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Dynamic Simulation and Control: Application to Atmospheric Distillation Unit of Crude Oil Refinery

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Abstract

Nowadays dynamic simulation has become a key tool in the study of the behaviour of almost every process. The benefits that proper modelling can bring to any industry have a very high value, especially one that cannot be directly measured, which is the increase of knowledge about the process. The simulation allows the study of transient states of complex processes without the need of leading the real processes into those operating states. In this work, dynamic simulation is applied to the Atmospheric Distillation Unit of a crude oil refinery. This unit represents the core of almost all such refineries and it is also one of the most complex processes, characterised by multiple interactions and high level of non-linearities. The model conjugated with a control system is analysed for several process operating conditions, showing in particular how the behaviour of the unit, under severe circumstances, can be studied.

Keywords: atmospheric distillation, process modelling, dynamic simulation, control.

1. Introduction

The models for chemical processes are generally developed for steady-state and/or dynamic modes. The first group has been widely developed and used, not only in 'in-house' applications, but also, during and after the 1980s, through commercial simulators. The increase of computational power observed along the nineties, paved the way for the emergence of more and more engineering solutions based on complex models (Ponton, 1995), including the use of commercial dynamic simulators, embedding dynamic models with sufficient complexity for application at industrial level (Luyben, 2006a).

Both types of models have their specific use and domain of applications.

Steady-state models can generally perform steady-state energy and material balances and evaluate different plant scenarios, which is very useful at project stage. These models are also used for optimizing capital and equipment costs to obtain best profits. However, since chemical plants do not operate in truly steady-state, they are of limited usefulness in studying routine operation. It is very important to know, understand and simulate the plant dynamics (AspenTech, 2008a).

Thus, dynamic modelling has been receiving increased attention over the recent years and has now become a powerful tool, allowing users to obtain a better understanding and operational capability of their processes.

Safety evaluations, transitions between operating conditions, start-up/shutdown conditions and optimization of controllers' parameters are some examples that could not be achieved easily with steady-state simulators (AspenTech, 2008a).

Although modelling, as mentioned before, can be rather complex, the main end result is both a deeper and faster acquisition of knowledge concerning the plants' behaviour, by reducing the need of plant experimentations that take days or months, and an improved control of plant operability and profitability (Madhusudana Rao et al., 2004; Pannocchia et al., 2006).

2. Case Study: Atmospheric Crude Distillation Unit

The case study considered here is the complex process corresponding to atmospheric distillation unit of crude oil refinery. This unit is the central and the most important unit of all crude oil refineries. Therefore, the detailed knowledge of the processes involved is fundamental to evaluate the operational/economic performances of the total oil refinery.
The operation aims at the production of naphtha, kerosene, diesel and residue through a physical distillation of crude.
The plant flow diagrams are represented in Fig. 1 and 2, respectively.
Essentially, crude oil is heated in a heat train and a furnace to elevate temperatures (from 20 ºC to about 350 ºC), simulated here by a heat exchanger (H-101) and then subjected to distillation under atmospheric pressure separating the various fractions according to their boiling range. This distillation is carried out in the main distillation column (T-101) associated with two side-strippers (T-102 and T-103) and three pump-arounds.
The final products' qualities are evaluated through the ASTM D86 distillation curves for naphtha, kerosene and diesel. The most important points of these curves, which define the separation between products, are the 95% ASTM D86. These correspond to temperatures where 95% of the products are vaporized under the specific conditions of this laboratory quantification method.

