

Experimental Investigation and High Resolution Simulator of In-Situ Combustion Processes

Quarterly Report

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Abstract

Accurate simulation of in-situ combustion processes is computationally very challenging because the spatial and temporal scales over which the combustion process takes place are very small. In the last report, we focused heavily on experimental work. In this current and **tenth** report, we report on our numerical as well as experimental work. We discuss scaling analysis we have performed for the in-situ combustion equations and also present our new computational framework for time-integration of the equations. On the experimental side, we have looked closely at UGNU oil from Alaska, a candidate for ISC processes, and have started a new investigation into the effects of permeability onto ISC processes.

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1. Introduction

In-situ combustion, or air injection, is the process of injecting oxygen into oil reservoirs to oxidize the heaviest components of the crude oil and enhance oil recovery through the heat and pressure produced. The emphasis of this work is to study and model numerically in situ combustion processes. The ultimate objectives are to provide a working accurate, parallel in situ combustion numerical simulator and to better understand the in-situ combustion process when using metallic additives and/or solvents combined with in situ combustion. For this purpose, experimental, analytical and numerical studies are conducted.

This report presents results of the second quarter of the third year of this project.

2. Executive Summary

2.1. Personnel

Current personnel include Prof. Margot Gerritsen (PI), Prof. Tony Kovscek (Co-PI), Dr. Louis Castanier (Technical manager), Mr. Rami Younis (PhD student). Mr. Rotimi Awoleke (MSc student) is also working on the project, albeit paid from departmental sources. We have also continued collaboration with Mr. Morten Kristensen (PhD student) from the Technical University of Denmark, and his advisors Prof. Erling Stenby and Prof. Michael Michelsen. Finally, research associate Dr. Jim Lambers has been instrumental in the development of the integrated upscaling and adaptivity methodology.

2.2. Important accomplishments

2.2.1 Towards a new framework for ISC equations

The purpose of our research is to improve our predictive capabilities of the physically and mathematically very complex ISC process. In this report in particular, we suggest a computational framework that has promise in addressing the *temporal* multi-scale character of the various physical processes that play a role in ISC. In previous reports we have addressed spatial adaptivity.

The multi-scale ISC process

In-Situ Combustion (ISC) processes are physically complex. In addition to strongly coupled phase behavior, compositional transport, and flow, such processes also involve thermal effects and chemical reactions. The characteristic time-scales associated with each of these sub-processes can vary substantially over the duration of a combustion process as well as over the reservoir domain. This implies that throughout the life of a combustion process, the set of dominant physics that influences behavior the most can vary as well. For example, it is clear that conductive and convective heat transport dictate the recovery until reactions dominate. On the other hand, the fashion by which the reservoir is heated, and associated transients, can dictate if and how a sustainable front develops. This operational dependency is thought to be related to the chemical properties of the system. Once combustion starts off, reactive and convective transport tend to dominate, and the sustainability of a front and its dynamics will then depend on relative timescales between sub-reaction steps and species transport.

The physically distinct sub-processes are also very different from a numerical integration standpoint. For example, the chemistry can be stiff, and be best treated by implicit methods, whereas transport is often treated with high-resolution explicit methods. In general, it is inefficient or practically infeasible to apply the same integration method to all processes. Furthermore, fully-implicit methods result in large nonlinear algebraic systems to be solved, where due to the thermal and reactive components time-step robustness cannot be fully leveraged because of the imposed nonlinearity in the system. Often, in such cases, the convergence rate of the nonlinear solver suffers dramatically with increasing time-step size, and consequently, despite of the implicitness, short time-steps have to be taken. This is especially observed when the solution is near multiple phase transitions.

One approach to addressing this issue is the development of specialized solvers for the fully-implicit system, in a way that respects the differences amongst processes. Another general approach involves the development of so-called splitting methods. Such methods numerically break-down the problem into independent sub-problems and present a coupling framework to tie sub-solutions. Specialized techniques can then be used to solve each sub-problem. For example, a high-resolution scheme can be used for transport, while an implicit, stiff ordinary differential equation solver can be used for the reactions. The splitting must be designed so as to minimize the errors introduced by this de-coupling. These additional error terms are referred to as splitting errors.

2.2.2 Towards a new framework for ISC equations

Scaling of the equations and dimensionless parameters

We derived the physical parameters that describe the ISC process. The formulation is summarized in Equations (1.1) through (1.4) below, with more detail given in Younis and Gerritsen (2006). Equation (1.1) is the pressure equation which can be derived by summing conservation over all mobile components. Equation (1.2) governs heat conservation. Finally Equations (1.3) and (1.4) govern pseudocomponent mass conservation for the remaining $N_c - 1$ mobile components and the solid fuel respectively.

