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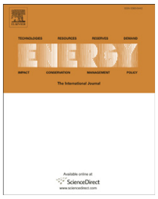

The use of reduced models for design and optimisation of heat-integrated crude oil distillation systems

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ABSTRACT

The importance of exploiting degrees of freedom within a crude oil distillation process for improving energy performance has been a feature of process integration from the earliest days. Combining process changes with changes to the heat recovery system leads to far better results, compared with changes to the heat recovery system alone. However, in order to obtain the best results, the distillation process and heat exchanger network need to be optimised simultaneously. Whilst in principle this is straightforward, there are many difficulties. Methods for the optimisation of heat exchanger networks are well developed. In these methods, heat exchanger network models are based on network details, such as stream connections between heat exchangers, heat transfer area of individual units, etc. The consideration of these network details is important to design and optimise crude oil distillation systems. On the other hand, the distillation process model to be coupled with the heat exchanger network model needs to be simple and robust enough to be included in an optimisation framework. If distillation models and heat recovery models can be combined effectively, then there are not just opportunities for design and retrofit, but also for operational optimisation. One of the big challenges to progress the application of this approach is the effective generation of reduced distillation models. Short-cut distillation models can be used, but many other options are available, such as the use of artificial neural networks. This paper reviews various crude oil distillation modelling approaches and highlights the areas of application of these different approaches. An example illustrates the computational performance of reduced and rigorous crude oil distillation models.

1. Introduction

Crude oil distillation is an energy-demanding process. In a refinery, the energy consumption from the atmospheric and vacuum distillation units represents approximately 35–45% of the total energy requirements [33]. Heat integration is applied as a tool to increase the energy-efficiency of these units, thus reducing pollutant emissions and operating costs.

Since the early development of thermodynamic approaches to process integration, there has been huge progress in the development of approaches based on optimisation. These optimisation-based methodologies have been applied to design new processes (i.e. grassroots design), modify existing process configurations (i.e. retrofit design) and improve processes by considering only variables that can be manipulated during operation (i.e. operational optimisation). In order to obtain the best results from the optimisation of heat-integrated crude oil distillation processes, degrees of freedom within the distillation process need to be optimised simultaneously with the heat exchanger network. The simultaneous consideration of the distillation process and heat recovery network allows interactions within this ‘system’ to be exploited, thus allowing more design options to be evaluated. Crude oil distillation systems typically consist of a preheat train, a preflash unit, an atmospheric distillation unit (configured as a distillation column with side coolers and strippers) and a vacuum distillation unit. These heat-integrated crude oil distillation systems are complex configurations with strong interactions between their components. Thus, representing and optimising the performance of the distillation process and heat exchanger network is not a simple task.

Models are needed that allow the designer to simulate, visualise and gain intuition about the distillation system. However, models are never a complete representation of reality, as there

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will always be factors (i.e. variables and phenomena) that cannot be included in the model equations. A model must include at least the most influential factors when fullfilling the purpose for which the model was initially considered. If the purpose of the model is clearly defined, the characteristics of the model can be identified (e.g. degrees of freedom, information that the model needs to provide, type of equations, model generation process, etc.).

A number of approaches have been developed to obtain models that represent the separation and energy performance of distillation processes. These approaches can be grouped into three main categories: rigorous models, semi-rigorous or simplified models, and statistical models. The selection of which model is most suitable for a certain application (e.g. design, retrofit, process control) depends on such issues as the amount of information that needs to be provided by the model, the difficulty of generating, implementing and validating the model, and whether the model is to be used to modify the process as well as the heat recovery system. In an optimisation scheme, it is crucial to use models that, in addition to accurately representing the distillation system, can be stable and perform calculations in a short period of time.

The objective of this manuscript is to critically review and illustrate the use of reduced models (i.e. simplified and statistical models) in the optimisation of heat-integrated crude oil distillation systems. A brief discussion about the main features of reduced models has been presented by Smith et al. [31]. However, this manuscript provides a more detailed analysis of these features in the context of crude oil distillation. The benefits and disadvantages of each type of model will be discussed, and the suitability of such models for different optimisation purposes will be reviewed. An example is used at the end of this manuscript to illustrate the computational performance of reduced and rigorous crude oil distillation models. The resulting distillation models are compared in terms of accuracy, simulation time and robustness.

