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# Numerical Modeling and History Matching of Super-Wet Combustion Tube Test

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NORWEGIAN UNIVERSITY OF SCIENCE AND  
TECHNOLOGY (NTNU)

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Master Thesis

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## **SUMMARY**

A number of laboratory experiments are defined and implemented to reveal the in situ combustion behavior on core samples drilled from heavy oil reservoirs under specifically designed conditions. The accelerating rate calorimetry (ARC) test, the ramped temperature oxidation (RTO) test and the combustion tube (CT) test are the main screening experiments which can provide relevant data for the in situ combustion process.

There are different types of combustion process depending on the injection fluid, normal dry combustion with injection of air or oxygen, the wet combustion is termed when water is injected with air and the super wet combustion process is defined with relatively high water-air ratio. Wet and super wet combustion is a primarily object of this study.

In the present work, a modeling and history matching study has been performed on the wet/super wet CT experiment in order to get better insights into the in situ combustion process occurred during the experiment. The literature has been carefully reviewed to recognize the experimental details and analyze the kinetic reactions. The main kinetic reactions are thermal cracking process, low temperature oxidation and high temperature oxidation. The parameters influencing the kinetic reaction are identified and evaluated.

The modeling and history matching work has been done to understand the kinetic reactions happened in the experiments. The simulation model is created based on the Belgrave's model for the CT experiment and the data file is run with the STARS. The results are presented and analyzed. The simulation results are aimed to match all experimental results. History matching has been performed to get the best match between the simulation and experiment on the temperature profiles. Different parameters have been considered as variables: frequency factor, activation energy and coke precipitation parameter, relative permeability, saturations and gas injection rates.

The results show that the frequency factor, activation energy and coke precipitation have significant influence on the kinetic reactions, mostly on the reaction where Maltene is converted into Asphaltene in the Belgrave's model. After manual history matching, the automated history matching algorithm by utilizing BASRA HM tool has been successfully tested.

# 1 INTRODUCTION

## **1.1 Scope**

The main scope of the present work is to understand kinetic mechanisms of super wet/wet in situ combustion by modeling. Modeling and history matching have been tested for the super wet combustion tube test.

## **1.2 Outline**

The present thesis contains seven main chapters as follows.

The first chapter is the introduction part and prepares the scope and outline of the work.

The second chapter gives a literature review of bitumen reserves, the concept of in situ combustion (ISC) process, relevant laboratory tests and numerical approaches.

The third chapter is the main body of this study. It contains the numerical modeling and history matching on the super wet CT experiment. The simulation

package from the Computer Modeling Group (CMG) is used to model the kinetic reactions.

The fourth chapter presents results obtained from the numerical modeling and history matching and discusses the results.

The fifth chapter summarizes main conclusions and the sixth chapter includes references and the seventh chapter is Appendix and presents the data file.



## 2 LITERATURE REVIEW

### 2.1 Heavy Oil Reserves

There are two types of oil resources; the conventional and unconventional resources. The term conventional resource is used for a reservoir that liquid hydrocarbons (mostly gas and oil) flow naturally into reservoir rocks. The unconventional resource is named to the reservoir having unconventional oils which cannot flow easily. The unconventional oils are characterized by high viscosities and high densities compared to the conventional crude oils. The main products of unconventional oils are heavy oil, extra heavy oil and bitumen. The density and viscosity of different subdivided crude oils are shown in **Table 1**.

**Table 1:** Classification of crude oils (after Cornelius 1987)

Type of oil	Density range (Kg/m <sup>3</sup> )	Viscosity range (Pas)
Conventional oil crude	<934	<0.05
Heavy oil	934 – 1000	0.05 – 5
Extra heavy oil	1000 – 1044	5 – 10
Natural bitumen	> 1044	> 10

Sarathi (1998) and Turta et al. (2007) have reported many heavy oil fields around the world. It is estimated that there is more than 4000 billion barrels of extra heavy oil and bitumen accumulated worldwide. These resources are primarily located in Venezuela and Canada.