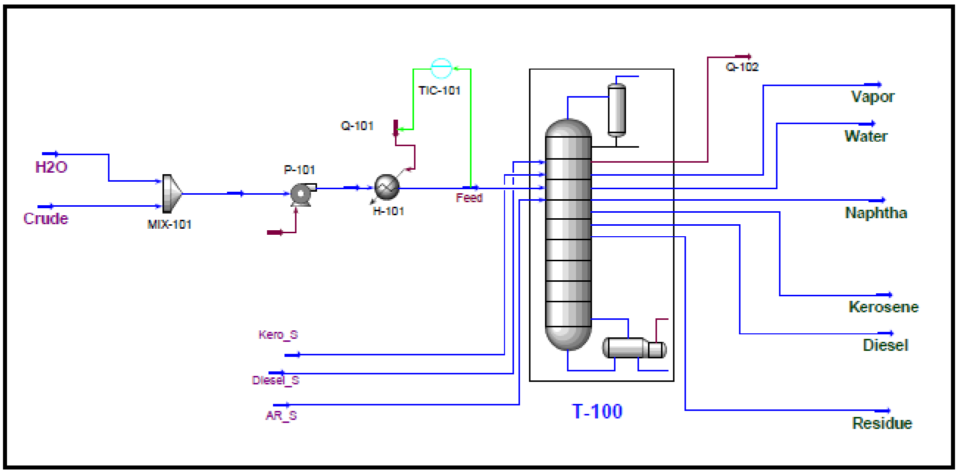


Fig. 1. Scheme of the crude distillation unit

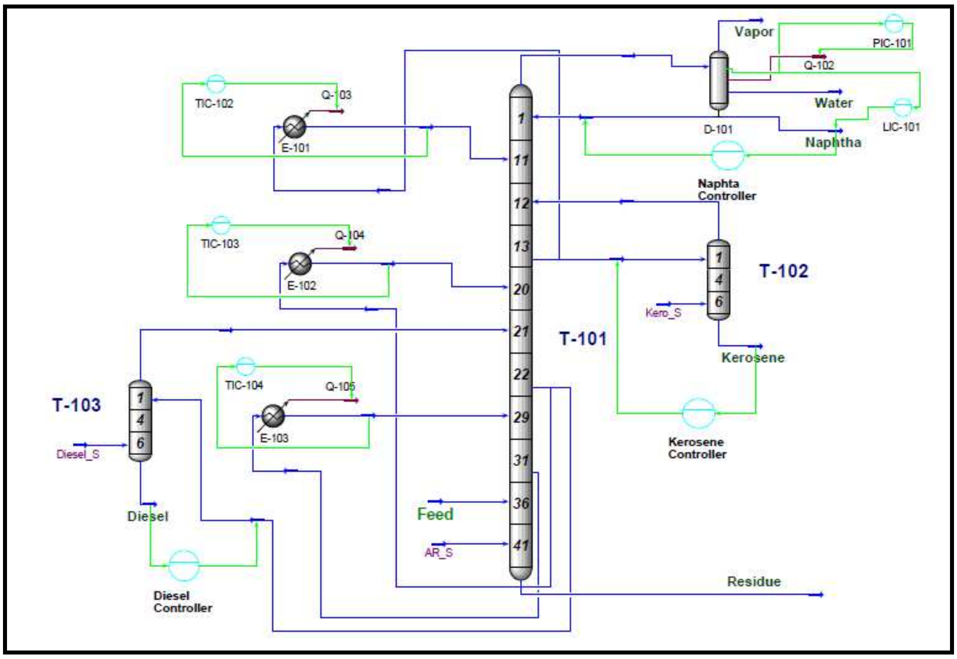


Fig. 2. Details inside the T-100

This is a highly non-linear system, with multiple interactions. The use of dynamic simulation is required for evaluation of the performance of such type of units (Luyben, 2006b; Mahdipoor et al., 2007).

For the present application the dynamic model was developed using the Aspen HYSYS process simulator, integrating the process dynamics and the control scheme designed and implemented for the present work. This control scheme incorporates: i) quality properties of the products (naphtha, kerosene and diesel), ii) temperature control (furnace and pump-arounds), iii) pressure control (condenser) and iv) level control (condenser). The controllers implemented are the velocity forms of PID control algorithms.

The plant flow diagrams detailed above were represented inside the simulator.

The main process conditions are presented in Table 1 and the True Boiling Point (TBP) curve of the crude, that characterizes the feed, is shown in Fig. 3.

Table 1. Main process conditions

Column plates	
Main column	41 stages
Kerosene side stripper	6 stages
Diesel side stripper	6 stages
Top pressure	1.85 bar
Feed	
Mass Flow	375 tonne/h
Temperature	350 ºC
Vapour phase fraction	0.91
Feed stage	36

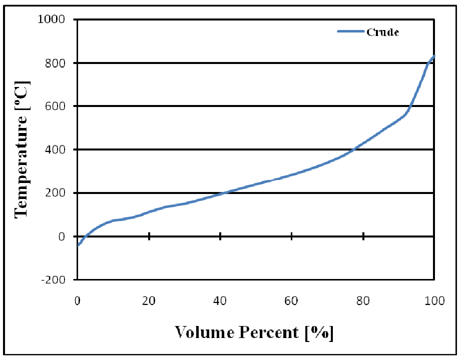


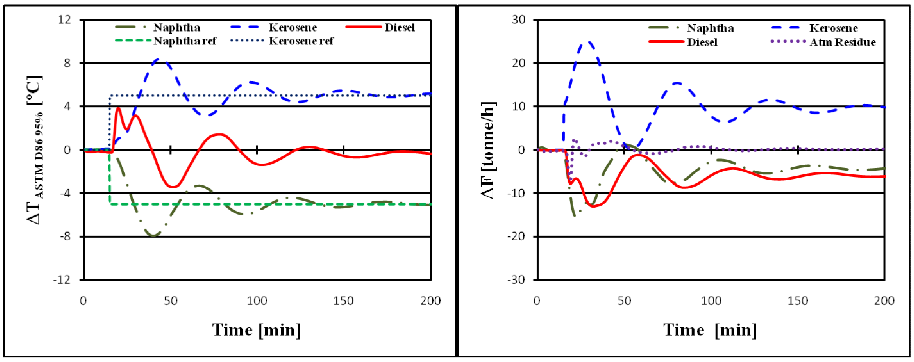
Fig. 3. Crude TBP curve

The models developed allow the evaluation of the transient behaviour of the unit for different operational situations.
In this paper the following cases were analyzed:

1. Changes in products' qualities:
   Step changes in the products' specification (Cut ASTM D86 95%) were performed corresponding to a reduction of 5ºC in the Naphtha set point and an increase of 5ºC in the Kerosene set point. The set point of Diesel was not changed;
2. Change in topping pressure:
   A sudden reduction of 0.3 bar in the topping pressure of T-101 was also analysed, without any changes in the original products' specifications;
3. Change in the feed temperature:
   A reduction of 10 ºC in the feed temperature of the main column T-101 was performed without changes in either the original products' specifications or topping pressure.