2. Classes of models

2.1. Rigorous models

Rigorous models are generally considered acceptable for distillation process simulation. Rigorous distillation models are deterministic models used to calculate temperatures, stream flow rates, compositions, pressures and heat transfer on each stage of the distillation column. The models incorporate material and energy balances, and equilibrium relations for each stage [29].

Rigorous models provide accurate stage-by-stage information. This feature makes rigorous models an essential tool to design distillation columns. For instance, it is recommended to use rigorous models in the final steps of column design to corroborate and validate results that may have been obtained with other types of distillation models. Simulations with rigorous models are also used to monitor the real-time operation of distillation columns, for which the scope is to identify potential problems during operation.

Much information is generated, facilitating the evaluation of the distillation performance. However, the detail also creates problems when used in optimisation. In a column with C components and N stages, the total number of equations to solve is $2NC + 3N$ [29]. Many of the equations are highly non-linear and implementation can be problematic. Especially when used in optimisation, the system of non-linear equations becomes sensitive to initial guesses. Depending on the process, convergence of the model equations can be slow. However, when used in optimisation, perhaps the greatest problem is that the models are generally not robust to significant changes, relative to the base case. Frequent failure of simulation during the course of an optimisation causes problems for the optimisation. Nevertheless, rigorous models remain key in many applications for corroborating other models, such as simplified or statistical models.

Despite the limitations of rigorous distillation models mentioned above, several researchers have employed these models for design and optimisation of crude oil distillation units. Liebmann et al. [19] proposed an iterative procedure for grassroots and retrofit design. In their work, the complex crude oil distillation column is decomposed into a sequence of simple columns. Fig. 1 illustrates the decomposition of an atmospheric distillation column. The sequence of simple columns is then simulated using rigorous models. In the design procedure of Liebmann et al. [19], Pinch Analysis (applying the Grand Composite Curve) is used to identify modifications to the system that reduce energy consumption. For example, replacing steam stripping with reboiling, or introducing thermal coupling. After all modifications are performed, the sequence of simple columns is merged to obtain the complex column configuration.

Seo et al. [30] used rigorous models to reduce energy costs of an existing crude oil distillation unit. Bagajewicz and coworkers proposed a strategy for grassroots design of atmospheric [3,4] and

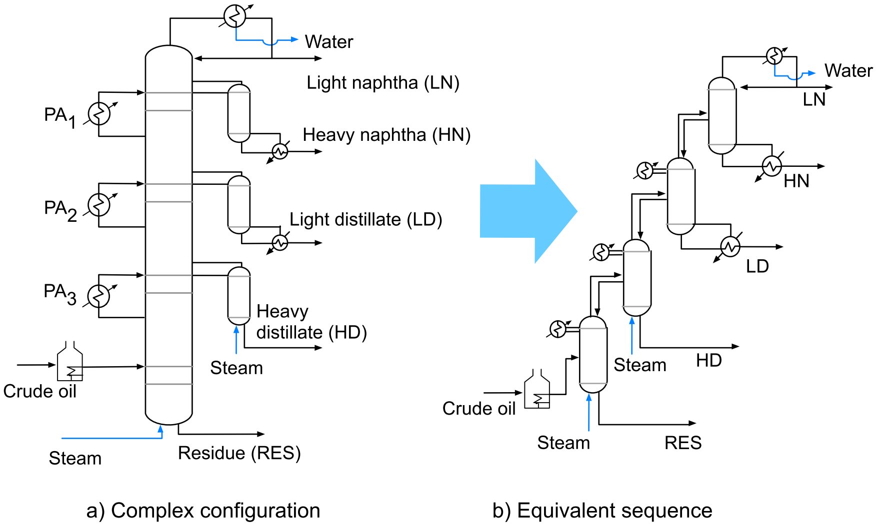

Fig. 1. Atmospheric distillation column, illustrating the equivalent sequence of simple columns [18].

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