Up-to-date, the most of bitumen is recovered by thermal recovery methods. One of the promising methods for development of bitumen is the *in situ* combustion technique (Ursenbach et al, 1993).

## **2.2 Concept of In Situ Combustion Process**

The oil recovery method by air injection is one of Enhanced Oil Recovery (EOR) technologies. Known that the term "In Situ Combustion" (ISC) is called to the air/oxygen injection implemented into the very heavy oil (bitumen) reservoirs to assist oil production. In general, air is injected into the reservoir, and oxygen in air reacts with hydrocarbons, thereby resulting oxidation and combustion reactions. As a result, heat is generated and the temperature at the combustion front is rapidly increased and oil viscosity is reduced. An oxidation bank is formed and propagated through the reservoir. The oil is mobilized through the unheated portion of the reservoir to production wells. Although various mechanisms like steam drive, hot water, water drive, gas flood, and thermal alteration are introduced for the ISC process, but the oil viscosity reduction is the main recovery mechanism under the ISC process.

The ISC process was commercially applied in fields at 1950's, with success and failures (Turta et al. 2007). In the past, there were practical problems such as ignition, control of combustion front propagation, corrosion and emulsion giving less creditable application of ISC to oil fields. However, an analysis of the past tests may activate a renewed interest in ISC (Turta et al. 2007).

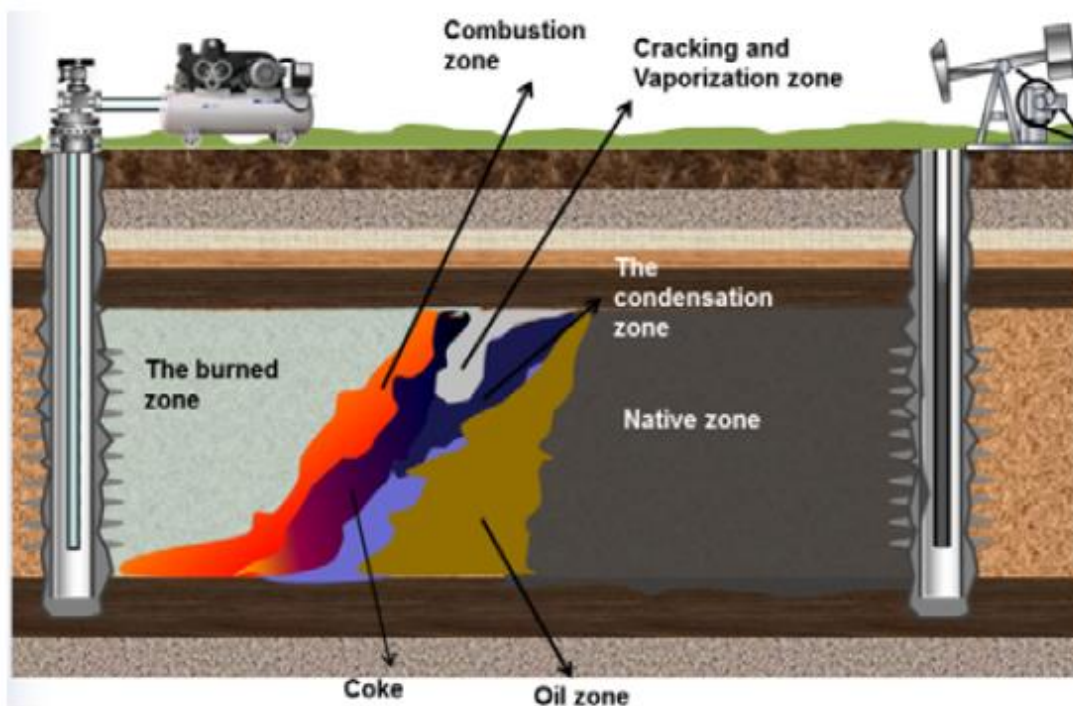
Today, due to increasing oil price, high demand for oil and recent technological development, the ISC method is being interested, especially to the bitumen or extra heavy oils where other recovery processes are uneconomic or ineffective. Using the ISC has few advantages, for instance, air is freely available, therefore only air compressor is required and also air can penetrates to low permeable

layers where the water cannot be injected. Besides to advantages, it should be pointed out that the evaluation of ISC process is difficult, because oxidation and combustion reactions are complicated. Therefore, experiments and numerical reservoir simulations are essential to evaluate the applicability of ISC to heavy oil field (Panait-Patica et al. 2006).

