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Interface level regulation in an oil sands separation cell using model-based predictive control

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ABSTRACT

Large-scale separation cells, used in primary extraction in the oil sands industry, are integral parts of the overall process of bitumen extraction. Good regulation of the interface level between the bitumen froth and the middlings in these cells can result in a significant improvement in bitumen recovery and throughput and heavily influence process economics. This paper details a case study application of identification and design of a model based predictive controller for the separation cell process. Internal model control (IMC) and model predictive control (MPC) schemes using linear models are designed and implemented in real time on the industrial separation cell. The industrial implementation result shows that both IMC and MPC schemes provide significant benefits over the current operations which use a PID controller. The benefits include significant reduction in the variance of the interface level and underflow pump movement, resulting in higher bitumen recovery, smoother operations downstream and pump energy savings.

1. Introduction

Oil sands mainly contain mineral solids (silica sands and clays), water, and bitumen, a highly viscous petroleum-like hydrocarbon. The Athabasca oil sands reserves in Northern Alberta, Canada, have one of the largest deposits of oil in the world next to Saudi Arabia and Venezuela (Alberta Energy, 2011).

A majority of the oil sands industries that use surface mining to prepare the feed use hot water based extraction to extract bitumen from the oil sands. One of the earliest papers in this regard was Clark (1944). The economic benefits from the extraction of oil from oil sand deposits in Alberta are huge (Dougan and McDowell, 1997) and with such huge quantities of material being processed in an oil sands extraction operation, even a small improvement in process efficiency and operation can greatly influence bitumen recovery, reduce environmental impact and influence process economics. The extraction process is the next step after mining and most of the variability in the oil sands feed is channeled to the extraction process. There is tremendous scope for improvement in the way advanced process control is used in oil sands processing; and the extraction process is an ideal candidate for the application of dynamic model based control (Dougan and McDowell, 1997).

The extraction process consists of large gravity vessels known as primary separation vessels (PSV) or just separation cells (SepCell). Inside the cell three layers are formed due to density of the slurry mixture; the interface level between the top layer (bitumen froth) and the middle layer (middlings) is particularly important as it influences froth quality and process economics. More details on the entire process is explained in the beginning ofsection 2. In the oil sands industry, control of this interface at an optimum level to improve bitumen recovery is of particular interest to the operating engineers. However, interface level control in separation cells presents a lot of challenges for controller design. Modeling of these separation cells to control the interface level based on the physical laws is difficult not only because of the constantly changing nature of the oil sands entering the plant (disturbances in the feed quality and quantity), but also because of the lack of plant information due to lack of available measurement systems which can reliably track the various process and disturbance variables. In the last few years, reliable estimation of the interface level has been obtained from an image based soft sensor. Recent development in the area of soft sensors and their industrial implementation includes Jampana et al. (2010), Fortuna et al. (2006), Domlan et al. (2011). Using the image based soft sensor developed by Jampana et al. (2010), Jampana and Shah (2011), interface level estimation is currently available every second and may be used to design a suitable model based predictive control scheme.

The complex flow dynamics, because of the multi-phase flow inside the separation cell, presents a big challenge. Inside the SepCell, the interface dynamics are distributed in nature because of the presence of three layers. Modeling of the interface dynamics is non-trivial. The phenomenon is highly nonlinear and fundamental understanding of

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the interface level is a multidisciplinary area that overlaps with colloid science and surface chemistry, and requires understanding of the interfacial properties of oil/water and water/sand grain layers at the molecular level. In contrast to this, building a data based input–output model offers a relatively simple way to design a model based control scheme for such processes. The common practice in industry is the awareness that many of the industrial processes are nonlinear; however, locally linear models are often sufficient to approximate a process around single operating condition. Modeling the process using data based nonlinear models is an attractive option for this complex process but the idea is to simplify the control design and make it work in practice. Even though some of the measurements of flow and densities are available for mass balance calculations and validation, since there is a lot of wear and tear due to nature of the slurry that is being transported, the quality of these measurements are not reliable and depends heavily on maintenance programs. Therefore, the operating strategy for the separation cell efficiency is totally dependent upon the quality of the information used to build models and the control design schemes which use these models.

