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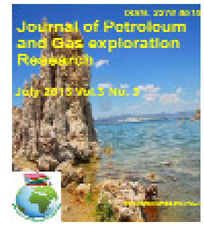

Review

Dynamic modelling and simulation of crude fractionation column with three side strippers using Aspen HYSYS Dynamics: A best practice for crude distillation column dynamic modelling

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Steady state and Dynamic simulations play a vital role in most of the Refineries and Petrochemical industries to evaluate and optimize key process variables. Apart from operation, simulation helps in design engineering in many ways. Simulation allows studying the transient behaviour of complex processes without the need of real plant operating information or even without a pilot plant. In this study, dynamic simulation is applied to atmospheric distillation unit (ADU) in a refinery. Crude oil refining process is one of the complex processes characterised by multiple interactions and high level of non-linearity. This paper describes the best practice for crude fractionation column dynamic modelling, starting from the given crude assay using Aspen HYSYS Dynamics. It includes crude assay characterization, steady state model development, transitioning from steady state model to dynamic model, designing a control strategy for plant disturbances and running the dynamic model.

Keywords: Crude oil characterization, atmospheric distillation unit, process modelling, dynamic simulation, control.

INTRODUCTION

Dynamic modelling of process simulations is vital to process plant design, operation and troubleshooting of existing plant facilities. Although there are many scenarios where steady state modelling alone is sufficient, however accuracy can be significantly improved by accounting for system's dynamic response to changes. Additionally, dynamic simulation is necessary to have an optimum plant design and better control strategy accounting for a variety of scenarios including,

- Plant startup and shutdown
- Plant upset and Pressure relief
- What-If study
- Process optimization

The Dynamic Simulation Software such as Aspen plus Dynamics, PRO/II DYNSIM and Aspen HYSYS Dynamics are some of the widely used applications in chemical and hydrocarbon industries for Dynamic Simulation. Among these Aspen HYSYS Dynamics (Version 7.3) has been chosen for this study. Aspen HYSYS Dynamics allows users to easily convert steady state Aspen HYSYS simulation into powerful dynamic models.

Crude Fractionation Column with three side stripper is widely used in most of the refinery units. The complexity of the process, high level of non-linearity, multiple interactions provides a challenge to develop a dynamic model. The study explained development of crude column dynamic model starting from crude oil characterization, followed by steady state modelling, transitioning steady state model to dynamic model building a control strategy and running a dynamic model.

Crude Oil Characterization

Analysis of True Boiling Point (TBP) data for the given crude oil is essentially the first step in crude oil characterization. Assay datasheet comprises of light ends

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Table 1. Selection of Property Method

Type of System	Recommended Property Method
TEG Dehydration	PR
Sour Water	Sour PR
Cryogenic Gas Processing	PR, PRSV
Air Separation	PR, PRSV
Atmospheric Crude Towers	PR, PR Options, GS
Vacuum Towers	PR, PR Options, GS (<10mm Hg), Braun K10, Esso K
Ethylene Towers	Lee Kesler Plocker
High H_2 Systems	PR, ZJ or GS
Reservoir Systems	PR, PR Options
Steam Systems	Steam Package, CS or GS
Hydrate Inhibition	PR
Chemical Systems	Activity Models, PRSV
HF Alkylation	PRSV, NRTL
TEG Dehydration with Aromatics	PR
HC Systems where H_2O solubility in HC is important	Kabadi Danner
Systems with select gases and light HC	MBWR

Table 2. Ranges for PR and SRK EOS

Method	Temp (^{o}C)	Pressure (kPa)
PR	> -271	< 100,000
SRK	> -143	< 35,000

composition, bulk properties and TBP data of crude oil. Pure component list for light ends given in assay datasheet has been created using Simulation Basis Manager (SBM) in HYSYS.

