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Interdisciplinary semantic model for managing the design of a steam-assisted gravity drainage tooling system

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ABSTRACT

Complex engineering systems often require extensive coordination between different expert areas in order to avoid costly design iterations and rework. Cyber-physics system (CPS) engineering methods could provide valuable insights to help model these interactions and optimize the design of such systems. In this work, steam assisted gravity drainage (SAGD), a complex oil extraction process that requires deep understanding of several physical-chemical phenomena, is examined whereby the complexities and interdependencies of the system are explored. Based on an established unified feature modeling scheme, a software modeling framework is proposed to manage the design process of the production tools used for SAGD oil extraction. Applying CPS methods to unify complex phenomenon and engineering models, the proposed CPS model combines effective simulation with embedded knowledge of completion tooling design in order to optimize reservoir performance. The system design is expressed using graphical diagrams of the unified modelling language (UML) convention. To demonstrate the capability of this system, a distributed research group is described, and their activities coordinated using the described CPS model.

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1. Introduction

Building a comprehensive understanding of complex physical processes often relies on the coordination of the knowledge and methods of many different expert domains. Managing the effective flow of information in such systems is challenging, as the efficiencies gained through concurrent processing can be easily negated by excessive iterations. The development of methods to optimize such activities is an area of active research. While in some cases these systems are controlled by a central authority (i.e. the management structure of an engineering firm), many complex engineering problems are investigated in a distributed way, through formal and informal relationships between smaller organizations and individual experts each working on a different aspect of the greater problem. These distributed expert systems (DES) are common in academic research settings and in industries where fundamental problems are not yet well understood.

One such problem is the extraction of heavy oil from the oil sands formations found in Alberta, Canada. The oil sands, a mixture of unconsolidated sand and bitumen, is extremely viscous at room

temperature. Shallow reservoirs are dug up and the oil is separated from sand at an extraction facility. Surface mining of these reservoirs has been ongoing in Northern Alberta since 1930, but approximately 80% of this resource is too deep for surface mining (Oil Sands Discovery Center, 2014). For reservoirs deeper than 70 m, *in-situ* upgrading is required to separate the bitumen from sand underground, or partially upgrade, before it is pumped to surface. Most *in-situ* techniques are thermally driven, where bitumen is heated to lower its viscosity so that it flows. Alberta's oil sands are the third largest reserve of oil in the world (Canadian Association of Petroleum Producers, 2016) with, as of 2014, 166 billion barrels of proven reserves in its oil sands (Alberta Energy, 2014), and 133 billion barrels requiring *in-situ* production methods (National Resources Canada, 2017). This industry represents a giant piece of the Canadian economy with expected investments of \$300 billion in Canadian *in-situ* projects between 2016 and 2036 (Canadian Energy Research Institute, 2017).

Steam assisted gravity drainage (SAGD) is the most widely used *in-situ* recovery technology for Alberta's oil sands. SAGD is responsible for nearly a third of all bitumen recovered in Alberta in 2014, and is the fastest growing extraction technology in the province with compounded annual growth of 25% (Holly, Mader, Soni, & Toor, 2014). The SAGD technique requires drilling pairs of horizontal wells through the reservoir, separated vertically by approximately 3 m. Steam is injected through the upper well to heat the reservoir up to the point where the bitumen flows under gravity

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to the lower well where it is collected to be pumped to surface. These wells are expensive to install and operate, and must be expected to operate reliably for upwards of 15 years to maximize the recovery and economic payback of the resource.

There are several known phenomena that result in below-optimal levels of operation of SAGD systems. These include: fines migration, pore space plugging, sand control plugging, and steam breakthrough (Kaiser, Wilson, & Venning, 2002; Romanova & Ma, 2013; Taubner, Subramanian, & Kaiser, 2015) that cause failure of the wells. It has also been shown that the performance of SAGD wells is very sensitive to downhole completions design and that modular configuration design methods may be employed to achieve desired production levels (Renpu, 2011).

Understanding the root causes of these issues, and improving the design and operation of SAGD completions is an area of ongoing research. Due to the complex nature of the SAGD process, this research is typically conducted in a distributed way, leveraging subject matter experts at various institutions and leaving the integrative work to the end user (oil producers). However, progress in only one domain has limited applicability in the integrated system, and integrating the work of independent expert areas represents a significant challenge. Further, managing the development of technology from the proof-of-concept phase through to commercialization represents a significant challenge.

