Journal of Mechanics Engineering and Automation 6 (2016) 167-179
doi: 10.17265/2159-5275/2016.04.001

Design of a Simulation Tool for Steam Assisted Gravity Drainage: Based on the Concept of Unified Feature Modeling Scheme

Yishak Yusuf and Yongsheng Ma

Department of Mechanical Engineering, Faculty of Engineering, University of Alberta, Edmonton T6G 1H9, Canada

Abstract: CPS (cyber-physics system) engineering brings new revolutionary opportunities for multi-disciplinary and complex processes, like oil extraction from oil sands. Based on an established unified feature modeling scheme, a software modeling framework to simulate the process of SAGD (steam-assisted gravity drainage) is proposed. The main purpose of this work was to apply CPS in the complex production engineering informatics modeling as it applied to SAGD. Existing physics models and simulation algorithms for main SAGD phenomena were reviewed, and an integrated ontology model via a feature-based approach has been developed. Conservation laws were used as the governing principles, while the transport phenomena were modelled via the primary *phenomenon features*. The representation of typical data flows targeting to the functional simulation scenarios by applying the concept of *phenomenon features* was also done. The definition of this feature type represents a new expansion of the emerging unified feature scheme for engineering software modeling. Slotted liners were taken as the well-completion option and their design and specifications were included in the case study model. The unique representation of the planned software design is developed and expressed with graphical diagrams of the UML (unified modelling language) convention.

Key words: CPS, model-driven system engineering, SAGD, phenomenon features, unified feature.

Nomenclature

H_{lv}	latent heat of condensation of steam
c_{vr}	initial reservoir volumetric heat capacity
c_{vo}	overburden volumetric heat capacity
k_t	overburden thermal conductivity
η_s	effective sweep efficiency
ν_s	kinematic viscosity of oil
μ	viscosity
A	area
F_S	external surface area of liner
g	acceleration due to gravity
h	height of (reservoir) model
H	total heat consumption
k	permeability
L	slot length
m	dimensionless viscosity constant defined as

$$m = \left[\nu_s \int_{T_r}^{T_s} \left(\frac{1}{\nu(T)} - \frac{1}{\nu_r}\right) \frac{dT}{T - T_r}\right]^{-1}$$

M_x	mass flux
P	pressure
q	volume flux
Q	volumetric flow rate
t	time since first steam injection
T_R	reservoir temperature
T_s	steam temperature
w	slot width
α	thermal diffusivity
α_S	Total slot area percentage of total external surface area of liner
ΔP	pressure drop due to slot
ΔS_o	oil saturation change
ϕ	reservoir porosity
O	cumulative oil production
S	the total steam injected
$cSOR$	cumulative steam-to-oil ratio as defined in Eq. (7)
ΔT	temperature rise in the reservoir

Corresponding author: Yongsheng Ma, Ph.D., professor, research fields: SAGD tooling design and manufacturing, associative plastic injection mold design and analysis, ERP extension for engineering supply chain, interoperability in industrial engineering informatics, feature-based CAD and CAE integration.

1. Introduction

Modular configuration design and effective SAGD (steam-assisted gravity drainage) tooling components such as well completion, and upstream/downstream fittings are aimed at achieving desired production levels [3]. When a company that produces all or some of these components wishes to supply for different clients, it has to develop custom solutions to deal with different reservoir conditions. Their produced SAGD components, say slotted liners, will therefore need to be different which requires specific design, production process simulation, and configuration. The need for a computerized system that can predict production performance via combined simulations of the SAGD processes with different design solutions of under-the-well tooling can thus be acknowledged.

Applying a CPS (cyber-physics system) engineering methodology in the complex modeling and simulation of enhanced oil recovery processes has many great advantages. Reservoir conditions can be represented in such models to provide substantial information for the design of the recovery process under consideration. Important process parameters such as oil recovery rate, production rate, and pressure distribution could be adequately predicted and optimized. Making use of such simulation methods also saves much time and monetary costs that would otherwise have been spent for laboratory or field experiments.

The conditions in reservoirs are far from enabling direct examination of the processes due to lack of a comprehensive model with the complexity of multi-disciplinary dependencies. One of the huge challenges along the proposed simulation purpose is therefore to understand and predict phenomenal occurrences quantitatively that are far from reach. So far, several thermal recovery processes have been modelled from the remarkable works supported by reservoir simulators [4]. Such works showed the feasibility to predict important process parameters for steam flooding, CSS (cyclic steam stimulation), and SAGD [5, 6].

The future development of a software tool for SAGD process simulation for production and tooling design optimization was the main motivation behind this paper. It also aims at identifying the object-oriented system to embed the governing physics principles for a SAGD operation. This objective can be achieved by incorporating the concept of phenomenon features which encapsulate properties and/or constraints in the oil sands development modelling as a generic feature-based tool. The feasibility of such a computer-aided simulation tool and the required data model in support for its innovative application are forwarded from the unified feature modeling approach with a collaborative and concurrent engineering prospect [7]. Laying out the conceptual models for SAGD features, this work defines a new generic *phenomenon feature* type whose interactions can be demonstrated during the SAGD lifecycle processes as a template. The governing principles like conservation of mass and energy as well as flow phenomena have been considered in depth to come up with the presented framework model for SAGD process simulation.

This paper is organized into the five sections that follow. Review of relevant literature is presented in Section 2. The model considerations that were made in view of defining classes for the object-oriented model are given in Section 3. Section 4 presents the design of the simulation model the first part of which gives the definition of the phenomenon features concept mentioned above. Potential application of the simulation software with the sources and flow of data is shown in Section 5. The significance and novelty of this work along with future works required are given in the conclusion presented in Section 6.