After adding pure components, selection of right thermodynamic property package is highly important to perform accurate Vapour-Liquid Equilibrium (VLE) calculations. For oil and gas and refining processes, the recommended thermodynamic property package is Peng-Robinson Equation of State (EOS). Peng-Robinson EOS is ideal for VLE calculations and property prediction for both vapour and liquid phases in hydrocarbon systems. Several enhanced forms of Peng-Robinson models are available to extend its range of applicability and to improve its predictions for some non-ideal systems. However, in situations where highly non-ideal systems are encountered, the use of Activity Models rather than EOS is recommended for better simulation model. EOS can be used primarily for non-polar or slightly polar components.

Table 1 lists some typical systems and suitable correlations as a ready reckoner for property package selection as recommended by Aspen HYSYS.

The Peng-Robinson EOS is enhanced to yield accurate phase equilibrium calculations for systems ranging from low temperature cryogenic systems to high temperature, high pressure reservoir systems. The temperature and pressure ranges for PR and SRK EOS are shown in Table 2.

The same EOS satisfactorily predicts component distribution for heavy oil, aqueous glycol and CH_3OH systems. For this study, PR EOS has been used as the thermodynamic property package.

Oil Manager vs. RefSYS Assay Manager

The petroleum assay is a vector that stores physical properties and assay properties for specific components. Physical properties include all properties used in a typical HYSYS simulation case. Assay properties comprise refinery related properties such as cloud point, octane numbers, flash point, freeze point, sulphur content, PONA distribution, GC data etc. Aspen HYSYS has two options for creation of petroleum assay, i.e. Oil manager and RefSYS assay manager. Oil manager is used when TBP data is available whereas RefSYS assay manager is used when PONA (Paraffins, Olefins, Naphthenes and Aromatics) Distribution or macro cut (Gas Chromatography) data of crude is available. The differences between the petroleum assays

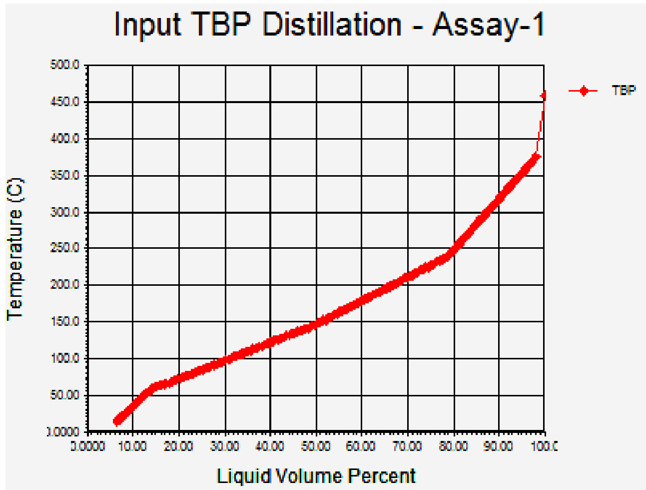

Figure 1. TBP Curve for Crude Assay

Table 3. Oil Manager vs. RefSYS Manager

Oil Manager	RefSYS Assay Manager
Simplified options to characterize petroleum assay.	Advanced options to characterize petroleum assay.
Each installed blend has its own component list.	One component list is shared among multiple assays.
Property values are not calculated based on blending rules, because each assay has its own component list.	Contains blending rule equations for more accurate calculation.
Only few petroleum properties can be modified.	More petroleum properties can be modified.
The normal boiling point of hypothetical components is the centroid (average) boiling points.	The normal boiling point of hypothetical components is the final boiling point.

Table 4. Product cut distribution

Product	Cut Point (°C)	Mass Fraction
LPG	IBP - 150	0.47
Kerosene	150 - 270	0.34
Light Gas Oil	270 – 380	0.16
Heavy Gas Oil	380 - FBP	0.03

created in Oil Manager and Petroleum Assay Manager are listed in Table 3.

Aspen HYSYS has the flexibility to convert oil manager assay to RefSYS assay for advanced characterization of crude. The interesting factor on crude oil characterization is its ability to give fractions of each cut specifications which can help us on column convergence in an initial stage as shown in Table 4 and Figure 2.

Using install oil option through oil manager, the stream data has been placed on flow sheet window for this model development.