It is important to understand the process and instrumentation constraints to have a successful application of advanced model based control schemes. The separation cell process has large and variable time delays, and in addition to this, because of the disturbances upstream and downstream of the process, the process gain and delay vary significantly. A varying feed flow (disturbance) because of improper design at the upstream end, is one shortcoming commonly found in the mining and oil sands industries. The ore quality, which translates into the amount of bitumen and sand grain particles present in the oil sands slurry being carried to the SepCell, has a direct effect on the process gain between the interface level and the pump speed. Also, if there is too much back pressure in the underflow line which occurs at one operating condition, it becomes difficult to pump heavy sands and it adds up as a significant dead time for the interface level dynamics. Because of these limitations it is important to have multiple models at different operating conditions because the interface level dynamics change very quickly with changes in feed conditions (upstream) as well as downstream changes. If there is too much turbidity or the fuzziness due to the presence of too many fine particles, the interface level is generally not well defined and measurements from the image based soft sensors are not available. Sometimes the operator workload and behavior also have an effect on process operations and this clearly does not offer favorable conditions to reap automation benefits. A recent paper by Bergh and Yianatos (2011) highlights some of the challenges for multivariable predictive control in the mineral processing industry. The challenges discussed in Bergh and Yianatos (2011) are also applicable in the oil sands industry. Model-based control, or more specifically MPC, is appropriate for these highly complex processes. However, the conditions in the oil sands processing plant are not commensurate for a regular MPC application due to the challenges discussed above. Such issues are not commonly encountered in the refining and petrochemical industries where MPCs are now commonly employed.

The widespread adoption of MPC methods in the process industry is a clear indication of its success and these ideas are now starting to attract interest in other process industries as well. For single-input single-output (SISO) systems, internal model control (IMC) proposed in Rivera et al. (1986) achieves good robustness and predictive controller capabilities. However, it cannot explicitly handle constraints. In contrast to any other controllers, MPC computes optimal control moves by solving an optimization problem over a finite horizon, taking into account dynamic behavior of the process as well as the operational constraints (Qin and Badgwell, 2003; Rawlings, 2000). MPC techniques have been explored and implemented in various forms, some of which have found their way to the market place. The review by Qin and Badgwell (2003) describes some of these implementation algorithms. Some of the recent industrial MPC applications include applications as reported in Stadler et al. (2011), O'Brien et al. (2011). Even though most industrial processes are nonlinear, locally linear models are often sufficient to approximate a process around single set point. Also, since linear models simplify the control design, they are easy to work with when the control involves rejection of disturbances. Industrial application of MPC relies mainly on linear empirical models obtained by employing time series analysis (Qin and Badgwell, 2003). Linear time series model development from operating data is a well researched area and a wide variety of model structures are available for capturing the dynamics of a system with respect to known inputs and unmeasured disturbances (Ljung, 1999; Garnier and Wang, 2008).

The separation cell is a very important front end to a variety ofmineral processing industries, and the main contribution of this paper is that this case study should serve to inform the industrial reader and the research community, the benefits of advanced process control in oil sands and in particular, to regulate the interface level in an oil sands separation cell. Model based predictive controllers, IMC for SISO design and MPC controllers for SISO with and without feed forward control for feed rate, are designed for the interface level control and experimentally evaluated on an industrial separation cell. The implementation was carried out at the primary extraction unit at Suncor Energy Inc.'s, operation in Fort McMurray, Alberta, Canada. The principles of the IMC and MPC controllers are the same; however, real industrial implementation is tailored to this separation cell application. The objective of the control is to regulate the interface level when subjected to process feed rate changes, and provide reduction in the variance of the main controlled variable, the forth bitumen and middlings interface, and thereby improve bitumen recovery and also save on pump energy with smoother operations downstream. Both feedback and feedback plus feed forward control are applied to operate the process dynamically using MPC.

The organization of this paper is as follows: Section 2 provides a brief description of the investigated process. The model identification approach to build reduced order linear models for control purpose is described in Section 3. The formulation of the control algorithms used for testing on the process is described in Section 4. The closed loop results for the on-line testing on the SepCell are presented in Section 5. Section 6 presents the economic benefits followed by concluding remarks in Section 7.

2. Process description

An overview of an industrial hot water based extraction process can be found in Masliyah et al. (2004), Dougan and McDowell (1997). The extraction process flowsheet at Suncor Energy Inc., Fort McMurray, is shown in Fig. 1.

The surface mining of the oil sands is done using big trucks and shovels at the mining site. The mined oil sand lumps are crushed, moved on to the conveyor and then mixed with process water in slurry boxes, stirred tanks, and rotary breakers. This forms the oil sands slurry which is sent to hydro-transportation pipelines or to tumblers, where the oil sand lumps are sheared, and reduced in size. Some chemical additives are also added during the slurry preparation stage. Within these hydro-transport pipelines, bitumen is liberated from the sand grains and entrained air attaches to the bitumen particles. The flow from these hydro-transport pipelines is transferred to large gravity separation vessels, normally referred to as separation cells (SepCell), as shown in Fig. 1. Inside these cells the slurry separates into three different layers: 1) primary bitumen froth, 2) middlings and 3) underflow (also known as tailings). Typically, a 60 °C or 65 °C slurry temperature is used in the current operations. Hot process water is also added to the top of the SepCell to enhance the extraction process and cold water is added into the cone section of the SepCell to help with the underflow flow. The aerated bitumen floats on the top and is subsequently skimmed off from the slurry. In this layer very small quantities of fine sand particles called fines can also be present. The bitumen frothrecovered is then de-aerated, and transported to the later stages