2. Literature Review

2.1 The SAGD Phenomenon

Looking more closely into the SAGD processes, fundamental phenomena and their interactions could be represented as shown in Fig. 1. A broader view of the roles played by major physical and chemical phenomena is shown here. For instance, consideration

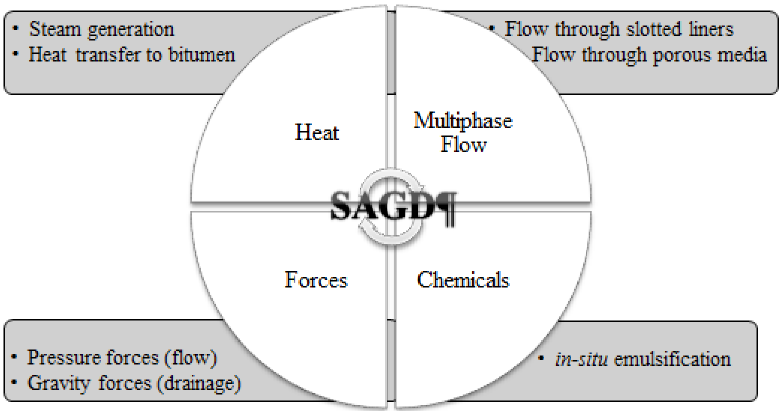

Fig. 1 Phenomena involved in SAGD process.

of heat transfer phenomenon is fundamental in SAGD due to its significance in steam generation phase and lowering the viscosity of bitumen. It could be fairly challenging to understand the intricate domains within this representation. However, the real challenge arises when it is attempted to depict the system in more detail where much association complexity is involved.

The model developed by Butler [8] in 1994 held the assumption of a conduction heat transfer that occurs on the edges of the steam saturated zone called the steam chamber. The steam chamber forms when steam is injected and has the temperature which is essentially equal to the temperature of the steam injected [9]. Homogeneous and isotropic reservoir was assumed in his model without consideration for capillarity because most bitumen reservoirs usually having high permeability led to small capillary pressure [10]. Rapid reduction of viscosity due to an increase in temperature, and its drainage (flow) due increased mobility may be considered the primary governing principles for the SAGD phenomena.

Drainage models proposed by Butler (1985) and Reis (1992) were discussed in Ref. [11]. A triangular shape of steam chamber was assumed in both theories which predicted a constant rate of oil production and hence a cumulative oil which was a linear function of time. Azad and Chalaturnyk [11] gave the modified version of Reis' model—GAB (Geo-mechanical Azad Butler) model—accounting for heterogeneity in the reservoir permeability.

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 [11, 12]. 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, i.e. SOR.

2.2 Near-Wellbore Modeling

Butler (1985) proposed a model that can be used to predict the drainage of bitumen around an expanding steam chamber [13]. In his method multiple segments were used to represent the interface and oil drainage from each segment was calculated. The displacement of the interface was determined using the calculated rates after which an approximate differential equation was used to estimate the change in the penetration of accumulated heat. This computation was done iteratively. Details for the method as well as the calculation sequence can be found on the publication [13].

Several different options were added to Butler's model by Dehdari et al. [14] to improve SAGD performance estimation also taking account heterogeneity of reservoir. A new rising model was developed along with volumetric computation of oil production rate to develop a semi-analytical approximate thermal simulator. Optimization of well trajectories was achieved using proxies that included injector constraints and automatic calibration of their results [14].

Alali et al. [15], on the other hand, developed a new calculation for the drainage rate based on Butler's TANDRAIN theorem. Formulation of transient temperature distribution ahead of oil-steam interface; estimation of interface position; and indirect formulation to evaluate the interface velocity were also included in their work. A three phase thermal model was used for a box-shaped reservoir model with predefined drainage area and thickness.

2.3 Modeling for Flow and Sand Control Devices

After a reservoir has been identified and its properties specified, a well completion procedure is required to make the well ready for injection and production. The specific goals of using a well completion technique are to ensure economic benefit; prolonged life of the oil reserve; and effective development of the oil and gas field. Downhole operations that are enabled by the tooling assembly under the well along the horizontal section during the production should be considered in the design of the well completion method.

OCD (outflow control devices) are installed on the injector well to improve steam placement and chamber growth and ultimately improve productivity of the SAGD process. Lei et al. [16] did a computational fluid dynamics modeling specifically on OCD with particular reference to their performance in SAGD operation. A simplified model for the device was used in a series of simulations using commercial software. The control mechanism and flow distribution along with comparison to different flow models were reported.

Slotted liners are the most common type of completions used for SAGD wells [17-19]. The common procedure followed in the slotted liner completion involves running in (inserting) an intermediate casing after the first drilling of the top boundary of the reservoir. The well is cemented after this stage and a smaller bit is used to drill through the oil reservoir at the design depth [3, 20]. The process is completed when a liner slotted in advance is inserted in the position of the reservoir. The same process is used for both injection and production wells [20].

Kumar et al. [21] considered the design and optimization of slotted liners with respect to sand control, productivity, and economic performances. Slot specifications' effects such as size, and slot density on pressure loss due to flow convergence were considered in their work.

Kaiser et al. [22] studied the characteristics of the inflow of oil to the production well and the effect of the slot arrangements to optimize the design with respect to slot density and orientation. In their semi-empirical work, they considered the coupling of two types of flows—radial flow through the reservoir to the liner and axial flow through the pipe to the production pump.

The change in the velocity distribution for the flows on Newtonian and non-Newtonian fluids through micro scale orifices due to the variation of slot geometry was studied by Ansari et al. [23]. Particle image velocimetry was used to determine the variations of flow at various positions from development of velocity profiles. The results discussed jet formation due to slot geometry variations the presence of shear thinning properties of the fluids tested.

3. Phenomenon Model Considerations

Simulation of reservoir conditions for SAGD commences with development of the conceptual model. In general, reservoir basics such as its geography, specification of the reservoir fluid, properties of the flow medium and the driving mechanisms, and visualization of the flow patterns need to be included. Performance descriptions and predictions could hence be accurately achieved [11, 24].