Steady State Model Development

The steady state model will provide the complete material and energy balance across the flow scheme. Also the model could be used to derive the properties and compositions of all product and intermittent streams. After filling the essential data in the basis environment (component and property package) the flow scheme has been developed in the simulation environment as shown in the Figure 3. The steady state model shall be converged to an optimum solution (mass and energy

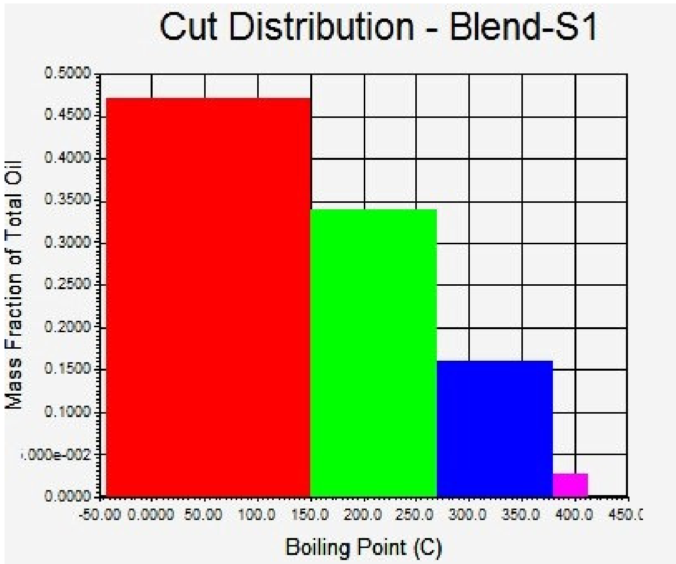

Figure 2. Product Cut Distribution for Crude Assay

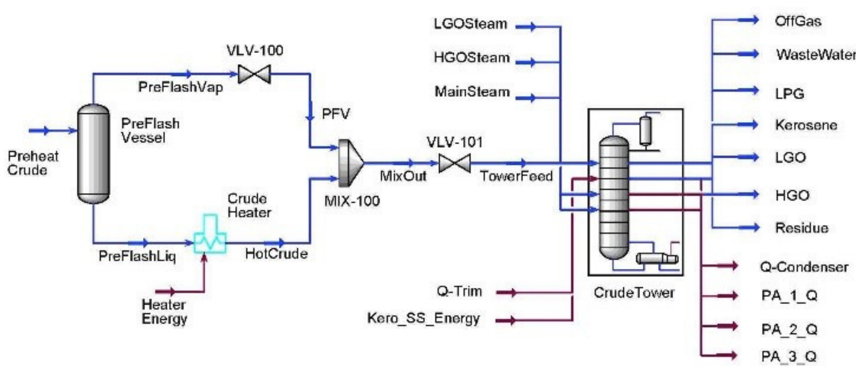

Figure 3. Steady state model of Crude Fractionation Column converged into a solution

Table 5. Crude Column Profile

Column	No. of Stages
Main Tower (Top Down)	29
Kerosene Stripper	3
LGO Stripper	3
HGO Stripper	3
Main Tower	
Top Stage Pressure (Barg)	0.35
Bottom Stage Pressure (Barg)	1.25
Top Stage Temperature (^{o}C)	150
Bottom Stage Temperature(^{o}C)	350
Feed Tray Location	28
Feed Temp (^{o}C)	335
Feed Rate (TPH)	730

balance) before switching to dynamic model. Crude column profile is given in Table 5.

In steady state model development the challenging task is the crude column convergence. Unlike absorbers and

Table 6. Degrees of Freedom specifications

Specifications	
Off Gas Rate (TPH)	5
LPG Rate (TPH)	325
Kerosene Rate (TPH)	270
LGO Rate (TPH)	110
HGO Rate (TPH)	20
Pump Around-1 Rate (TPH)	700
Pump Around-2 Rate (TPH)	700
Pump Around-3 Rate (TPH)	700
Pump Around-1 ΔT (^oC)	60
Pump Around-2 ΔT (^oC)	60
Pump Around-3 ΔT (^oC)	60
Gap Cut Point (^oC)	25
Kero SS Reb Duty (MJ/Hr.)	60,000

strippers, crude distillation columns are characterized by multiple interactions and high level of non-linearity due to complexity of process.