We found that there are seven independent parameters. The first two (Π_{rf} and Π_{sf}) relate the capacity of the rock and solid to retain heat compared to the fluid. These numbers provide insight into the systems sensitivity to convective heat flow upstream of combustion as well as to heating by external sources. Three of the remaining five parameters are mass Damkohler numbers (Π_{mp} , Π_{ml} , and Π_{mh}) expressing the ratio of mass transfer by each of the three types of reactions to the convective transfer. Finally, the ratios of the heats of reaction appear as the last two parameters (Π_{hl} and Π_{hp}). In essence, parameters derived specific to one of the three reactive modes can serve physically to characterize the oil burn mode. For example, groups for a particular oil with very low values for Π_{hp} and Π_{hl} may not even develop high peak temperatures if group Π_{mh} is also small. Note that choosing not to distinguish scalings for each reaction category results in four groups less; the characteristic heats of reaction and the Arrhenius factors become constants taken over all reactions. We remark also that in these parameters the compressibility effects do not come into play. They are however included in the dimensional analysis and appropriate scaling numbers for such effects can be derived.

$$A_\tau^T = -\left(F_\xi^T + Q_{rx}^T\right) \quad (0.1)$$

$$E_\tau^T = -\left(F_\xi^h + \Delta H_{rx}\right) \quad (0.2)$$

$$A_\tau^\nu = -\left(F_\xi^\nu + Q_{rx}^\nu\right), \quad \nu = 2, \dots, N_c - 1 \quad (0.3)$$

$$A_\tau^s = -Q_{rx}^s \quad (0.4)$$

Here, A^T is the total mobile phase mass accumulation, E^T is the total internal energy accumulation, C_ν are the component total molar densities, F_h^T , F_h^e , and F_h^ν are the spatially

discretized advective flow terms for all mobile phases, total fluid enthalpy, and total components respectively. ΔH_h is the net heat loss by reactions. Finally, Q_h^T and Q_h^V are the net mass destruction due to reactions for all mobile components and for component v respectively.

A second purpose of the scaling is to cast modeling analysis in a more physically motivated form. The system of reactions can be regarded as isolated from flow. For example, in a batch reactor where pressure and temperature are uniform, and flow only occurs by an oxidation and an effluent feed. In such a setting, we may be interested in the evolution of the composition of the system with time. The governing system of equations is a system of coupled, autonomous ordinary differential equations. The eigenvalues of the Jacobian matrix of the reaction rates with respect to the concentrations characterize the stiffness of the problem. In Appendix B of Younis and Gerritsen (2006) we derive these eigenvalues for a simple yet representative system of five reactions and two oil pseudocomponents. The eigenvalues, depending on the dimensionless parameters and conditions, can become quite stiff. This numerical characteristic of reactions typically calls for specialized numerical integration methods that are considerably different than methods used to solve pure compositional transport problems.

Building the framework

There is a vast literature on the development of splitting methods and their applications to various problems. Classic texts include Yanenko's seminal (Yanenko (1971)) and reviews include Reinout and Quispel (2002) and LeVeque and Olinger (1983). The ISC problem however does not immediately fit into a single splitting approach. This is due to the fact that the governing equations couple additive (hence separable) and non-additive operators, and that all physics are constrained by the instantaneous phase equilibrium constraints. In the ISC equations for example, reactions and advection are additively separable, whereas the saturation dependent mobility and pressure gradient parts of advection itself are not. In this section, we first present a broad categorization of splitting frameworks, followed by a novel framework tailored to ISC which combines several classic ideas.

In the broadest sense, numerical *operator splitting* can be achieved in two ways. The first, referred to here as Implicit-Explicit splitting (IMEX), is most familiar to reservoir simulation contexts through semi-implicit methods such as IMPES and sequential methods. The second, referred to here as Additive Splitting (ADS), is Yanenko's additive splitting. Well-known applications of ADS are dimensional-splitting such as the Peaceman-Rachford ADI method. For the purpose of clarity, we choose the simple illustrative system (1.5) where we can think of the first operator \mathbf{f}_A as advection, and the second \mathbf{f}_R as reaction, and u_1 as pressure or temperature, and u_2 as a saturation or concentration.

$$\mathbf{u}_t = \mathbf{f}(u_1, u_2) = \mathbf{f}_A(u_1, u_2) + \mathbf{f}_R(u_1, u_2) \quad (0.5)$$