3.1 Reservoir Properties

Geological review is primarily required to understand the physical and flow properties of the reservoir [5]. The primary considerations in the development of mathematical model are mass conservation, a transport law, and an equation of state. The ultimate result for this is the development of partial differential equations which govern the model.

Fig. 2 shows a schematic for derivation of the mass conservation [5]. Assuming accumulation of mass in the considered differential element gives the governing equation.

$$\frac{\partial M_x}{\partial x} = \frac{\partial(\rho\phi)}{\partial t} + q \quad (1)$$

Description of the fluid's state with respect to pressure and temperature dependence and its flow in terms of Darcy's law are required to expand this equation. The material balance for reservoir modeling is usually done assuming real gas law for gasses and dissolved gas for liquid phases. A linear function of pressure is also assumed for water which is characterized as a liquid of low compressibility [5].

Darcy's law describes the flow through porous media. Pressure drop across a sand pack is a linear function of an intrinsic sand property (permeability, k), the applied pressure drop, the length of the sand pack, and the cross sectional area of flow, A. The relation was given as

$$Q = -A\frac{k}{\mu}\frac{\partial \mathrm{P}}{\partial x} \quad (2)$$

where, Q is the total discharge; μ is the viscosity of the fluid.

Butler's theory for production rate of heavy oil and bitumen combined the heat conduction theory with Darcy's law [8, 10, 25]. The resulted equation from his theory to predict the production rate was

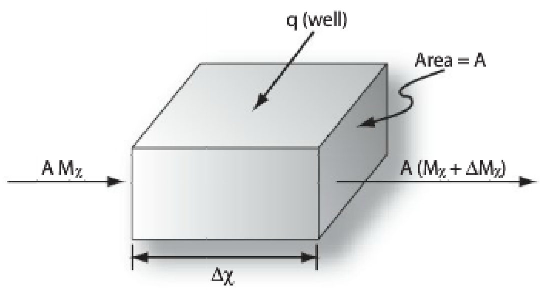

Fig. 2 Representative element for mass balance [5].

$$Q_o = \sqrt{\frac{2\phi\Delta S_o k g \alpha h_f}{m\nu_s}} \quad (3)$$

where, Q_o is oil production rate; κ is permeability; α is reservoir thermal diffusivity; ϕ is porosity; ΔS_o is initial oil saturation – residual oil saturation; h is the height of model; m is dimensionless (between 3-5, dependent on oil viscosity-temperature relationship); and ν_s is oil kinematic viscosity.

The theory meets a specific and perhaps the most appealing parameter in the SAGD—production rate. Nonetheless, prediction of this parameter needs to base on prior calculations that simulate the recovery process in the reservoir to specify the required properties. According to Carlson [5], simulation of thermal recovery processes like SAGD need to base on unique aspects for its model.

3.2 PVT Behaviors of Steam and Bitumen

Steam properties pertaining to the temperature and pressure conditions in the reservoir are required to determine critical point based on the vapor liquid line. PVT (pressure, volume, and temperature) behavior is used in the calculation of energy required for steam generation as well as the latent heat of vaporization [6, 25].

Heat losses are inevitable from the injection of steam to the system. Loss calculations around the wellbores and the formation's over-burden and under-burden regions require analytical methods to be included in the SAGD simulation model [5, 6, 25]. A detailed example of such calculation for heat losses in a SAGD operation are given in Ref. [5]. Temperature dependence of viscosity is one of the phenomena that are of great importance. Experimental data are hence needed to form the database for any software and/or simulation package.

Prediction of cSOR (cumulative steam-to-oil ratio) in steam based bitumen recovery was developed using a unified model [6]. In this work a simplified heat loss model was used to arrive at the description of cSOR. Dependence of this parameter on time and drainage geometry was also shown. It was also reported that the predictive model came in good agreement with predictions from simulators.

The heat loss model derived was based on the reservoir's heat consumption scheme shown in Fig. 3 [6].

The derivation first computed the heat in the chamber followed by the cumulative heat loss to a semi-infinite plane which considered the overburden as well. Assuming the production of steam condensate near steam temperature (low sub-cool), the steam consumption was determined by latent heat at operation pressure. Enthalpy in the produced oil was neglected. The equations that resulted in the derivation were given as:

$$H = A\Delta T\left(C_{vr}h\eta_s + \sqrt{k_t C_{vo} t}\right) \quad (4)$$

$$S = \frac{H}{H_{lv}} \quad (5)$$

$$O = Ah\eta_s(S_{oi} - S_{or}) \quad (6)$$

where, H is the total heat consumption; A is the planar area of the steam chamber; ΔT is the temperature rise above initial; C_{vr} and C_{vo} are the initial reservoir, and the overburden volumetric heat capacity, respectively; h is height of reservoir above the production well; η_s is the effective sweep efficiency; k_t is the overburden thermal conductivity; t is the time since first steam injection; H_{lv} is latent heat of condensation of steam; S and O are the total steam injected and the cumulative oil production at time t.

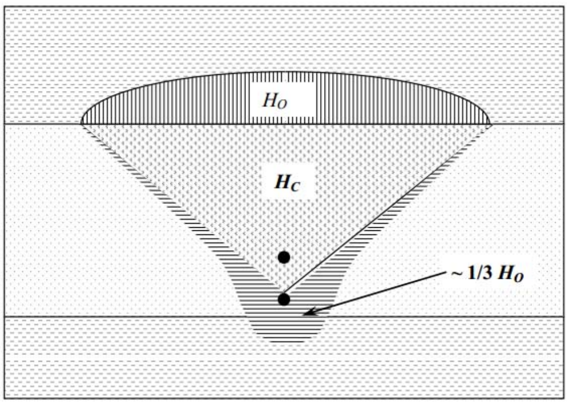

Fig. 3 Reservoir heat consumption [6].