The total degrees of freedom to converge a typical crude column with three side stripper are 13. Closest assumptions of thirteen relevant variables have been specified which will lead to easy convergence. Specifications used to converge the column are given in Table 6.

Upon convergence of the crude column model, process parameters have been further fine-tuned to meet the product specs.

Transitioning To Dynamic Model

Aspen HYSYS allows transitioning a steady state model to dynamic model with the help of dynamic assistant. The dynamic assistant allows analysing what adjustments need to be made in the model to simulate dynamically and suggests suitable changes. Dynamic assistant can be used as a preliminary guide and best possible models could be built by good engineering practices.

Transitioning to dynamic state comprises of the following tasks.

- Specifying pressure and flow relations
- Boundary stream pressure / flow specifications
- Specifying the equipment sizes and geometry
- Designing a control strategy

In HYSYS Dynamics, pressure and flow are related such that one cannot be calculated without the other, i.e. specifying a zero pressure drop across a resistance unit in Dynamics, the flow rate through that unit will be zero. In dynamic simulation all unit operations are classified as either pressure node operations or resistance equation operations. A pressure node operation calculates pressure drop based on vapour hold up in the unit (vessels, etc.) A resistance equation operation calculates pressure drop based on a resistance equation (pumps, compressors, valves, etc.).

In the Process Flow Diagram (PFD), there should be at least one resistance operation in between two adjacent pressure nodes. Else, the solver may assume that the pressures in the adjacent vessels are equal and eventually no flow between them. This modification is essential to run a model in Dynamic mode.

All boundary streams connected to a resistance operation shall have a pressure or flow (P/F) specification. Internal streams should not have P/F specs, since it will be determined by dynamic solver in line with pressure / flow relations. Adding a valve to all boundary streams is a best practice, since these could be used as flow / pressure controllers at later stages while developing a control scheme.

The equipment sizes and geometry are important to simulate the model in dynamic mode. The equipment performance, response to fluctuations in feed is highly dependent on the size of the equipment and also relative to the magnitude of the disturbance. If equipment is inappropriately oversized, the simulation will turn out with unrealistically dampened response and on the other side the response will be surging if the equipment is undersized.

In absence of equipment sizes and geometry, the sizing utility available in HYSYS could be used to calculate and specify the required data as part of the dynamic model.

For a distillation column the following information are required.

- Condenser volume
- Reboiler volume
- Column Tray / Packing Section dimensions and geometry

Table 7. Recommended Vessel sizing

Service	Residence Time
Liquid phase hold-ups	10 minutes
Vapour phase hold-ups	2 minutes