There are different forms of in-situ combustion, namely classified with respect to direction of combustion direct and reverse combustion; as well as with regard to injection fluid and injection conditions: dry combustion, reverse combustion and wet and super wet combustion.

### 2.2.1 Dry Forward Combustion

The dry forward combustion is a common form of the in situ combustion process. It is dry process because no water is injected with the air. The combustion is forward because ignition occurs near the injection well and the burning front moves from the injection well to the production well. The mechanism of the dry forward combustion process is explained on the schematic as shown in **Figure 1**.



**Figure 1:** Schematic of dry forward combustion (after Oliveros 2013)

**Figure 1** shows a cross section of the formation that is expected in the dry forward combustion process. Between the injection well on the left and the producing well on the right, there is a burned out region. Ahead of the burned region is the combustion front. Immediately ahead of this is the coke region, which contains the products (usually called fuel) from the reaction of high temperature with crude oil in the combustion zone. Ahead of the coke zone are the steam zone which contains hot water. Then ahead of the hot water zone is an oil bank zone which involves light hydrocarbons. This oil bank has been pushed from the rear zones. Finally, ahead of the oil bank zone is the native or undistributed reservoir at a temperature near the original reservoir temperature. This region contains oil, water and flue gas as these fluids move toward the producing well. The CO<sub>2</sub> in the fuel gas may be dissolved in the crude oil and then results in the viscosity reduction and swelling of the oil (Oliveros, 2013).

The dry forward combustion process has advantages and limitations. The advantage is that less valuable fraction of the crude is burned in the form of coke and clean sand is left behind the combustion front. There are two limitations, first is that a lot of produced heat during combustion process is stored in the burnt zone near the injection well and cannot be efficiently moved forward. The reason is that the injected air does not effectively carry the heat forward.

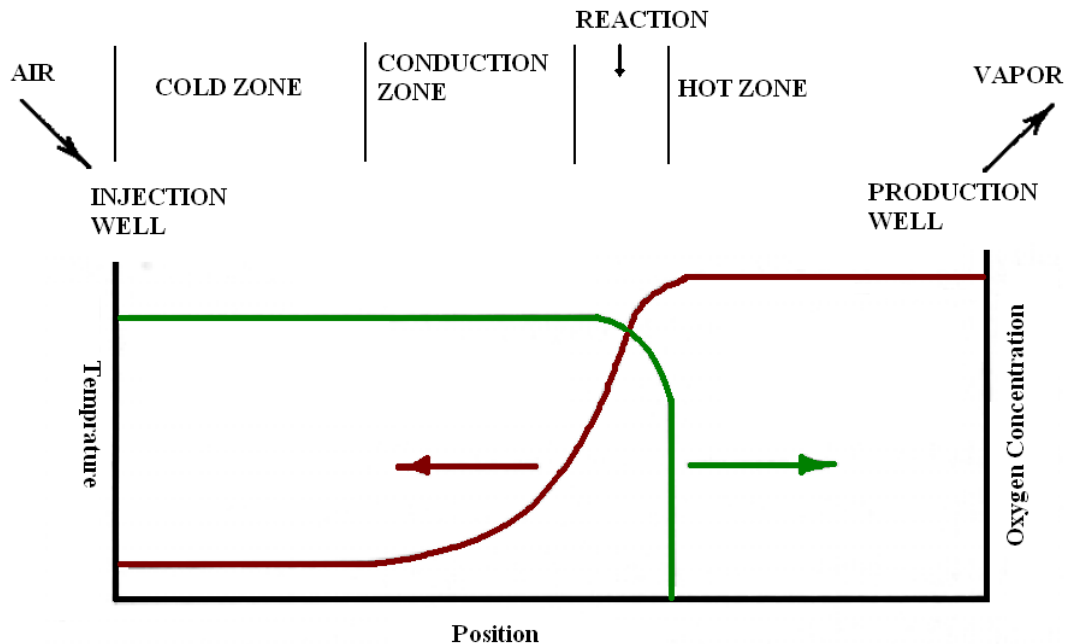
The second limitation is the pore blocking by liquid or the produced oil. Several laboratory and field studies show that during the dry combustion process, approximately 5 to 10% of the oil in place is consumed as fuel while the rest is mobilized and available for production. This feature indicates that the combustion front acts as a bulldozer to mobilize most of the oil immediately ahead of it. This action is not seen by the other driving mechanisms. This feature which is known as the bulldozing effect can be a problem for the heavy oil and bitumen reservoirs. The heavy oil and bitumen reservoirs have high oil saturations and the oil close to production well has low mobility (Moore et al. 1999).