The cSOR was calculated by combining the above relations.

$$cSOR = \frac{S}{O} = \left(\frac{\Delta T}{H_{lv}\phi\Delta S_o}\right)\left(C_{vr} + \frac{\sqrt{k_t C_{vo} t}}{h\eta_s}\right) \quad (7)$$

4. Design of Simulation Model

To arrive at the final conceptual model for the design of the desired software module, object oriented approach was employed to identify classes that correspond to model components. The main idea behind selection of this methodology is the possibility to use the results from this model to further expand the model scope to include manufacturing details. The concept of associative features which enables the design for dynamic systems based on the concept of features' relationships is planned to be used for this purpose [26].

The descriptions of derivation model and integrated workflow suggested that classes corresponding to model components have to be identified. Relationships between the physics involved in the process as well as thermal and flow phenomena will therefore primarily make up the reservoir-part of the model. In the following sub-section, a generic definition for the concept of phenomenon features is given. The principles underlying the usage of this powerful concept to model processes are forwarded. In Section 5, the application of these underlying principal phenomenon features is then described with the case of SAGD as the modeled phenomenon.

4.1 Definition of Phenomenon Feature Type

Definition of the feature concept was given by Sajadfar et al. [27] as a representation of an engineering pattern that contains the associations of relevant data with one another. For example, in product modeling, a feature refers to an information attribute set and their related methods (with object-oriented software modeling terminology) that represent a certain aspect of form or engineering pattern with variation behaviors. When various types of features are associated and combined to form a tree of data structures, they represent a feature model. A feature model hence contains recognizable entities that have specific representations supporting a working system for certain application purpose. The number and type of features that shall be included to form a complete model depends on the function that is intended to be supported. Any part of a process or a product whose change can have the engineering significance to make the system behave in a different way can be called a feature.

Phenomena can be considered as features themselves based on this concept. For a process that is being modeled as the combination of disciplinary phenomena, informatics modeling forms a framework of multiple tiers where we can find one within or related to the other. Each domain's parameters, attributes, constraints as well as their behaviors can be represented in the computer interpretable data structures, i.e. phenomenon features, via object-oriented software engineering approach. Each can be considered as an *instance*, or the *child class*, of a generic phenomenon feature type. A *class* definition that can be used to describe all of them regardless of their *instance* attribute values and application tiers is thus needed for a successful modeling of complex engineering system, where parent-child relationships can also be utilized.

The definition of a phenomenon feature is depicted in Fig. 4. Elements/components, conditions, and presumptions can be used to describe a phenomenon. The underlying principles for its behavior can come from general governing equations, and process constraints. The behaviors of the phenomenon can then be applied to solve the governing equations, to model the functions of phenomenon, and to predict and/or optimize its outputs.

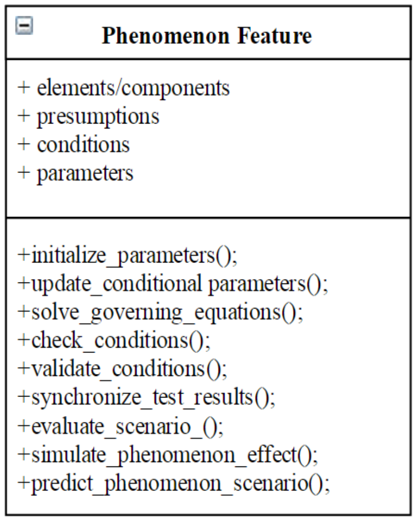

Fig. 4 Definition of phenomenon feature.

4.2 Oil Production Model

The process of SAGD can be represented as a phenomenon feature. However, from the definition given in the above section, the entire SAGD phenomenon forms the top-most tier and other sub-phenomena can be expected to make up the lower levels.

Oil production within the SAGD process technology is a combined transport phenomenon itself for which several aspects of the principal conditions have to be fulfilled, e.g. heat and mass transfer, and multi-phase flow in porous medium. Production rate, which is perhaps the most significant measure of SAGD production, can be predicted and optimized using a model for oil production. Reservoir properties, temperature and pressure distributions, fluid properties, and the flow regimes and schemes will result in the parameters that can be used to solve the conservation and governing equations such as those described in Sections 2 and 3 of this paper.

Based on the concept of disciplinary principal phenomenon features described and significant components identified, six child classes of phenomenon feature oil production shown in Fig. 5 were constructed with their respective and relevant attributes and methods.

The physical flow and heat transfer phenomena that take place in the SAGD system were the obvious foundations behind the construction of these classes.

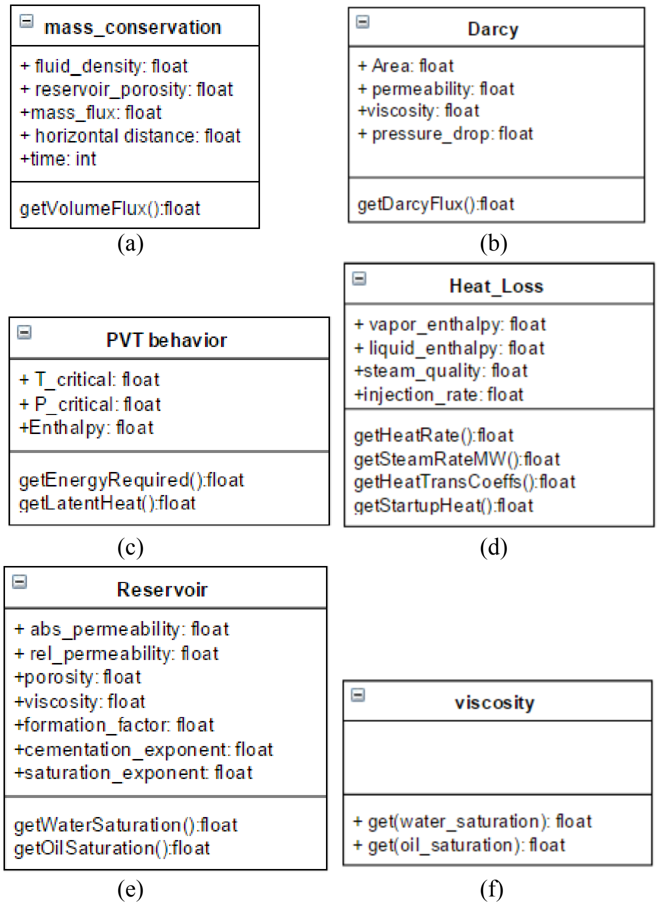

Fig. 5 Some of the defined child classes of phenomenon feature for SAGD simulation model.

