic acid and traces of unprecipitated salicylic acid. The low amount of salicylic acid in the mother liquor is the major point of difference from the reference. The acetic acid is reacted with ketene to form acetic anhydride which is fed back to the reactor for the next batch.
The mother liquor is introduced to a reactor (label: REACTR2) where the acetic acid reacts with ketene to form acetic anhydride. Almost complete conversion of acetic acid is achieved. Reactor product contains acetic anhydride, toluene and traces of salicylic acid and acetic acid. This stream is re-introduced to the reactor for the next batch.
The crystals that are obtained are 99.7 percent pure. The crystals are washed to remove impurities. The pure crystals obtained are dried and a 99.99 percent pure product is obtained.

5.2 Optimization of Profit (system wide and based on Aspen Simulation)

In both cases of optimization, GAMS[4] was used. To solve the optimization problem, we have utilized IPOPT solver. Following are the advantages of using IPOPT as a solver in GAMS:

1. Work in full space of all variables
2. Second derivatives useful for objective and constraints
3. Uses specialized large-scale Newton Solver
4. Fast if the value of degree of freedom is high
5. No variable partitioning is required

In solving optimization problems using IPOPT, algorithm computes (approximate) solutions for a sequence of barrier problems. In order to solve the barrier problems, a damped Newton's method is applied to the primal-dual equations. For the computation of search directions, second derivatives are used.

5.3 Temperature Control

We have carried out the calculations for temperature control using Simulink. Simulink. is a block diagram environment for multidomain simulation and Model-Based Design. It supports simulation, automatic code generation, and continuous test and verification of embedded systems.
It provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB®, enabling you to incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis[11] .
Simulink is capable of performing following:

- Mmodel hierarchial subsystems with predefined library blocks
- Simulate the dynamic behaviour of your system and view results as the simulation runs
- Connect model to hardware for real-time testing and embedded system deployment.

6 Results and Discussion

6.1 Aspen

6.1.1 Stream Data

Table 4: Feed (Pure Components)

Stream	temperature (C)	Pressure (bar)	Phase	mass Flow (Kg/hr)	Mass Fraction
Acetic Anhydride	29	1	Liquid	152.8	1
Salicylic Acid	29	1	Liquid	155.64	1
Toluene	29	1	Liquid	135.1	1

Table 5: Products

Stream	Temp(C)	P (bar)	Phase	Component	Mass flow (Kg/Hr)	Mass Fraction
R2P	50	1	Liquid	Salicylic Acid	8.08	0.03
				Acetic Anh.	145.8	0.5
				Acetic Acid	4.03	0.01
				Acetylsalicylic Acid	0	0
				Toluene	134.96	0.46
				Total	293.06	1

Table 6: Desired Products

Stream	Temp (C)	P (bar)	Phase	Component	Mass Flow (Kg/hr)	Mass Fraction
ASP-CRST	25	1	Solid	AcetylSalicylic Acid	192.5	99.99

Figures 6 and 7 gives detailed information on the Stream data used in Aspen.

6.1.2 Equipment Specifications and Results

Table 7: Reactor 1 (Batch Reactor)

Operating Specification	Constant Temperature (60 C)
Reactor Pressure (bar)	1
Total Cycle Time (hr)	22.5
Stop Criteria	Conversion of Salicylic Acid at 0.948

Table 8: Reactor 1 results

Heat Duty (cal) (per cycle)	reaction Time (hr)
658	22

Table 9: Crystallizer, user definitions

Fraction of Solids to solid outlet	Fraction of liquid to liquid outlet
0.999	0.999

Table 10: Crystallizer results

Solid load of liquid outlet	Fraction of liquid to liquid outlet
$76.72 * 10^{-6}$	$31.3 * 10^{-}4$

Table 11: Centrifuge, user definitions

Temperature	Pressure
25	1

Table 12: Result (centrifuge)

Heat Duty	Crystal Product
0.2	192.5

Table 13: Ketene Reactor

Type	Fraction conversion
Reactor Pressure (bar)	0.5
Reactor temperature (C)	50

Heat Duty	Liquid to Solid mass ratio
-0.02	0.01

Table 14: Washer

Bypass Fraction	Outlet temperature
0	24.95

Table 15: Result (Washer)