When air is injected in this type of reservoir, the thermal front (due to bulldozing effect) has high ability at mobilizing oil. As a result, the oil saturation in the region

ahead of the combustion zone is immediately increased and creates pore blocking. Therefore, the reason for pore blocking is that the liquid saturation of mobilized oil becomes sufficiently high, thereby dropping the injection of air (Moore et al.1999).

### 2.2.2 Reverse Combustion

The reverse combustion is suggested to solve the pore blocking feature occurred in the dry forward process. Berry and Parrish (1960) have explained the principle of the reverse combustion. **Figure 2** shows the schematic of the reverse combustion process.



**Figure 2:** Schematic of reverse combustion (after Berry and Parrish 1960)

In contrast to dry forward combustion, the direction of the flame and air is opposite. Air moves from left to right. Ignition occurs near the production well at the right side, and the burning front moves countercurrent (against direction) to the flow of the injected air, from right to left.

As seen from the figure, the oil flows through a high temperature zone, where the oil viscosity is reduced. As the crude is displaced through the combustion front, it is cracked. The light ends vaporize and the heavy ends contribute residue to be burned as fuel. When the vapors go towards to the production well (right side),

they approach to the region behind the combustion front where the temperature is lower than for vapors. Then some condensation processes occur and the saturation of liquid oil and water becomes high close to the production well.

The reverse combustion is not as efficient as the dry forward combustion because a desirable fraction of the oil is burned as fuel and the undesirable fraction remains in the region behind the combustion front. This process requires about twice as much air as the dry forward combustion.

Another problem in reverse combustion is the strong tendency toward spontaneous combustion. The crude oil exposed to air will oxidize for few weeks to months. This naturally oxidation process will occur quickly at higher temperature near the air injection well and a forward combustion process will be initiated.