To complete this model and meet the objectives, further inclusion for the design and manufacturing of well tooling components of a SAGD system was required.

4.3 Well Completion

Desired thermodynamic and fluid mechanic phenomena for the effectiveness of a SAGD process can be initiated by well completion. Well completion is implemented to serve the purposes of flow control, sand control, ensuring strength and stability of the well bore. For a specific completion method there are corresponding conditions that need to be maintained within the reservoir and the wells to attain acceptable levels of pressure and flow control performance under the working temperatures.

As the structural and sand control components of the well completion, slotted liners have significant effect on the thermal and fluid mechanic phenomena in SAGD. For example, along the production well, two competing criteria which require small and large slots for minimal sand production and maximum oil production, respectively, prevail in the design of slotted liners. Plugging and corrosion also need due consideration. Four associated conditional *classes* of *well completion* were identified namely Reservoir, Drilling, Liner, and Slot with their respective properties as shown in Fig. 6.

In this section the main objective was to come up with a separate model for the design of slotted liner to be incorporated in the overall model for SAGD modeling and simulation.

4.4 Integrated Model

The relationships between these classes shown in Fig. 7 were established based on the dependencies and

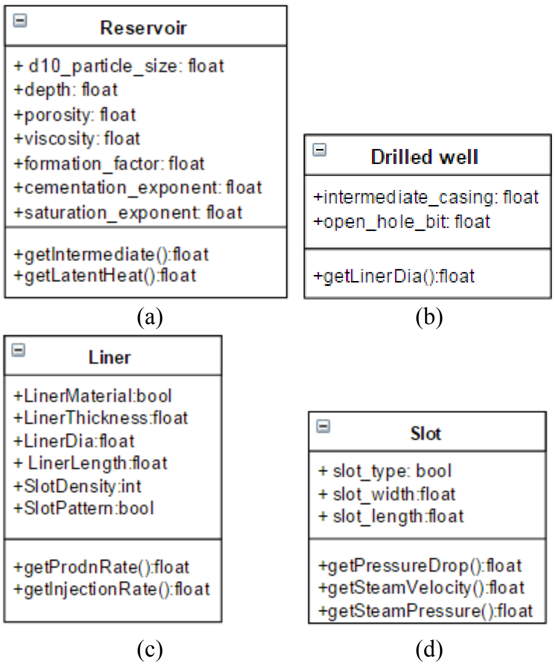

Fig. 6 Defined classes for SAGD simulation with slotted liners.

aggregation of attributes and/or output parameter(s) (shown in respective methods' section). Such modules make up the final model for the integrated system of SAGD process. The Reservoir was common for both the class groups listed for the reservoir and well completion considerations. Its corresponding version for the final model was therefore made by combining the attributes identified in the separate considerations.

It should be noted that thermodynamic data that are required to specify some of the attributes included require table data to be stored in a reference database. Steam properties of enthalpy and critical points vary with temperature and pressure conditions. Viscosity of the bitumen is also dependent on the reservoir initial properties and the change in temperature induced by the SAGD process. Parameters which include but certainly not limited to these require referring to standard thermodynamic data.

Coupled with the reservoir model, like the model for slotted liner, other modular components can be effectively supported by advanced intelligent design automation. Therefore, the applied CPS systematic engineering informatics modeling approach completes the entire picture of the SAGD modeling representation.

The end goal of this CPS based engineering informatics research effort is to use the results from the proposed SAGD model to determine operation properties that are required. The attributes shown under the classes related to well completion contain geometric information for the slotted liners and the related flow controlling devices considered. These values may be used to characterize tooling design and manufacturing features to specify the detailed specifications of the mechanical system.

5. Simulation Software Model Based on Phenomenon Features

So far, developments of analytical models for the SAGD process have already been reported to describe the phenomena of fluid flow, and heat and mass transfer as well as the effects of reservoir properties and temperature [15, 28]. There were also works that have developed computational models by specifying the workflow pattern based on analytical and semi-analytical/empirical models [11]. Works like the one by Dehdari [14] specifically aimed at developing simulation tools to be used as modules in existing reservoir and/or thermal simulation packages.

The flow into the producer well through the slots on the slotted liner has a significant effect on production rate [22]. Slot specifications such as the geometry and shape will have a profound effect on the inflow in terms of the pressure drop they impose and the undesirable conditions like plugging that they are susceptible to.

In the consideration of the flow of oil through the slot, development of a model shall be sought for so that description of the effects of a single slot can be extended for multiple slots on the producer well. This model can then be incorporated with others that have already been developed for the flow through porous media (such as those based on Darcy's model), and temperature dependence and distribution (the steam chamber front velocity and location) [15].