Heat Duty	Liquid to Solid mass ratio
0.0	0.01

6.2 Optimization based on Aspen Simulations

For the batch reactor, the first objective function we optimized was profit per batch, and the GAMS solution list as below:

6.2.1 Maximum Profit per Batch

Table 16: Values obtained for maximizing profit per Batch

Variable	Value
x1	3359.1
x2	3725.2
x3	4131.1
x4	1377.8
x5	2915.7
t	1428.0
xw	9340.8
conv	0.943
Obj	$1.59*10^5

The optimal reaction time is 1428 min, 23.8 hours and conversion is 0.943 for each batch reactor. At this condition, equilibrium conversion is achieved and maximum profit per batch is $159,000

6.2.2 Maximum Profit per day

Table 17: Values obtained for maximizing profit per day

Variable	Value
x1	3359.1
x2	3725.2
x3	3948.6
x4	1316.9
x5	2915.7
t	1155.7
xw	8651.8
conv	0.901
Obj	$1.67*10^5

Time incorporated batch reactor optimization was conducted. When operation time is considered, the maximum profit is achieved at 1155.7 min, 19.3 h with a conversion of 0.901, and the profit per day is $167,000 Comparing these two solution, we find that optimal solution per batch isn't the same as optimal solution per day. This can be explained from the first order rate law, conversion increases as time proceeds but the rate of conversion decreases along the reactants. max profit/day os obtained at 19.3 hours at which the conversion is lower than maximum conversion..

6.3 System wide optimization

For the batch reactor, the first objective function we optimized was profit per batch, and the GAMS solution list as below:

6.3.1 Maximum Profit per Batch

Table 18: Values obtained for maximizing profit per Batch

Variable	Value
x1	2938.1
x2	6291.7
x3	3808.1
x4	1175.4
x5	2550.2
xw	1540
Conv	0.948
Obj	$1.504*10^5

So for each batch reaction, the optimal reaction time is 1428 min, 23.8 h and the conversion is 0.943. At this condition, the equilibrium conversion is achieved and the maximum profit per batch is 1.064e7.