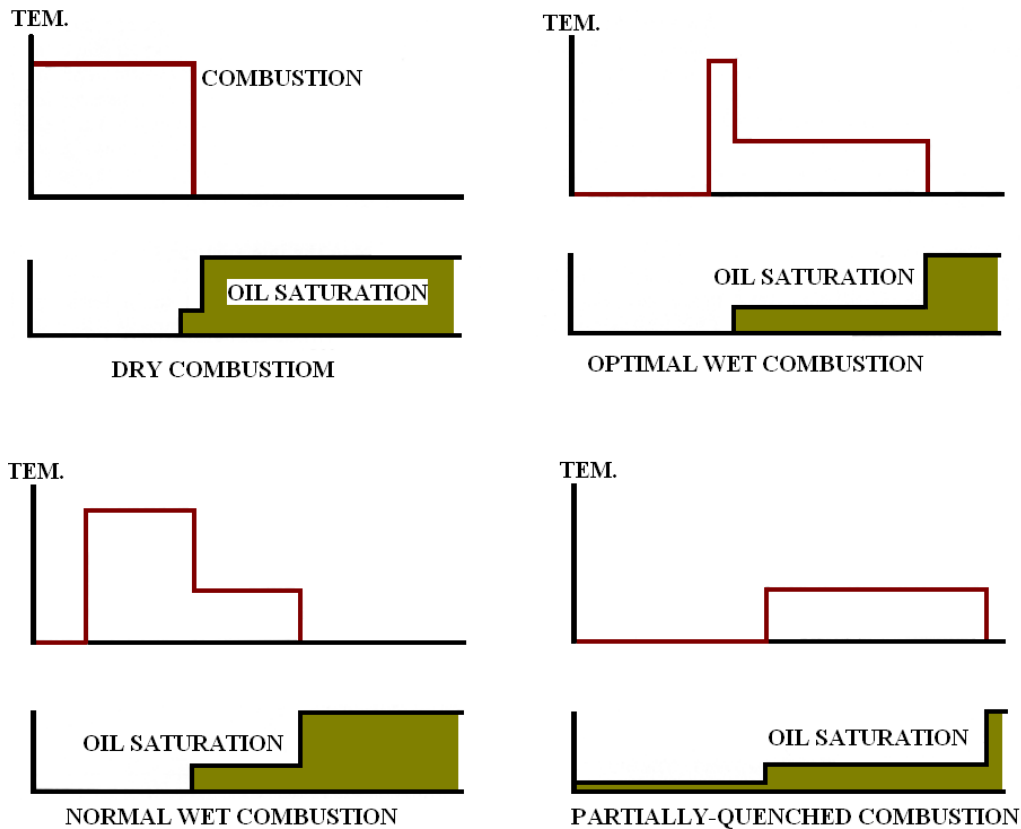
### 2.2.3 Wet and Super Wet Combustion

As mentioned above, more than half of the total generated heat is stored behind the combustion front during the dry forward combustion. Many attempts have been made to solve the problem. One of these attempts is to use water because water has high heat capacity and vaporization ability. Since water has a volumetric heat capacity approximately hundred times greater than air, it can utilize heat from the burnt zone, which eventually provide more efficient displacement of the front with steam. So summarizing the idea of using water during combustion, the main advantages is to reduce air requirement during the process and increase velocity of combustion front which positively will reflect economies of the projects.

In the wet combustion or after Parrish and Craig (1969) named it as COFCAW (combination of forward combustion and water flooding), water is injected into an injection well in a forward combustion process. The water can be injected with air alternately or simultaneously (normally wet combustion operations is proceeded by about 3 month of dry combustion). All or part of water will vaporize and pass through the combustion front and transfer heat ahead of the front. This treatment has many favorable benefits.

- First, this method can extend the steam or hot zone which has high capacity to reduce the viscosity of the cold oil.
- Second, the method can also be operated at lower pressure and with less fuel.
- Third, the amount of injected air or ratio of air to oil is reduced which aids to enhance economic.

A key parameter in the wet combustion method is to optimize the water to air ratio (WAR). Dietz and Weijdema (1968) have quantitatively discussed the water air ratio required for the wet combustion. **Figure 3** shows the change in temperature profile within the reservoir as the WAR varies.