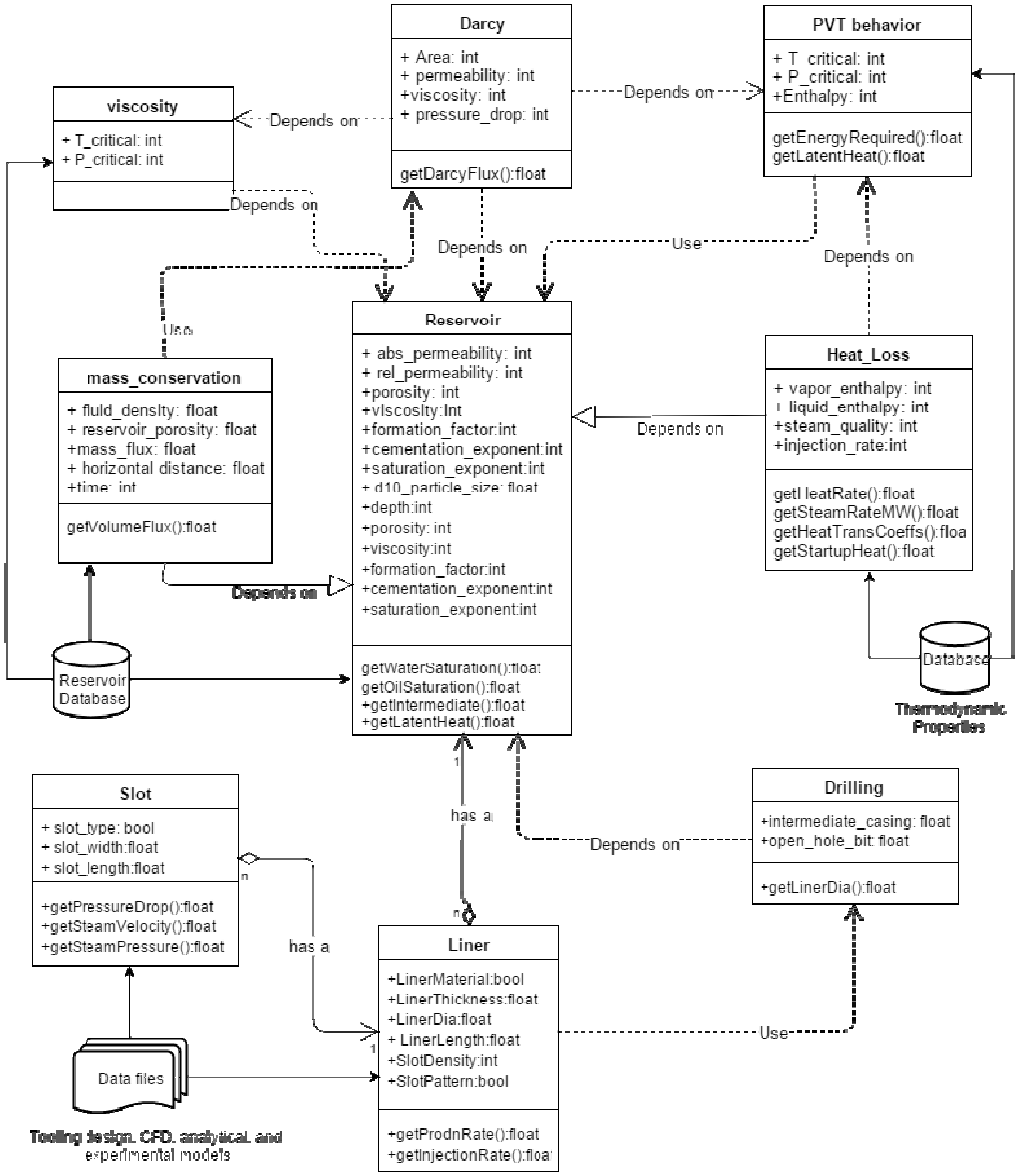

Fig. 7 Preliminary and integrated phenomenon model for SAGD simulation software.

The UML representation given in Fig. 7 shows the relationship between the classes that can be used to design software for SAGD simulation. Nonetheless, this work would like to take the view one level higher to the concept of phenomenon features and employ the practices among modeling and simulation works in multidisciplinary systems' design [29].

The flow of major parameters as an input to the simulation model to give the required outputs is shown in Fig. 8. It should be noted that the input

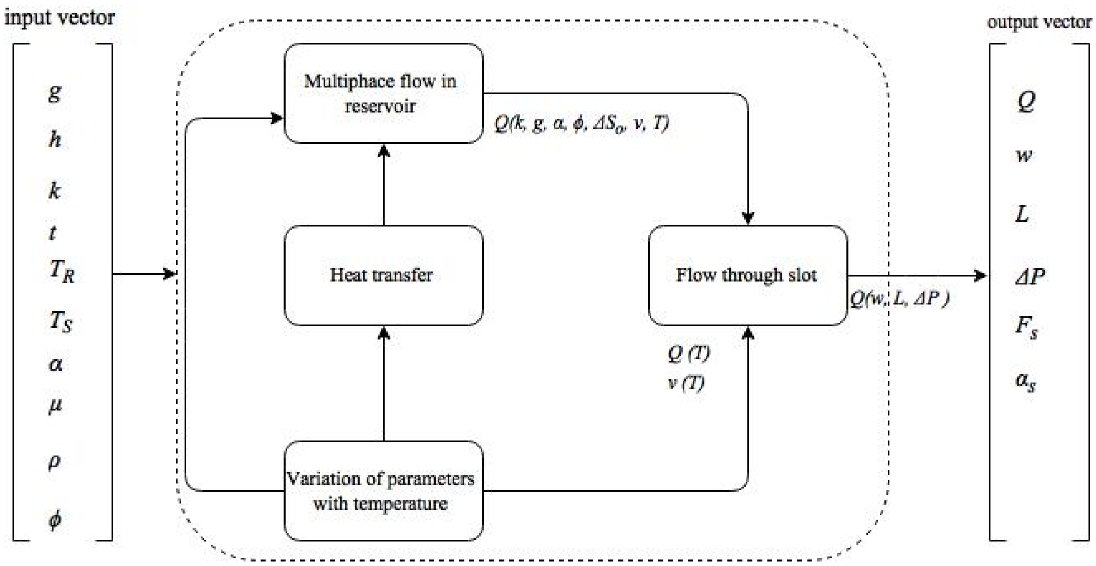

Fig. 8 Block diagram representing the relationship between phenomenon features in SAGD.

vector shown in the figure does not list all the parameters that will be used as inputs but rather shows the ones that are part of the reservoir properties, and input steam. The outputs from the multiphase flow and temperature dependence phenomena are shown as a functional representation of the production rate for the purpose of clarity.