This paper presents a modelling framework based on cyber-physics systems (CPS) methods to manage the multidisciplinary design process that is required to effectively optimize the performance of complex systems such as those found in the heavy oil industry. The objective is to highlight a toolset which can help coordinate the efforts of distributed expert systems and simulations to most effectively manage the design process. This toolset is described in the context of a highly customized SAGD production tooling system. The resulting knowledge model aims to identify an object-oriented structure, using the unified feature modelling approach (Ma, 2013), to embed the mathematical principles which govern SAGD performance within a collaborative and concurrent engineering design process. Reservoir conditions are represented from different functional viewpoints in such a way to provide substantial information for the overall design of the recovery system. Important process parameters such as oil recovery rate, steam-to-oil ratio, temperature, and pressure distribution can then be predicted and optimized based on the chosen design parameters. Making use of such simulation methods saves significant time and costs that would otherwise be spent on laboratory or field experiments.

This paper is organized into 5 sections: In Section 2 the relevant theories and literature describing the SAGD technique are evaluated, in order to determine the requirements of the system. The available modelling techniques are also evaluated. Section 3 describes the resulting SAGD knowledge model in detail. Classes are defined to represent the relevant phenomena using UML notation, with attributes and functions that serve to represent the functionality of the associated expert systems. Section 4 discusses the use and implications of the model. The paper is concluded in Section 5 with a summary of the significance and novelty of this work, a brief discussion of the limitations of our study and the future work required.

2. Theory

2.1. Steam assisted gravity drainage

2.1.1. The SAGD phenomenon

The steam assisted gravity drainage process involves drilling a pair of horizontal wells in the bituminous formation (oil sands),

separated vertically by approximately 3 meters. The upper (injection) well is used to inject steam into the deposit to heat the bitumen to a point where its viscosity is low enough to flow under gravity, while the lower (production) well drains the hot bitumen and pumps it to the surface (Azom, 2013). The reservoir's geological properties, physical and chemical properties of the bitumen deposit, operating conditions (pressure, temperature, and injection rate of the steam), and the design attributes of the completion tooling have significant effects on the production rate (Nguyen, Bae, Tran, & Chung, 2011). Fig. 1 from Gates and Larter (2014), shows a good nominal schematic of the cross section of a SAGD horizontal well pair.

While conceptually simple, the use of steam to change the properties of the bitumen (lowering its viscosity) affects the reservoir more broadly. The changes to the chemistry and geology of the system brought about by the introduction of steam and hot water can significantly affect the nature of the multiphase flow through porous media, especially over long periods of time. Further, operators are constantly experimenting with new enhanced oil recovery methods designed to boost the performance of SAGD systems such as vapor extraction and electro-thermal dynamic stripping (Sands Discovery Center, 2014). It is challenging to understand the intricate domains within this representation and when, in fact, each of these areas is the subject of significant ongoing research. Thus, a real challenge arises when attempting to depict the whole system in detail where much associative complexity is involved.

The SAGD model developed by Butler (1994) postulated a conductive heat transfer at the edges of the steam-saturated zone called the steam chamber. The steam chamber forms when steam is injected and expands over time to form a region that has essentially equal temperature to the temperature of the injected steam (Al-Bahlani & Babadagli, 2009). The relationship between flow velocity and oil production rate for each specific time and steam chamber shape can result from computation of material balance equations (Azad & Chalaturnyk, 2009; Patel, Aske, & Fredriksen, 2013). Their resulting equation is one that involves important parameters that describe the reservoir porosity and geometry. The result from energy balance calculations for a SAGD operation was the steam-to-oil ratio (SOR), a major measure of reservoir performance.

Each SAGD well is completed with two functional sub-systems. A sand control completion, typically in the order of a kilometer long, is installed horizontally within the 'pay zone' of the reservoir. The sand control completion serves two functions which are to

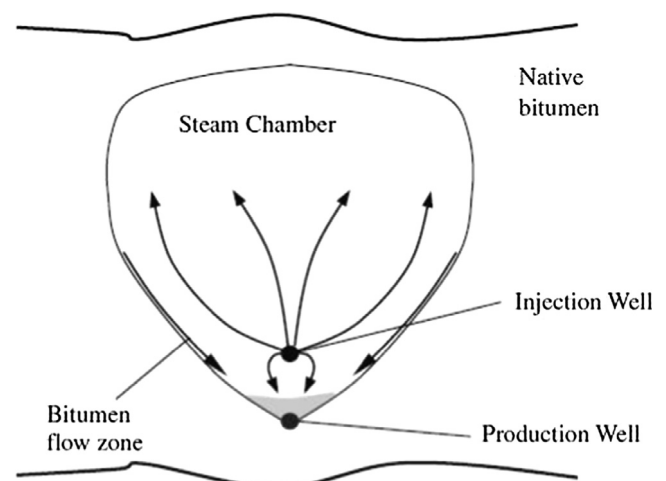


Fig. 1. Cross-section of the steam-assisted gravity drainage (SAGD) process. From Gates and Larter (2014).

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