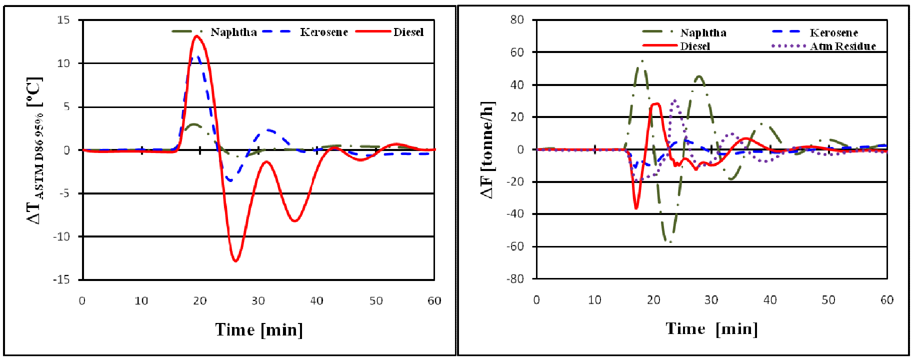
3. Results

In all cases, changes were performed after 15 minutes of steady operation and the simulations were allowed to run until new steady-state conditions were reached.
Fig. 4 (a) shows the unit response for Case 1, where changes in products' qualities are enforced. The figure illustrates how through the implemented control system it is possible to move the unit from one condition to a new one in a smooth way, satisfying completely the new requirements. Fig. 4 (b) presents further dynamical changes, showing the expected decrease in the amount of naphtha and diesel produced and the related increase of the kerosene mass flow.
Figs. 5 (a) and (b) show the system responses to re-establish the original conditions for the case of the modification of the topping pressure (Case 2). As it can be seen, Fig. 5 (a), this change has more impact in quality of diesel during the transient period. This is because this section is highly affected not only by the pressure change, but also by the interactions with the upper systems (naphtha and kerosene control).
In the case of the mass flows, Fig 5 (b) shows that there are not significant changes in the new steady-state condition, though it is known that a decrease in the pressure promotes the separation process, increasing the distillate streams. This is explained by the fact that in this application the crude fed to this unit is light and it is known that for this type of feed the topping pressure has no major effects in the final conditions.



(a) (b)

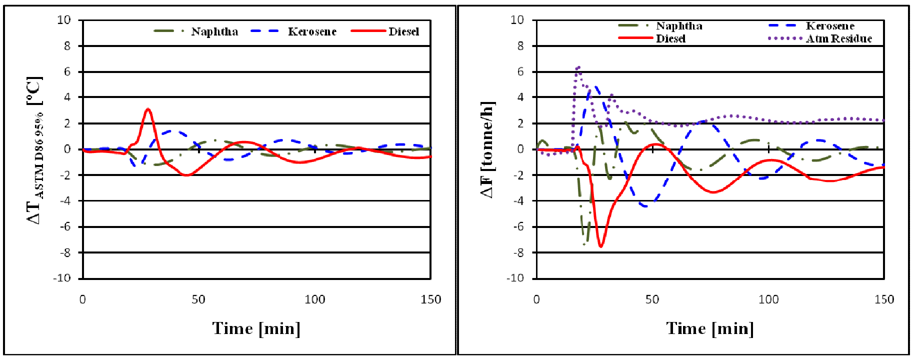
Fig. 4. Step responses for quality specifications: (a) changes in set-points - ASTM D86 95%; (b) production flow changes.



(a) (b)

Fig. 5. Step responses for topping pressure: (a) changes in ASTM D86 95%; (b) production flow changes.

Finally, the system behaviour for changes (reduction) in the feed temperature was also tested (Case 3). Results presented in Figs. 6 (a) and (b) illustrate the performance of the control scheme implemented to this type of disturbance. Fig. 6 (a) shows that the influence of this step change in quality properties of the products is slight. Looking to the mass flows, Fig. 6 (b), an increase of the residue and small decreases of the other three streams are observed. It should be pointed out that these are expected responses to the processing of light crudes, where a reduction in the feed temperature decreases the vapour fraction, implying an increase of the amount of residue.



(a) (b)

Fig. 6. Step response for feed temperature: (a) changes in ASTM D86 95%; (b) production flow changes.

4. Conclusions

This work concerned the application of Aspen HYSYS for the analysis of the operation of an Atmospheric Distillation Unit of a crude oil refinery. The dynamic model developed was successfully combined with a suitable control configuration, allowing in this way to study in detail the transient behaviour for new stationary levels of operation when subject to significant changes in operating conditions or requirements.

It has been shown that this is a powerful tool for studying complex unit behaviour and as such it serves well the purpose of improving routine operation in industrial units.

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