In an IMEX approach, one time-integration method is chosen for the accumulation terms of the full set of equations. Then, operator variables are chosen to be treated implicitly or explicitly. This choice can be made on a variable basis over the entire operator \mathbf{f} , or on each of the additive operators, \mathbf{f}_A and \mathbf{f}_B . These two IMEX approaches are illustrated in Equations (1.6) and (1.7) respectively. In (1.6) u_1 is solved for implicitly and u_2 explicitly. This leads to a natural decoupling where the equation for u_1 can be solved first, followed by the equation for u_2 . IMPES is an example of this approach with u_1 representing pressure and u_2 saturation. In the second

approach, the variables are treated implicitly in one of the additive operators and explicitly in the other as in Equation (1.7). The equations do not de-couple, but computationally this might be advantageous if complex nonlinear terms are partially or fully explicit. Here for example, advection takes an implicit pressure whereas reactions take only concentrations implicitly. It is easy to deduce that IMEX approaches can introduce robustness and accuracy issues. Also, they do not generally offer specialization to sub-process integration methods. However, for operators with non-additive nonlinear coupling IMEX based methods may be the only feasible alternative to complete coupling.

$$\mathbf{u}^{n+1} - \mathbf{u}^n = k \mathbf{f} \left(u_1^{n+1}, u_2^n \right) \quad (0.6)$$

$$\mathbf{u}^{n+1} - \mathbf{u}^n = k \left[\mathbf{f}_A \left(u_1^{n+1}, u_2^n \right) + \mathbf{f}_R \left(u_1^n, u_2^{n+1} \right) \right] \quad (0.7)$$

ADS methods do not necessarily start by fixing a time-integration scheme. Rather, the solution process is viewed as a composition of solution operators to sub-processes. That is for example, given a state at time t , the system evolves to $t + \tau$ by first allowing a number of sub-steps of reactions, followed by one step of advective propagation of the result. As those sub-steps become arbitrarily close, we hope to retain the continuously coupled solution. This implies that at each sub-step, we will generate intermediate sub-solutions that do not themselves honor the entire physical process. The way that these sub-steps are then composed into a coupled solution involves careful, problem-specific design. This is because a *splitting error* is introduced, and we want this error to disappear as time-steps become arbitrarily small (a notion of accuracy). Equation (1.8) shows an example ADS for system (0.5). We can apply ADS to all nonlinear additively separable operators, while affording highly specialized methods for each step.

$$\begin{aligned} &\text{Given } \mathbf{u}(t^n), \\ &\frac{d}{dt} \mathbf{u}^*(t) = \mathbf{f}_R(u_1^*, u_2^*), \quad \mathbf{u}^*(t^n) = \mathbf{u}(t^n), \\ &\frac{d}{dt} \mathbf{u}^{**}(t) = \mathbf{f}_A(u_1^{**}, u_2^{**}), \quad \mathbf{u}^{**}(t^n) = \mathbf{u}^*(t^{n+1}), \\ &\mathbf{u}(t^{n+1}) \leftarrow \mathbf{u}^{**}(t^{n+1}) \end{aligned} \quad (0.8)$$

It is shown in Younis and Gerritsen (2006) that the splitting process leaves no splitting error if this commutator is zero, using a Lie operator formalism through which the composed solution operators are linearized. This fact emphasizes that for nonlinear problems, there are no optimal black-box methods, since all depends on the actual physical coupling of the problem at hand. For linear problems on the other hand, it is easier to design generic methods since in this case, the splitting error depends on whether the matrix operators commute; an algebraically characterizable property.

We can combine this operator splitting method with fractional steps in two ways; at the splitting design level, as well as at the time-discretization level. The first option means that instead of (0.8) for example, we can write another system (1.9), where the sub-steps are symmetrically split in half for the reaction operator. This is known as a Strang splitting. This is suitable for well-understood problems, but can become technically overwhelming when the operators are highly

complicated. The second option means that the splitting (0.8) itself is selected, but that then, each ordinary differential equation is discretized in time with a scheme that has specialized intermediate stages. For example, the reactions can be integrated by a stiff Runge-Kutta method and the advection by an Euler scheme with a single step. The second approach simplifies the splitting analysis, and defers the fractional-step analysis to picking a highly robust method for each ODE. Finally, it is at least conceptually possible to apply both options.

$$\begin{aligned}
& \text{Given } \mathbf{u}(t^n), \\
& \text{Fix } \tau_{1,2} = k/2, \\
& \frac{d}{dt} \mathbf{u}^*(t) = \mathbf{f}_R(u_1^*, u_2^*), \quad \mathbf{u}^*(t^n) = \mathbf{u}(t^n), \\
& \frac{d}{dt} \mathbf{u}^{**}(t) = \mathbf{f}_A(u_1^{**}, u_2^{**}), \quad \mathbf{u}^{**}(t^n) = \mathbf{u}^*(t^{n+\tau_1}), \\
& \frac{d}{dt} \mathbf{u}^{***}(t) = \mathbf{f}_R(u_1^{***}, u_2^{***}), \quad \mathbf{u}^{***}(t^n) = \mathbf{u}^{**}(t^{n+1}), \\
& \mathbf{u}(t^{n+1}) \leftarrow \mathbf{u}^{***}(t^{n+\tau_2})
\end{aligned} \tag{0.9}$$

It is generally not always feasible to split reactions by applying one ADS approach directly to all equations. That is since the number of chemical reactions may be less than the number of primary concentrations; $N_r \leq N_c - 1$. This is common in the ISC problem, where there are several non-condensable gas components that are inert, and of all the components, only hydrocarbons and Oxygen are reactants. For this reason, we focus our attention to a more general approach.