The model equations for each phenomenon given by the blocks are to be found from respective analytical or semi analytical studies. Findings from experimental investigation on multiphase flow through a slot, for example, may provide with the corresponding block's model.

The progress of the development for this simulation software requires an exhaustive list of in-situ input and output parameters along with placement of the governing physics model equations in the respective nodes in a DSM (data structure matrix) or alike in order to have a better data organization and representation.

6. Conclusion and Future Work

The novelty of this paper is the concept of phenomenon features proposed on which the development of a CPS model for the sought SAGD simulation software is based. With this new concept, the interdisciplinary framework for integrating intricate complex interactions among engineering domains of SAGD process was developed. Major phenomena that occur in the reservoir during the extraction of oil formed the primary foundations to generate a credible conceptual software model.

Object-oriented unified feature modeling approach was employed to identify the components of the model and establish their relationship. The reason for selecting this approach is foreseeing the suitable application of the concept of associative features [7] in the expansion of the model. The relevance of this approach is to conclude the scope of the present paper at a point which directs future work. The contribution is the proposed guiding framework towards systematic and coherent data organization and representation of the governing engineering principles, intricate constraints, and dynamics integration interactions in the form of the flow of feature entities and parameters.

As an example component of the SAGD tooling system, slotted liners were referred to, to illustrate the standard (conventional) design considerations and calculations of parameters for SAGD. The overall objective was to devise a SAGD simulation model that will enable certain automation of the design and optimization of SAGD tooling system and predict the

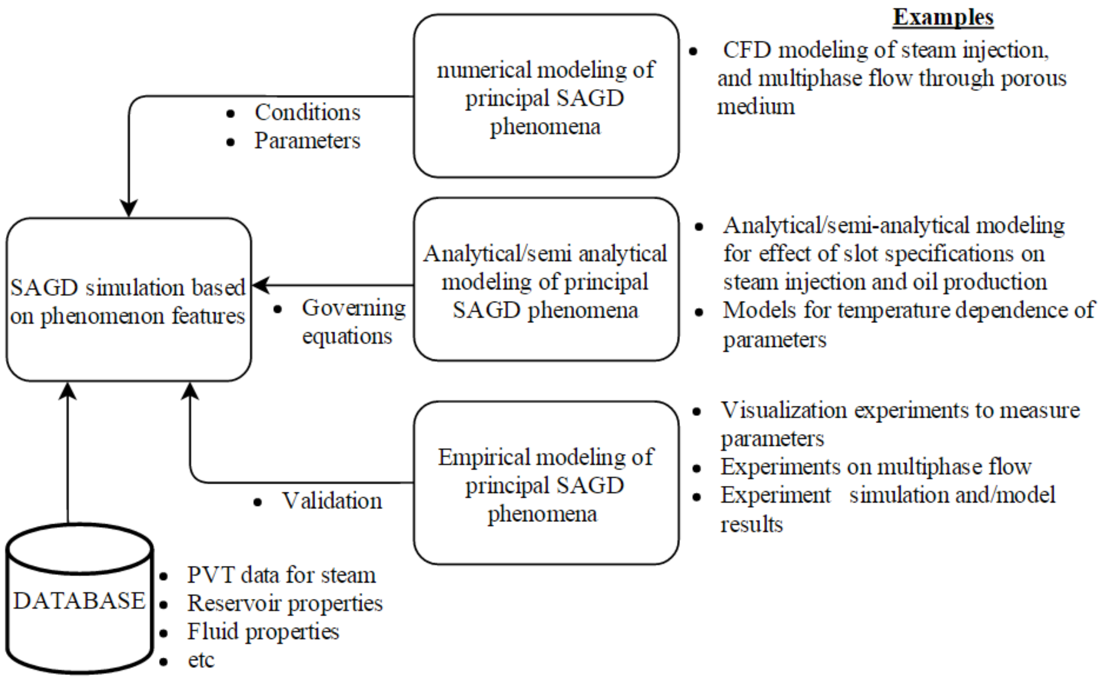

Fig. 9 Examples of working scenarios for simulation of SAGD based on phenomenon features.

performance of SAGD production. The proposed software framework model is expected to simulate the SAGD phenomena quantitatively in terms of production rate and to optimize the required tooling design geometry and dimensions for the corresponding components.

In light of the works described in the literature review section, potential applications of the simulation software can be foreseen as shown in Fig. 9. Analytical studies [23] , and computational modelling works [16] on flow and heat distribution can be used to draw *attributes* and *methods* for respective *classes* in the form of parameters they measure or model equations they result in. Experimental investigations of the different phenomena in SAGD such as inflow can be used to validate results.

As to the future work, adapting the concept of associative features to achieve the full functionality of SAGD simulation will be considered along with the required ontological representations and development of interfaces. Development of the DSM representation in full length along with the prototype modules for the software is expected to proceed.

References

[1] Azom, P. 2013. “Improved Modelling of the Steam-Assisted Gravity Drainage (SAGD) Process.” Ph.D. thesis, The University of Texas in Austin, Austin.

[2] Nguyen, H. X., Bae, W., Tran, X. V., and Chung, T. 2011. “Experimental Design to Optimize Operating Conditions for SAGD Process, Peace River Oil Sands, Alberta.” SPE Asia Pacific Oil and Gas Conference and Exhibition. Jakarta: Society of Petroleum Engineers.

[3] Renpu, W. 2011. *Advanced Well Completion Engineering* (3rd ed.). Elsevier.