6.4 Control

6.4.1 Block Diagram from Simulink

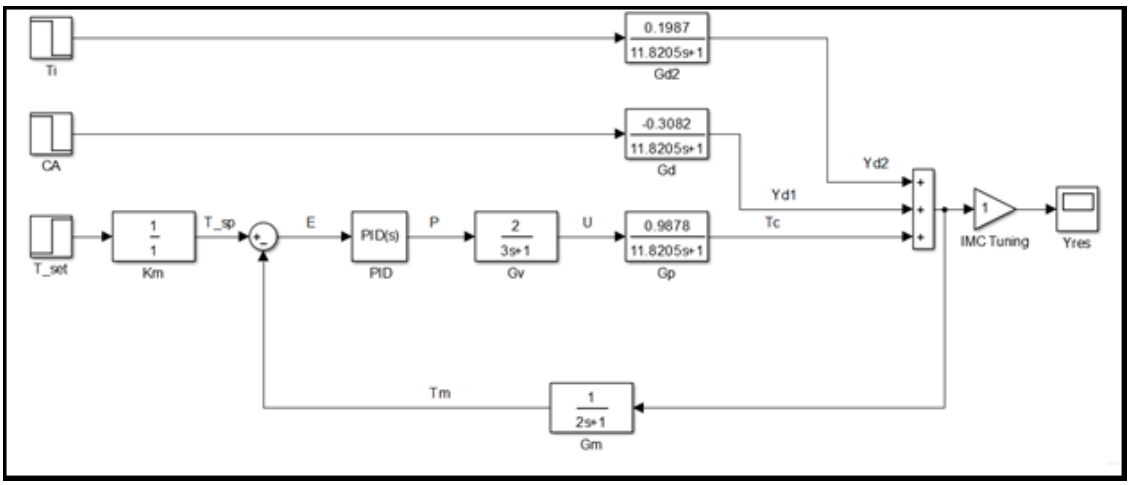

Figure 3: Block diagram for temperature control system

6.4.2 Bode Diagram

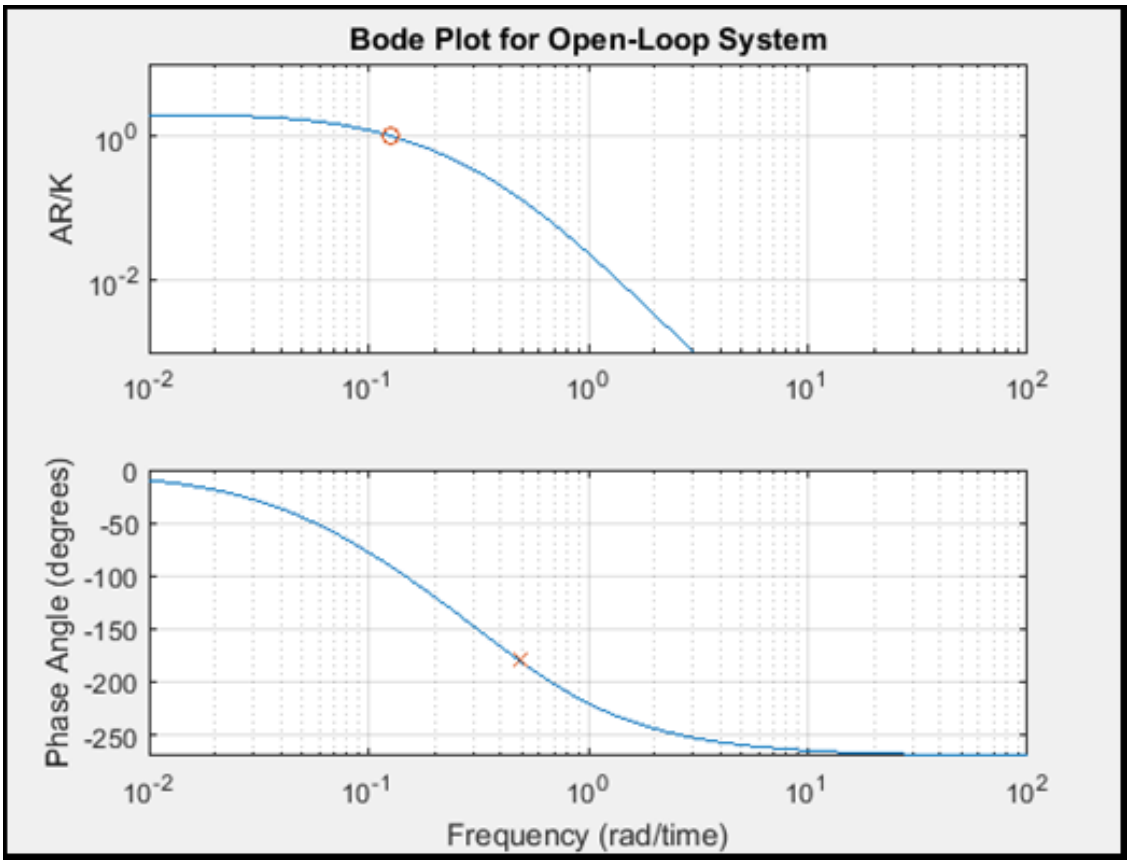

Figure 4: Bode Plot for open loop system (with kc = 1)

Based on Frequency Response analysis we get two characteristic values for the system:

$$K_{cu} = 7.1429$$

$$P_u = 12.9018$$

6.4.3 PID tuning

With $\tau_c = 2$ we can obtain the PID parameters for 2 tuning methods

Table 19: PID tuning Parameters

Tuning Method	k_c	τ_l	τ_D
IMC	5.9832	11.8205	1
T-L	3.2143	28.3840	2.0479

6.4.4 Closed Loop System Response

Step change of C_A, T_i, T_c were forced to the closed-loop system, and system response was obtained for each tuning method respectively. The input table and response plot are as follows:

Table 20: Input Signals

Input Terms	C_A (mol)	T_i	T_c (K)
Signal Start Time (min)	20	100	200
Signal Amplitude	-50	20	5

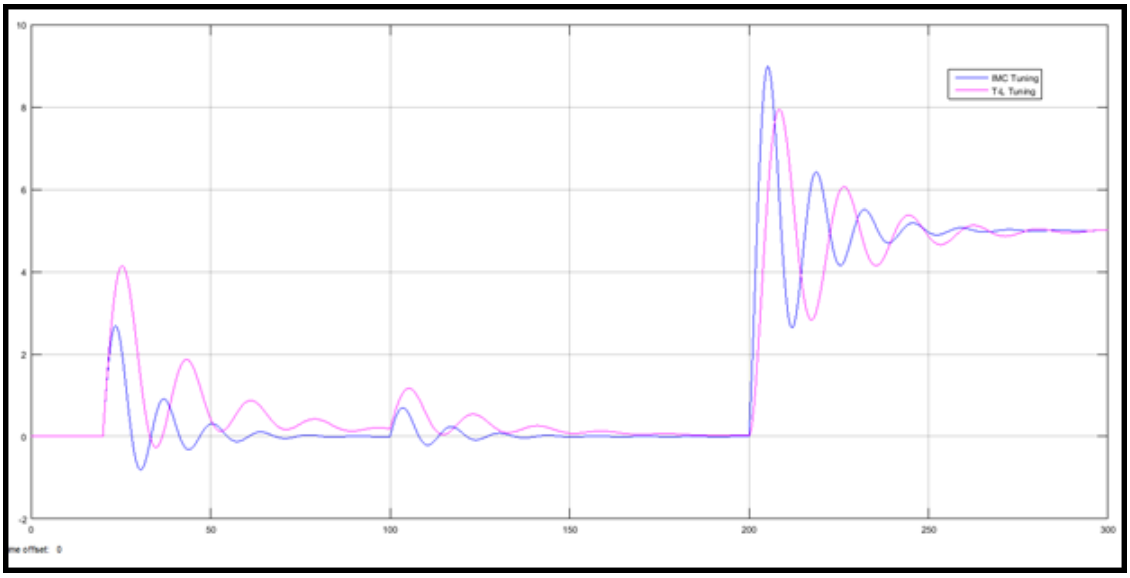

Figure 5: System Response for Step Test

7 Conclusion and Future Work

We have conducted simulation of manufacturing process of Aspirin in Aspen. While simulation of flowsheet, we encountered a few difficulties for simulating the recycle of unreacted Salicylic Acid and Acetyl Anhydride. Thus, we decided to perform the optimization procedure twice, first based on Aspen Simulated flowsheet and second the actual manufacturing process.[10] Both the results of optimization are comparable, considering the

fact that we haven't included the recycle in Aspen Simulation. In optimization based on Aspen simulation, we got conversion of around 0.9 which is lower than calculated conversion due to the fact that recycle is not included. For the system wide optimization, conversion results about 0.948. In both cases profit is around $160,000.

We also implemented temperature control over Batch reactor. T-L tuning method has a better performance towards set-point change, however, disturbance of feed temperature and concentration are the main factors for system stability. Considering this, IMC tuning is suggested to be adopted due to its quicker and more stable control performance.

For future work, we would like to have deeper understanding in terms of simulation using Aspen and have the entire flowsheet simulated. Besides this, we would like to implement more control aspects in the process to make it more realistic.