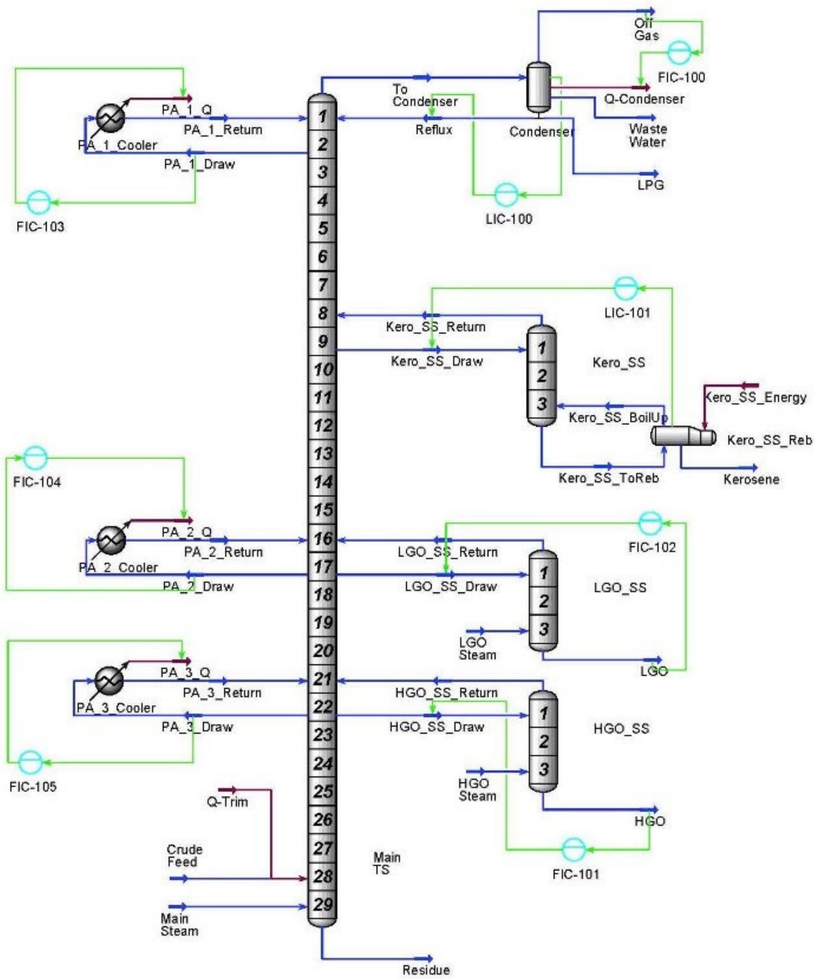

Figure 4. Crude Fractionation Column with three side strippers incorporated by control scheme

Recommended sizing parameters for vessels based on residence time are given in table 7. In Dynamics, the column pressure profile is calculated by the hydraulic calculations on each stage based on tray / packing geometry and vapour / liquid loading on the corresponding stage. If the steady state pressure profile (e.g. Pressure drop across the column) doesn't match the dynamic pressure profile, the column stage pressures and flow rates will keep oscillating until an equilibrium pressure profile is established. Sometimes the column could even become unstable. To overcome this issue, it is preferable to enter a column pressure profile and sizing geometry based on actual hydraulic calculations before switching to dynamic mode.

Distillation column sizing (hydraulics) can be done by using either the Tray Sizing utility in HYSYS or any other vendor applications such as KG-Tower from KOCH-GLITCH for high accuracy.

A process plant should be safe and continuously available to meet the design intent, for which a better control scheme is very much required.

Designing a control strategy is a vital step in developing dynamic model. With good control scheme, process can cope up with any sort of disturbances in the process parameters. If unmitigated, even small fluctuations can throw the entire system out of control. As such, a suitable control scheme has been implemented in the model as shown in the Figure 4 before starting simulation in dynamic mode.

Table 8. Recommended Controller Tuning Values

System	K_c	τ_i(mins.)	τ_d(mins.)
Flow	0.1	0.2	0
Level	2	10	0
Pressure	2	2	0
Temperature	1	20	0