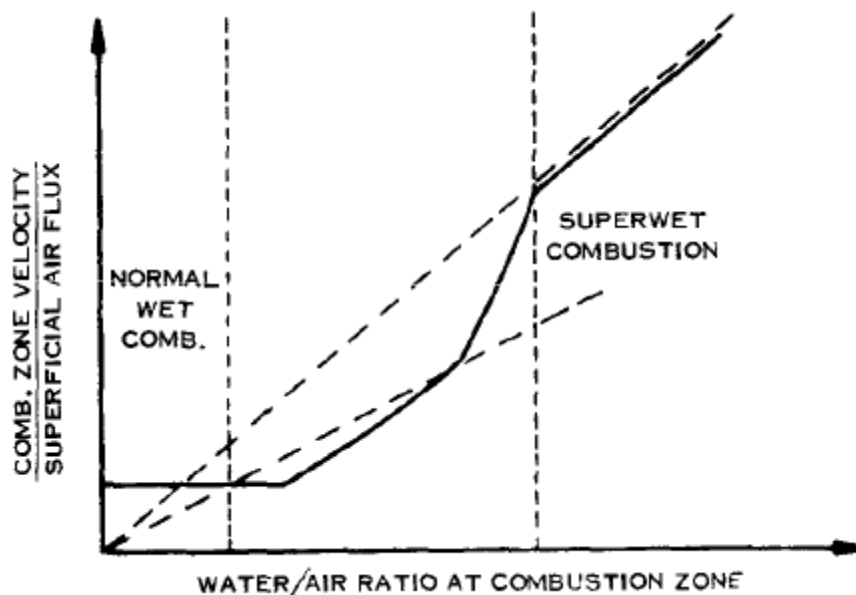


**Figure 3:** Schematic of wet combustion (after Dietz and Weijdema 1968)

If the WAR is zero, the combustion refers to the dry forward combustion. Thus adding water to the air converts the process into wet combustion and increases

the ability of the injection stream to recover heat. Increasing the water air ratio will increase the convection velocity to the point where it may match the velocity of the burning front. With the optimal WAR, the combustion zone temperature remains as high and the produced hot water front moves much faster than the combustion front. The heat is transferred forward and effectively used for oil displacement.

However, as the water air ratio increases (**Figure 4**), the dimension of the steam plateau is increased. The maximum temperature at the burning front declines and may reach the point where the burning is partially quenched. With further increase in the water air ratio the heat of combustion released is no longer sufficient to evaporate all the water projected through the combustion front. Some of the pumped water penetrating the high-temperature zone is evaporated and some passes through it in liquid form. This process has been called super wet combustion (completely quenched wet).



**Figure 4:** Water air ratio – Normal wet vs. super wet ISC (After Harmsen, 1969)

Therefore, super wet combustion is a modification of the wet combustion process that attempts to decrease the air requirement even further. The process does not increase oil recovery, but increases the velocity of the combustion front (reduce

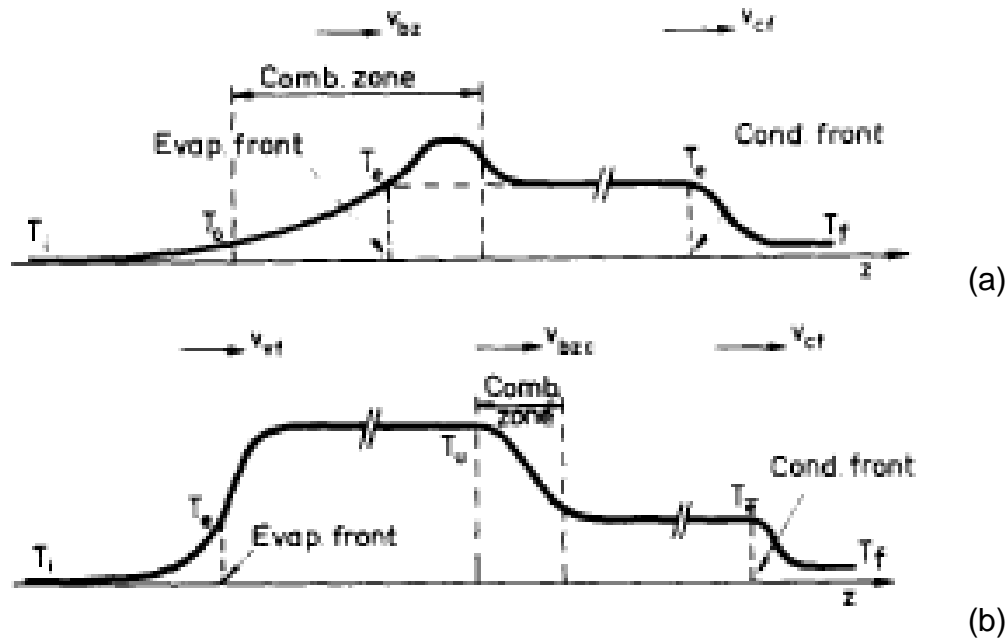


the time of the project-improve economics) and reduces compression costs. Water is injected at much higher rates than normal wet combustion. The temperature becomes lower than required for burning the front. Super wet combustion is more applicable in heavy oil reservoirs and less feasible for high gravity oils with low fuel deposits. Having introduced the optimal air/water ratio, it should be mentioned that its pressure and reservoir dependent and increase in water can bring negative effect.