The pressure equation is best treated implicitly for pressure. In the absence of conduction, the heat equation can be treated explicitly in temperature. So, first pressure is aligned with the pressure equation, where temperature and concentrations are taken explicitly on both operators. This is followed by temperature which is aligned with the heat equation, taking the new pressure, and explicit concentrations. Finally a symmetric Strang splitting is selected to separate the reactions from the transport. These are obviously aligned with the concentrations. Depending on the number of independent reactions present, we split a sub-set of the concentration transport equations. In particular for $N_r \leq N_c - 1$, we perform ADS on the concentration equations aligned with reactant components, and solve the remaining concentrations without splitting. This is possible since concentrations are taken explicit. For $N_r = N_c$, the ADS is performed on all concentration equations and the heat equation. This since temperature appears in all types of reactions, whereas pressure is only explicitly involved with oxidation reactions involving Oxygen. Finally, for $N_r \geq N_c + 1$, we perform a direct ADS on the entire system of primary variables.

The scheme for the case $N_r = N_c - 1$, and a backward-Euler time discretization is represented in Equation (1.10). Note that without the ADS the scheme (1.10) becomes an IMPEC form with explicit temperature treatment. Clearly, we may further leverage specialized solvers to numerically integrate the ADS sub-steps such as a Runge-Kutta method for reaction steps.

$$\begin{aligned}
\left[A^T \right]_{(p^n, T^n, C_v^n)}^{(p^{n+1}, T^{n+1}, C_v^{n+1})} &= -k \left[F_h^T + Q_h^T \right]_{(p^{n+1}, T^n, C_v^n)} \\
\left[E^T \right]_{(p^n, T^n, C_v^n)}^{(p^{n+1}, T^{n+1}, C_v^{n+1})} &= -k \left[F_h^e + \Delta H_h \right]_{(p^{n+1}, T^n, C_v^n)} \\
C_v^* - C_v^n &= -\frac{k}{2} \left[Q_h^v \right]_{(p^{n+1}, T^{n+1}, C_v^n)} \\
C_v^{**} - C_v^* &= -k \left[F_h^v \right]_{(p^{n+1}, T^{n+1}, C_v^*)} \\
C_v^{***} - C_v^{**} &= -\frac{k}{2} \left[Q_h^v \right]_{(p^{n+1}, T^{n+1}, C_v^{**})} \\
C_v^{n+1} &= C_v^{***}
\end{aligned} \tag{0.10}$$

The inclusion of various sets of phase equilibrium constraints with each of the three distinct splitting stages of scheme (0.10) is highly dependent on the particulars of the problem. In the case of the reactive steps for example, component molar phase fractions may be necessary if a reactant only reacts in one phase. In this case, the minimal number of necessary constraints are identified and added to the reaction system to be solved. For ISC in particular, since reactants tend to be oil phase components, solid fuel, and Oxygen only, constraints involving steam and non-condensable gases may be excluded. Any primary variables appearing in this subset of constraints that are not aligned with the reactions are taken at their respective time level in the scheme. This implies that for the ADS process in (0.10), the first reactive step computes flash calculations using old primary variables. For the subsequent advective and reactive stages, the latest primary variables are used.

The treatment of boundary conditions is very important to both the accuracy and stability of such methods. Analysis is particularly difficult for such problems since it is not generally known *a priori* how the boundary conditions contribute to the commutator. Several boundary correction techniques have been proposed, see, e.g., LeVeque (1985). These rely on physical intuition to decide which boundary conditions influence which operator most. In this discussion, we choose to include the gas injection as a source boundary condition in the reactive steps since otherwise, the reactions would lag behind, and the onset of combustion is retarded. The treatment of wells in general is similarly an issue requiring further consideration.

The present scheme is not necessarily optimal. We chose the same time-integration method for all equations (backward Euler), and a Strang Splitting for the ADS. Higher accuracy time-integration is deferred to further work, where the issues of flash calculations are to be addressed. As for the ADS, the splitting error analysis for nonlinear problems is technically involved, yet tractable. The idea is to select splittings motivated by the dimensionless parameters, and then to present the corresponding splitting errors. Another approach is to compute optimal fractional steps, given a splitting, once again in forms relating the dimensionless parameters.