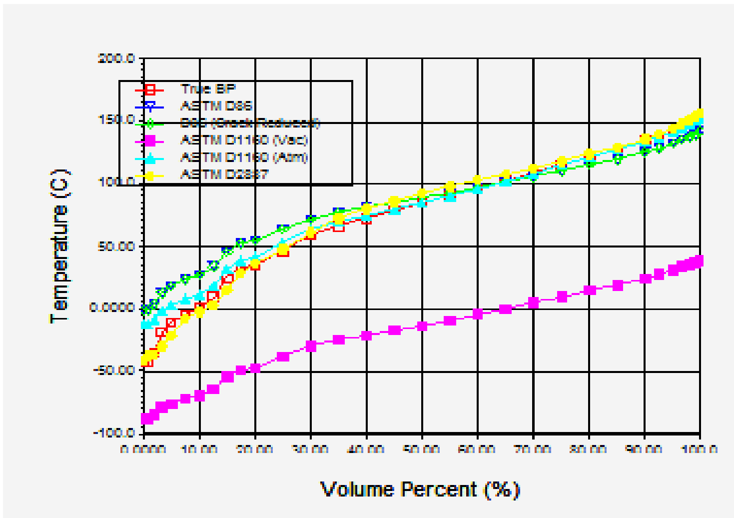

Figure5. Boiling Point Curves for LPG

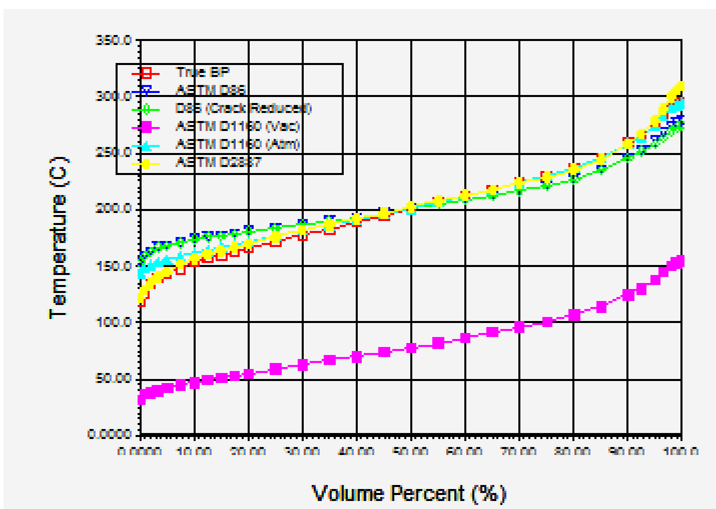

Figure 6. Boiling Point Curves for Kerosene

For most control schemes, proportional-integral-derivative (PID) controllers are used and the basic equation of PID controllers is given as,

$$OP(t) = K_c E(t) + \frac{K_c}{\tau_i} \int E(t)\,dt + K_c \tau_d \frac{dE(t)}{dt}$$

OP (t) is the controller output as a function of time and E(t) is the error between the set point and process variable. The controller can be tuned by adjusting the controller gain (K_c), the integral reset (τ_i), and the derivative gain (τ_d). The recommended initial controller tuning parameters for simulation are shown in Table 8.