[4] Computer Modelling Group Ltd. 2011. STARS—Thermal & Advanced Processes Reservoir Simulator.

[5] Carlson, M. 2006. *Practical Reservoir Simulation: Using, Assessing, and Developing Results.* Tulsa: PennWell Corporation.

[6] Edmunds, N., and Peterson, J. 2007. “A Unified Model for Prediction of CSOR in Steam-Based Bitumen Recovery.” Petroleum Society’s 8th Canadian International Petroleum Conference. Calgary: Petroleum Society.

[7] Ma, Y.-S. (Ed.). 2013. *Semantic Modeling and Interoperability in Product and Process Engineering.* London: Springer.

[8] Butler, R. 1994. “Steam-assisted Gravity Drainage: Concept, Development, Performance, and Future.” *Journal of Canadian Petroleum Technology* 33 (2): 44-50.

[9] Al-Bahlani, A.-M., and Babadagli, T. 2009. "SAGD Laboratory Experimental and Numerical Simulation Studies: A Review of Current Status and Future Issues." *Journal of Petroleum Science and Engineering*, 135-50.

[10] Azad, A. 2012. "Rapid SAGD Simulation Considering Geomechanics for Closed Loop Reservoir Optimization." Ph.D. thesis, University of Alberta, Civil and Environmental Engineering Department, Edmonton.

[11] Azad, A., and Chalaturnyk, R. 2009. "Geomechanical Coupling Simulation in SAGD Process: A Linear Geometry Model." In *ROCKENG09: Proceedings of the 3rd CANUS Rock Mechanics Symposium,* edited by Diederichs, M., and Grasselli, G. Toronto.

[12] Patel, K., Aske, E. M., and Fredriksen, M. 2013. "Integrating Reservoir Simulator and Model Predictive Control Software for Automating SAGD Well Pair Operations." SPE International.

[13] Butler, R. 1985. "A New Approach To The Modeling Of Steam-Assisted Gravity Drainage." *The Journal of Canadian Petroleum*: 42-51.

[14] Dehdari, V. 2014. *Development and Applications of a Semi-Analytical Approximate Thermal Simulator*. Banff: Canadian Society of Petroleum Geologists.

[15] Alali, N., Pishvaie, M. R., and Jabbari, H. 2009. "A New Semi-Analytical Modeling of Steam-Assisted Gravity Drainage in Heavy Oil Reservoirs." *Journal of Petroleum Science and Engineering* 69 (3-4): 261-70.

[16] Li, L., Lange, C., and Ma, Y. 2015. "Modeling of Outflow Control Devices in Steam Assisted Gravity Drainage." 23rd Annual Conference of Computational Fluid Dynamics. Waterloo.

[17] Xie, J., Jones, S. W., Matthews, C. M., Wagg, B. T., Parker, P., and Ducharme, R. 2007. "Slotted Liner Design for SAGD Wells." *World Oil*: 67-75.

[18] National Oilwell Varco. 2014. "Holing and Slotting of Casing." Retrieved from http://www.nov.com/uploadedFiles/Content/Segments/Completion_and_Production_Solutions/Intervention_and_Stimulation_Equipment/Elmar/TUBULAR_Completion_Equipment/TUBULAR.pdf.

[19] Bennion, D., Gupta, S., Gittins, S., and Hollies, D. 2009. "Protocols for Slotted Liner Design for Optimum SAGD Operation." *Journal of Canadian Petroleum Technology* 48 (11): 21-6.

[20] Surmont Energy. (2011, November 8). "(SAGD) Steam Assisted Gravity Drainage—Oil Sands Extraction." Retrieved April 2015, from https://youtu.be/uucXaKK-EnY.

[21] Kumar, A., Srivastava, A., and Kumar, R. 2010. "Design Optimization of Slotted Liner Completions in Horizontal Wells of Mumbai High Field." SPE Asia Pacific Oil & Gas Conference and Exhibition. Brisbane: Society of Petroleum Engineers.

[22] Kaiser, T., Wilson, S., and Venning, L. 2002. "Inflow Analysis and Optimization of Slotted Liners." SPE Drilling and Completion: 200-9.

[23] Ansari, S., Rashid, M. A., Waghmare, P. R., Ma, Y., and Nobes, D. 2015. "Newtonian and Non-Newtonian Flows throuh Micro Scale Orifices." 10th Pacific Symposium on Flow Visualization and Image Processing. Naples.

[24] Bogdanov, I., Ganaoui, K. E., and Kamp, A. 2007. "COMSOL 2D Simulation of Heavy Oil Recovery by Steam Assisted Gravity Drainage." Proceedings of the COMSOL Users Conference. Grenoble.

[25] Bao, X. 2012. "Thermal Simulation and Optimization of SAGD Process: Case Study on Surmont Pilot Project." M.Sc. thesis, University of Calgary, Chemical and Petroleum Engineering Department, Calgary.

[26] Ma, Y.-S., and Tong, T. 2003. "Associative Feature Modeling for Concurrent Engineering Integration." *Computers in Industry*: 51-71.

[27] Sajadfar, N., Xie, Y., Liu, H., and Ma, Y.-S. 2013. "A Review of Data Representation of Product and Process Models." In *Semantic Modeling and Interoperability in Product and Process Engineering,* edited by Ma, Y.-S. London: Springer, 31-52.

[28] Heidari, M., Pooladi-Darvish, M., Azaiez, J., and Maini, B. 2009. "Effect of Drainage Height and Permeability on SAGD Performance." *Journal of Petroleum Science and Engineering* 68: 99-106.

[29] Weck, O. D., and Willcox, K. 2010. ESD. 77 "Multidisciplinary System Design Optimization, Spring 2010." Retrieved August 12, 2015, from Massachusetts Institute of Technology: MIT OpenCourseWare: http://ocw.mit.edu.