2.2.2 Experimental work

In previous quarters we reported on the experimental work performed to assess the usefulness of metallic additives in improving the ISC process. The work has now been completed and is published in Crisofari et al. (2006).

This quarter, we started looking at UGNU oil from Alaska to understand the reactive behavior of this oil in a combustion process and assess its suitability for ISC processes. Because we currently only have a small amount of UGNU oil available we were not yet able to run a combustion tube run. An additional motivation for performing these kinetic runs was that they were an excellent way for our new MSc student Mr. Romiti Awoleke to become familiar with the experimental set-up and ISC processes. The experimental set-up is discussed in the next section.

3. Experimental

Figure 1 is a graphical summary of the experimental equipment. The combustion tube measures the ability of a combustion front to propagate through a given combination of crude oil, water, and porous medium. The kinetics cell is used to characterize activation energies of combustion as well as oxygen consumption. The combustion tube, or alternately the kinetics cell, is coupled to a gas analyzer, traveling thermocouple, and data logging system. Briefly, the gas analyzer collects effluent gas composition. Oxygen and nitrogen are provided by gas cylinders and metered using a mass flow controller. Temperatures are recorded every centimeter along the length of the sandpack during a combustion tube run, while in the kinetics cell tests, temperatures are measured in the center of the cell.

The combustion tube is made of stainless steel (316) with a wall thickness of 0.014 cm. It is 1.0 meter long with an inner diameter of 7.5 cm. It is packed with a multiphase mixture of sand, clay, oil, and water as detailed later. A 240V, 1000W igniter coil surrounds the tube between 10 to 15 cm from the top of the tube. Prior to ignition, the combustion tube is placed vertically in an insulator jacket and the annular space between the tube and the wall of the jacket is filled with insulating vermiculite. A Matheson mass flow controller (model 8240, range 0.1-5 SLPM) is connected upstream of the tube to control the rate of air injection. At the outlet of the combustion tube, liquid is separated from the gaseous products. Centrifuge vials (50ml volume) are used to collect the produced liquid for later analysis.

The gas leaving the separator is cooled by a condenser and then dehumidified. A backpressure regulator elevates the system backpressure to 100 psig (690 kPa). A part of the effluent stream then flows through two acid scrubbers containing potassium permanganate. All the other effluent is vented. The scrubbed effluent is then directed to a Xentra gas analyzer (model 4200, 0.1% error). This is a compact gas analyzer, measuring oxygen, carbon dioxide, carbon monoxide, and methane concentration. Measurements are made once per minute. The outlet streams from the analyzer are vented.

A thermal well (3.2 mm O.D., 316 stainless steel) is set in the center of the tube and spans from top to bottom. During the combustion process, a traveling thermocouple measures the temperature as a function of time and distance from the top. A measurement interval of 1-5 cm is generally used depending on the temperature profile and front velocity. The interval is chosen so that a complete traverse of the tube occurs with negligible movement of the combustion front.

The kinetics cell is a thick-walled stainless steel (316) cylinder that is 13.3 cm long and 4.82 cm (O.D) in diameter. The cylinder was sealed by means of knives and annealed copper gaskets. The 0.76 mm (0.030 in) knives were machined into the end face of the cylinder and the endcaps. With pressure at the two ends, the knives on the end of cylinder and the endcaps cut into the gaskets providing a contact seal. Air is injected from the bottom of the cell. Prior to injection, air flows

through coiled 3.2 mm (1/8 in.) tubing and is preheated. On the top of the cell air exits and the temperature is measured. The kinetics cell is packed with a mixture of oil, water, and sand. Two thin-walled stainless steel cups are put inside the kinetics cell. The upper cup is 7.1 cm long with I.D of 2.7 cm. This cup is filled with the oil and sand mixture. The lower cup is filled with dry sand. It serves as a preheater and disperses the inlet air to obtain one-dimensional air flow. Both cups are perforated on the bottom to allow air flow. Sand migration is prevented by 200-mesh stainless steel screens placed across the bottom of each cup.

Oil Sample

The characteristics of the Ugnu oil from Alaska are given in Table 1.

API gravity	19
Viscosity	123.28 cp at 25 degrees Celsius
Asphaltene contents	4.44%
Acid number	0.98 mg/g
Base number	3.39 mg/g

Table 1. Characteristics of UGNU oil.

Kinetic cell experiments

We placed 5 grams of oil mixed with 85 grams of sand, 5 grams of kaolinite clay and 5 grams of water inside the kinetic cell. Air was flown through the sample while the temperature was gradually increased as shown in Figure 2 which shows the temperature profile as a function of time.