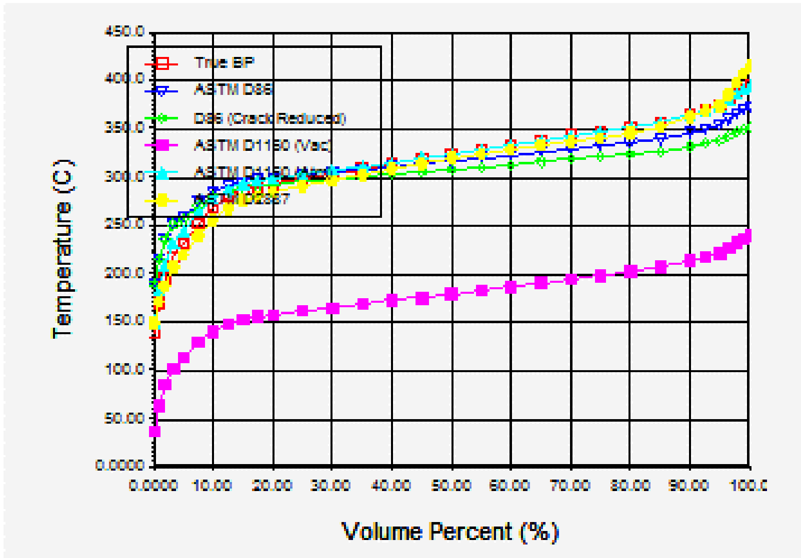

Figure7. Boiling Point Curves for Light Gas Oil

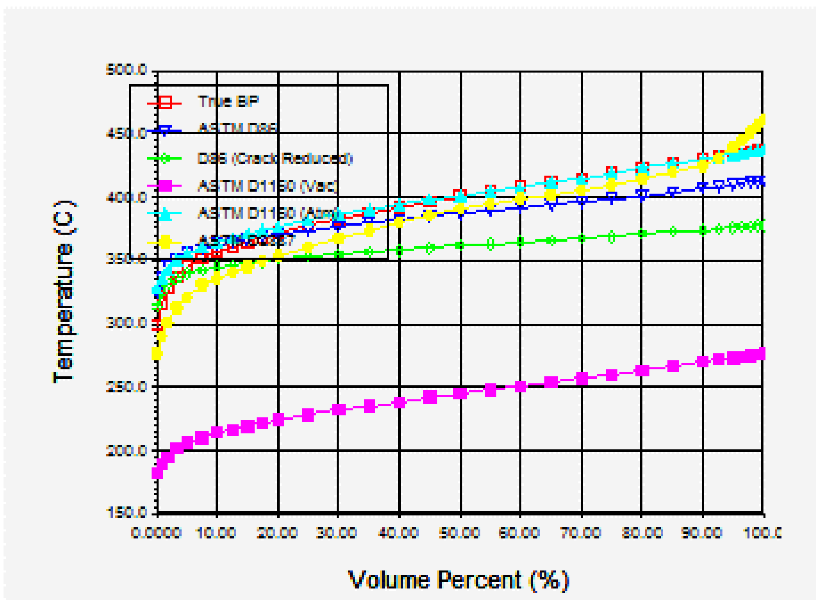

Figure 8. Boiling Point Curves for Heavy Gas Oil

In this dynamic study of crude column, the above tuning parameters have been used. An Aspen HYSYS Strip chart to graphically observe the dynamic fluctuations of model has been used with a greater interest to study the dynamic behaviour (graphical observation of dynamic model) of the crude column model. Also other dynamic tools such as Transfer functions to observe how a simulation responds to disturbances and Event scheduler to enable automatic event scheduling are available in Aspen HYSYS.

RESULTS

Resulting outcome from crude fractionation column product cuts have been confirmed by boiling point curves and shown in Figures 5 to 8.

The model has been successfully simulated in dynamic mode and control scheme has been tested. The behaviour of the model during start-up and gradual stabilization towards the desired product rates has been graphically shown in Figure 9.

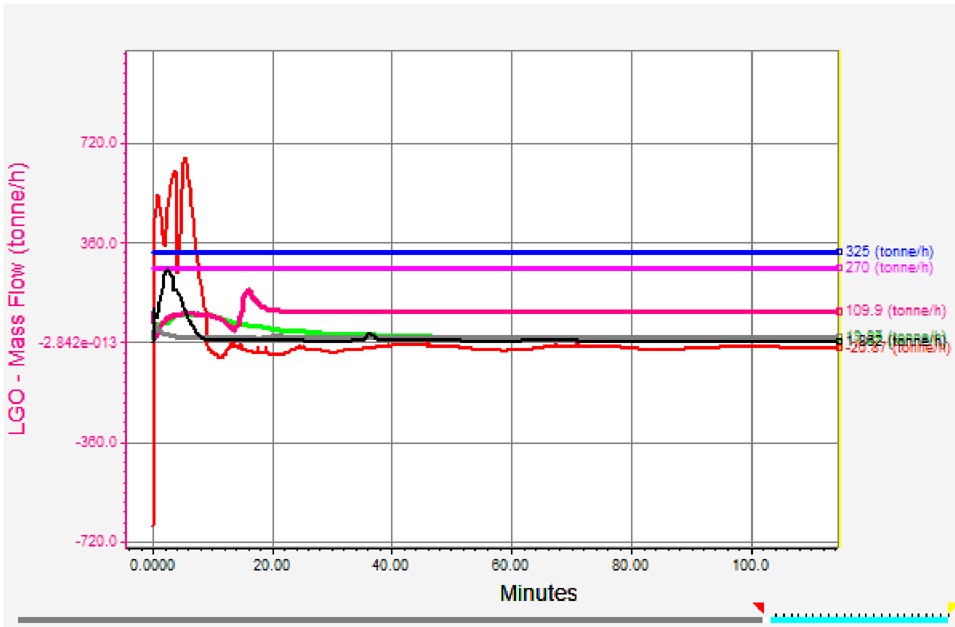

Figure 9. Dynamic Column Start-up Disturbance

CONCLUSION

Crude fractionation column with three side strippers unit has been modelled and dynamically simulated. The product cuts obtained were within the desired range and expected product specifications also attained. Crude assay has been used directly in oil manager instead of component generation saves time and accuracy. The result of the work indicates that a multivariable chemical process such as a fractionation column operation establishes a clear nonlinear behaviour and can be modelled, dynamically simulated to observe thousands of process variations. Best practice for crude fractionation column dynamic modelling has been identified.

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