8 Appendix

	Units	ACETANHY	ASP	ASP-CRST	CP	FEED2	KETENE	MTHR-LQR
From			WASHR	CNTRFGE	CRYSTLZR	MIXER1		CNTRFGE
To		MIXER1		WASHR	CNTRFGE	MIXER2	MIXER3	MIXER3
Substream: MIXED								
Phase:		Liquid	All	All	All	Liquid	Vapor	All
Component Mole Flow								
SALIC-AC	MOL/HR	0.0	0.0	0.1	58.6	0.0	0.0	58.5
ACETI-AN	MOL/HR	1496.7	0.0	0.4	428.5	1496.7	0.0	428.1
ACETI-AC	MOL/HR	0.0	0.0	1.1	1068.2	0.0	0.0	1067.1
ASP-L	MOL/HR	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOLUENE	MOL/HR	0.0	0.0	1.5	1466.2	1466.2	0.0	1464.8
WATER	GM/CC	0.0	92.8	0.0	0.0	0.0	0.0	0.0
KETENE	MOL/HR	0.0	0.0	0.0	0.0	0.0	1000.0	0.0
ASP-S	MOL/HR	0.0	1067.1	1067.1	1068.2	0.0	0.0	1.1
Component Mole Fraction								
SALIC-AC		0.00	0.00	0.00	0.01	0.00	0.00	0.02
ACETI-AN		1.00	0.00	0.00	0.10	0.51	0.00	0.14
ACETI-AC		0.00	0.00	0.00	0.26	0.00	0.00	0.35
ASP-L		0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOLUENE		0.00	0.00	0.00	0.36	0.49	0.00	0.49
WATER		0.00	0.01	0.00	0.00	0.00	0.00	0.00
KETENE		0.00	0.00	0.00	0.00	0.00	1.00	0.00
ASP-S		0.00	0.99	1.00	0.26	0.00	0.00	0.00
Mole Flow	MOL/HR	1496.72	1077.75	1070.17	4089.78	2962.96	1000.00	3019.62
Temperature	C	29.00	24.96	25.00	25.00	28.89	25.00	25.00
Pressure	BAR	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Vapor Fraction		0.00	0.00	0.00	0.00	0.00	1.00	0.00
Liquid Fraction		1.00	0.01	0.00	0.74	1.00	0.00	1.00
Solid Fraction		0.00	0.99	1.00	0.26	0.00	0.00	0.00

Figure 6: Complete Stream Tables Part 1

	Units	R2F	R2P	RF	RP	RPTANK	SALYACID	TOLUENE	WASHWTR	WATER
From		MIXER3	REACTR2	MIXER2	REACTOR	TANK			WASHR	
To		REACTR2		REACTOR	TANK	CRYSTLZR	MIXER2	MIXER1		WASHR
Substream: MIXED										
Phase:		Mixed	All	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
Component Mole Flow										
SALIC-AC	MOL/HR	58.5	58.5	1126.8	58.6	58.6	1126.8	0.0	0.1	0.0
ACETI-AN	MOL/HR	428.1	1428.1	1496.7	428.5	428.5	0.0	0.0	0.4	0.0
ACETI-AC	MOL/HR	1067.1	67.1	0.0	1068.2	1068.2	0.0	0.0	1.1	0.0
ASP-L	MOL/HR	0.0	0.0	0.0	1068.2	1068.2	0.0	0.0	0.0	0.0
TOLUENE	MOL/HR	1464.8	1464.8	1466.2	1466.2	1466.2	0.0	1466.2	1.5	0.0
WATER	GM/CC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14476.8	14569.5
KETENE	MOL/HR	1000.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ASP-S	MOL/HR	1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Component Mole Fraction										
SALIC-AC		0.01	0.02	0.28	0.01	0.01	1.00	0.00	0.00	0.00
ACETI-AN		0.11	0.47	0.37	0.10	0.10	0.00	0.00	0.00	0.00
ACETI-AC		0.27	0.02	0.00	0.26	0.26	0.00	0.00	0.00	0.00
ASP-L		0.00	0.00	0.00	0.26	0.26	0.00	0.00	0.00	0.00
TOLUENE		0.36	0.49	0.36	0.36	0.36	0.00	1.00	0.00	0.00
WATER		0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
KETENE		0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ASP-S		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole Flow	MOL/HR	4019.62	3019.62	4089.78	4089.78	4089.78	1126.82	1466.24	1654.47	1662.05
Temperature	C	30.35	50.00	29.30	60.01	25.00	29.00	29.00	24.96	25.00
Pressure	BAR	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Vapor Fraction		0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liquid Fraction		0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Solid Fraction		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 7: Complete Stream Table Part 2

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