4. Results and discussion

4.1. Computational framework for ISC equations

For time-integration of the inherently multi-physics and scale of the problem, we have worked towards developing a natural and intuitive method that incorporates physical scaling. The emphasis of the work is not only to develop methodology that is on par with the FIM in terms of cost, but also to introduce the possibilities for higher accuracy in a way that neither FIM nor IMEX-type methods alone could really do.

We have tested the new framework on 1D combustion tube test problems which we also simulated using a fully—implicit method developed in-house. The results so far serve as a proof of concept only and are reported on in full detail in Younis and Gerritsen (2006). The underlying solvers we are using are not optimized and further work is necessary. We will, for example, merge the solver with the specialized Virtual Kinetic Cell (VKC) time integrator reported in Kristensen *et al.* (2006).

We note that comparison with STARS is very difficult because of the great sensitivity of the solutions to boundary conditions, and the fact that we do not have available exact implementation details of these conditions in STARS. Also, property packages used may lead to small differences which in this nonlinear problem can affect solutions greatly. The agreement of the new framework solution with the fully-implicit solutions is good.

4.2. Experimental work

In the gas composition graphs depicted in Figure 3 two distinct regions can be observed: a low temperature oxidation (LTO) region and high temperature oxidation (HTO) region. They are visible as the two peaks on the graphs.

Analysis of the results gives the reaction rates R and activation energies E_a given in Table 2 for both HTO and LTO.

Reaction	E_a/R	E_a	R
LTO	11455.92	95247.98	0.9993
HTO	16319.74	135687.23	1.0000

Table 2. Reaction rates R and activation energies E_a for UGNU oil.

This is only part of the analysis required of the UGNU oil to assess its suitability for In-Situ Combustion processes. As soon as we received extra volume of oil we will conduct combustion tube runs to complete the analysis.

5. Conclusions

5.1. Towards a new ISC framework

In conclusion, we started from basic fundamentals on physical observation, and characterized scaling issues and stiffness at the modeling level. Through the dimensional analysis we identified seven important dimensionless parameters. We designed a fractional-step IMEX-ADS scheme that is general to thermally reactive transport, but specific enough for a viability study. While the particular details of the scheme are not necessarily optimal, we address the temporal multi-scale nature of ISC. We outlined how the dimensionless parameters may be used to help design.

Future research will be directed towards developing robust design criteria for the splitting method based on parameter guided analysis, and numerical studies for various ISC regimes and problems. We will also work on resolving criteria for the treatment of phase behavior constraints in both, multi-stage time integration, and in the context of ADS. Furthermore we hope to improve flash computation algorithms for coupled solutions.

In the not so near future we will couple this temporal solution approach to the spatial adaptivity that we developed in previous quarters and is published in Gerritsen and Lambers (2006), and implement and extend this temporal framework to general heterogeneous media.

5.2. Experimental work

In this quarter, we performed a preliminary analysis of UGNU oil to assess its suitability for ISC processes. The project was performed also as a lead-in project for our new MSc student Rotimi Awoleke.

Mr. Awoleke will in the next quarter and following year focus on the very interesting question of how the performance of ISC processes depends on reservoir heterogeneity. The answer to this question is not at all clear. We will use both numerical simulations (using our in-house simulator as well as STARS), and also experimental work. The experimental work will be done first as a guide to the numerical experiments. A first experiment will be using a Berea sandstone core inserted in our combustion tube and surrounded by Ottawa sand. The permeabilities are about 200 mD for the sandstone and 5 D for the sand, as seen below. The core is fractured through the middle to allow temperature measurements. Various arrangements will be investigated, one of which is illustrated in Figure 4. Besides the conventional temperature measurements we plan to use the CT-scanner to keep track of the combustion process in the heterogeneous tube. We expect to conduct the first run on this system by June 2006

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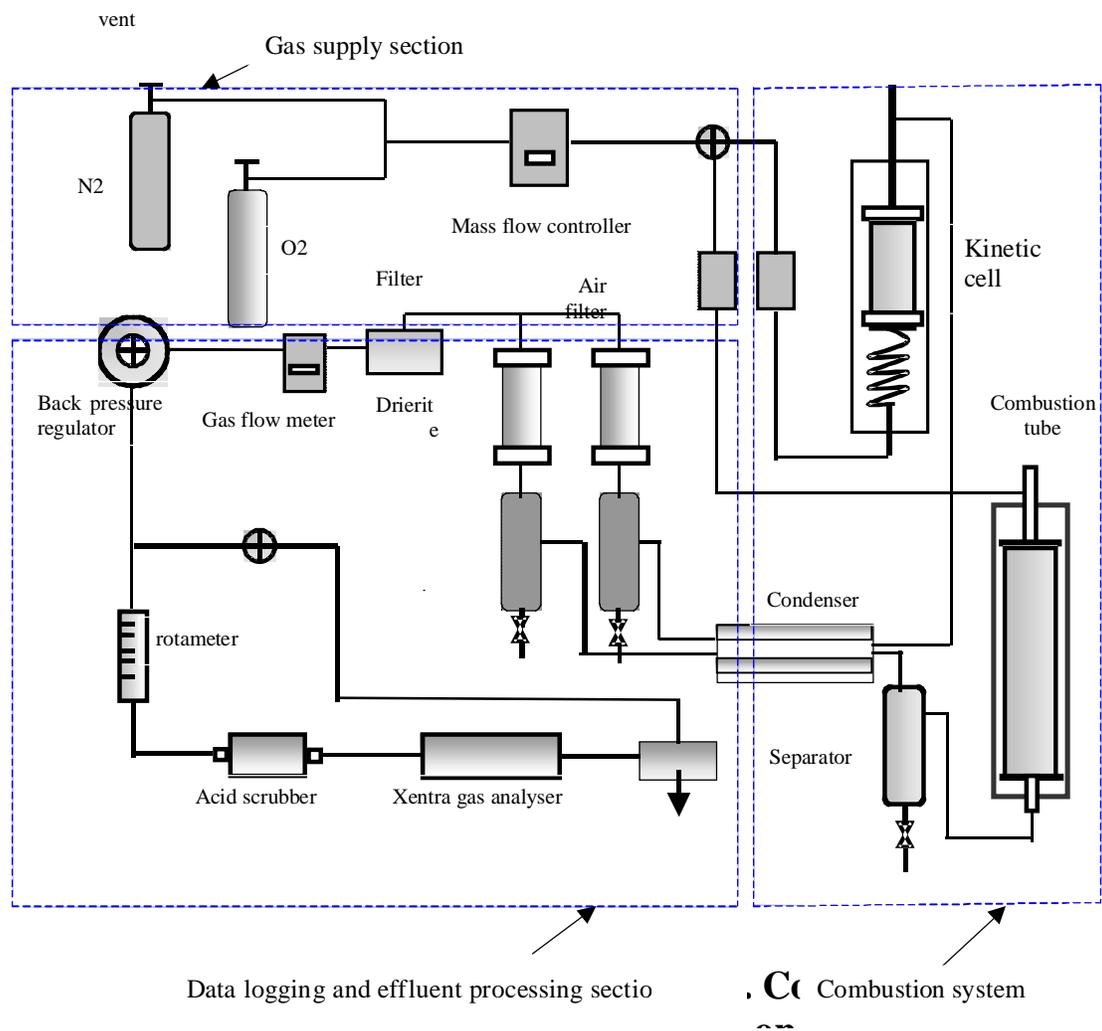


Figure 1. Schematic of combustion tube and kinetics cell assembly.

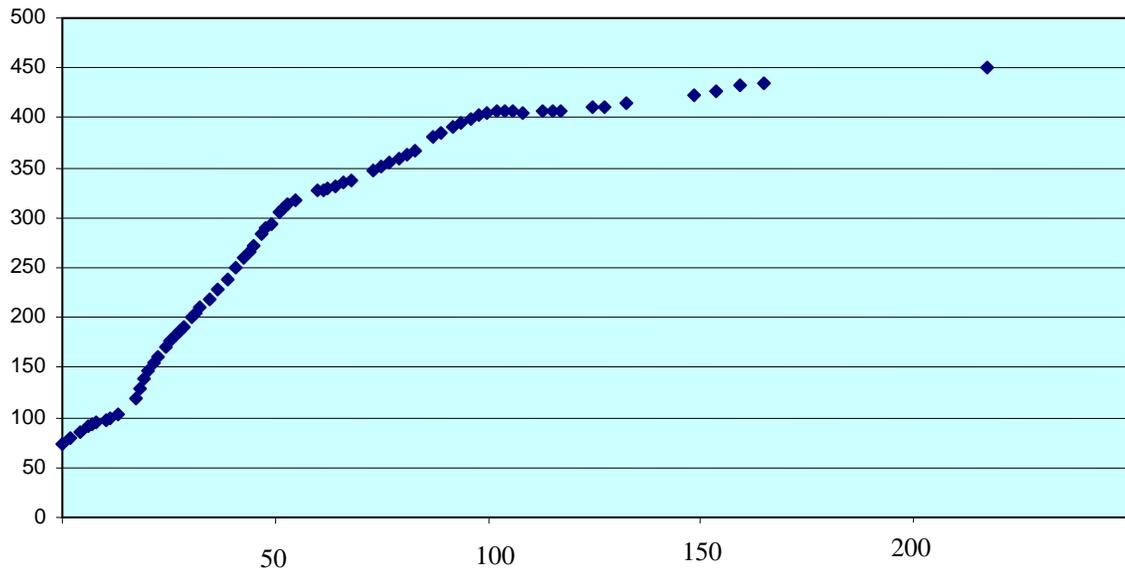


Figure 2. Temperature profile of the UGNU kinetic cell experiment as function of time (in mins)

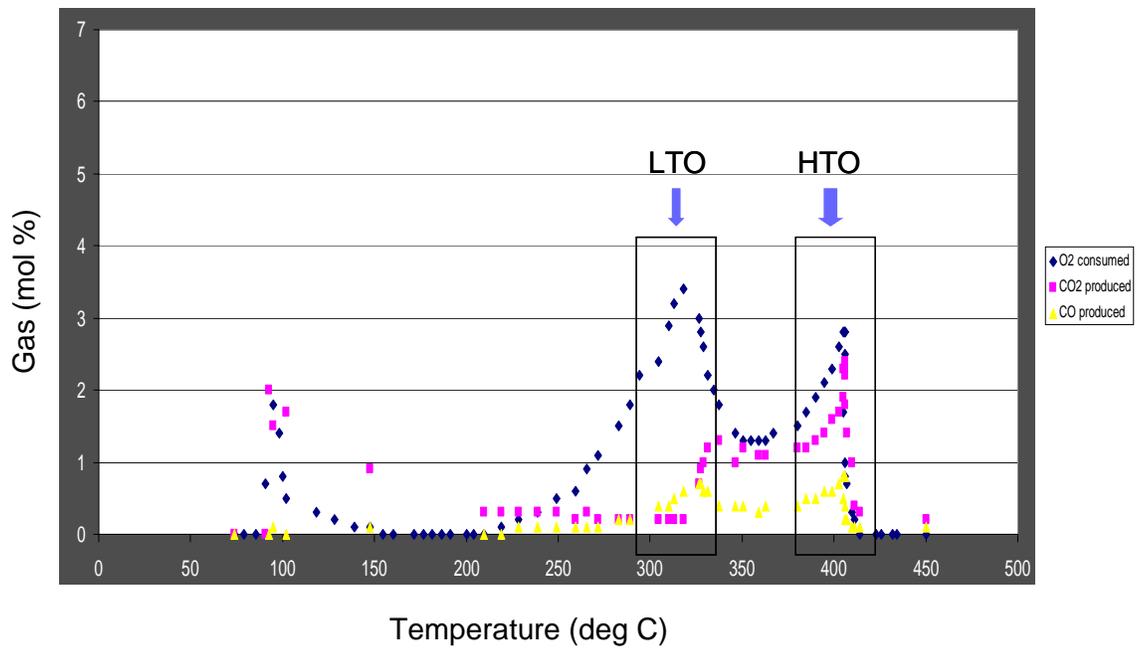


Figure 3. Gas composition vs temperature for the UGNU oil kinetic cell experiment

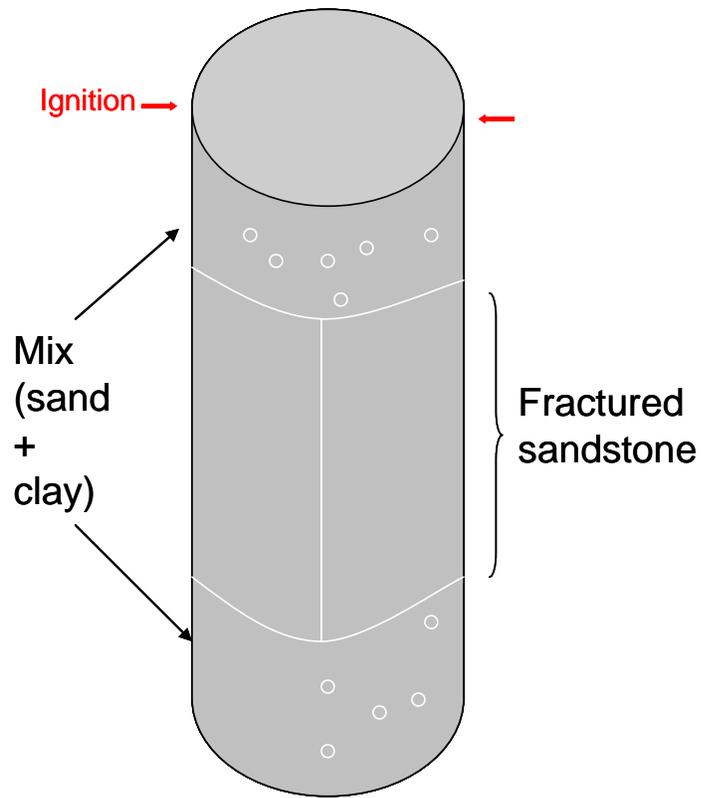


Figure 4. One possible configuration for future combustion tube experiment to investigate the effects of heterogeneity on ISC processes.