Comparing the normal wet and super wet combustion is that in the normal wet process, almost all injected water is evaporated and the peak temperature is reached, while in the super wet mode, some amount of injected water converts to vapor and the rest remains as water phase and floods in the reservoir (Ursenbach et al, 1993). In super wet combustion temperature is never greater than the saturation temperature of water at the particular pressure.

Another way to view these processes is by means of the fuel concentration, as indicated by **Figure 3**. Dry combustion consumes a portion of the crude and displaces the rest by movement of the burning front. Wet combustion consumes the same quantity of fuel, but displaces more crude at a given burning front location. It must mention this fact that the steam and hot water banks have moved far ahead of the burning front. Clearly, there should be some optimal condition as suggested by **Figure 3**.

Partially-quenched combustion results (**Figure 5**) in a reduction in the maximum combustion temperature such that less than the normal fuel concentration is consumed. This results in a lower unit volume air requirement and a less expensive operation. The air requirement in an optimal wet combustion may be one third that required for a dry combustion if frontal displacement is the major oil recovery mechanism.



**Figure 5:** Temperature profiles for (a) partially quenched combustion and (b) Completed quenched combustion (After Beckers and Harmsen, 1970)

### 2.3 Experimental Methods for Screening Combustion

Laboratory studies play an important role in ISC characterization because as the ISC process has to be well understood before a successful field application. Different laboratory tests are used to gain data and information about the behavior of the ISC process before it is used for a given field. Most important tests are the Ramped Temperature Oxidation (RTO), Accelerating Rate Calorimetry (ARC), and Combustion Tube (CT) tests.

#### 2.3.1 Ramped Temperature Oxidation Test

Ramped Temperature Oxidation (RTO) - A detailed description of the RTO test is addressed to papers published by Moore et al. (1999). The overall purpose of the RTO test is to study the oxidation behavior of a core sample under reservoir conditions. The core sample is recombined by using native core matrix, oil and synthetic brine. One active and one reference reactor are mounted in the RTO test. The active reactor contains the native core material saturated with water and oil, while the reference reactor is filled only with the dry and clean core material.

The core sample is exposed to maximum temperature set points. Then, the air is injected into the core with an injection flux. Inert gas and an oxygen containing gas are flowed with an injection flux of  $30 \text{ m}^3 \text{ (ST)}/\text{m}^2\text{h}$  through the reference and active reactors respectively, while both reactors are simultaneously heated at a fixed rate of  $40^\circ\text{C}/\text{h}$ . Temperatures from the reactors are measured and the produced gas composition from the active reactor and the oxidation behavior are determined.

### 2.3.2 Accelerating Rate Calorimetry Test

Accelerating Rate Calorimetry (ARC) test is used to study reaction kinetics by following reactions adiabatically. The main objective of the ARC test is to assess the ignition and oxidation/combustion characteristics of the bitumen or extra heavy oil reservoir during air injection. During this test, kinetic parameters for the reactions of the oil with air are obtained. The specific objectives of the ARC test performed are to identify the temperature intervals in which the oil reacts with air. Also, the extent and continuity of the oxidation reaction with temperature, and the Arrhenius parameters of the oxidation kinetics of the oil under the test conditions are determined. The Arrhenius parameters are used in thermal simulators to history matching the kinetic model (Yannimaras and Tiffin, 1995).

As practical point of view, the recombined sample is exposed to gradually heating at initial temperature at room temperature up to maximum designed temperature. Self-heating in the reaction cell due to the (exothermic) oil-air reaction is detected and maintained in an adiabatic condition by the ARC unit.

### 2.3.3 Combustion Tube Test

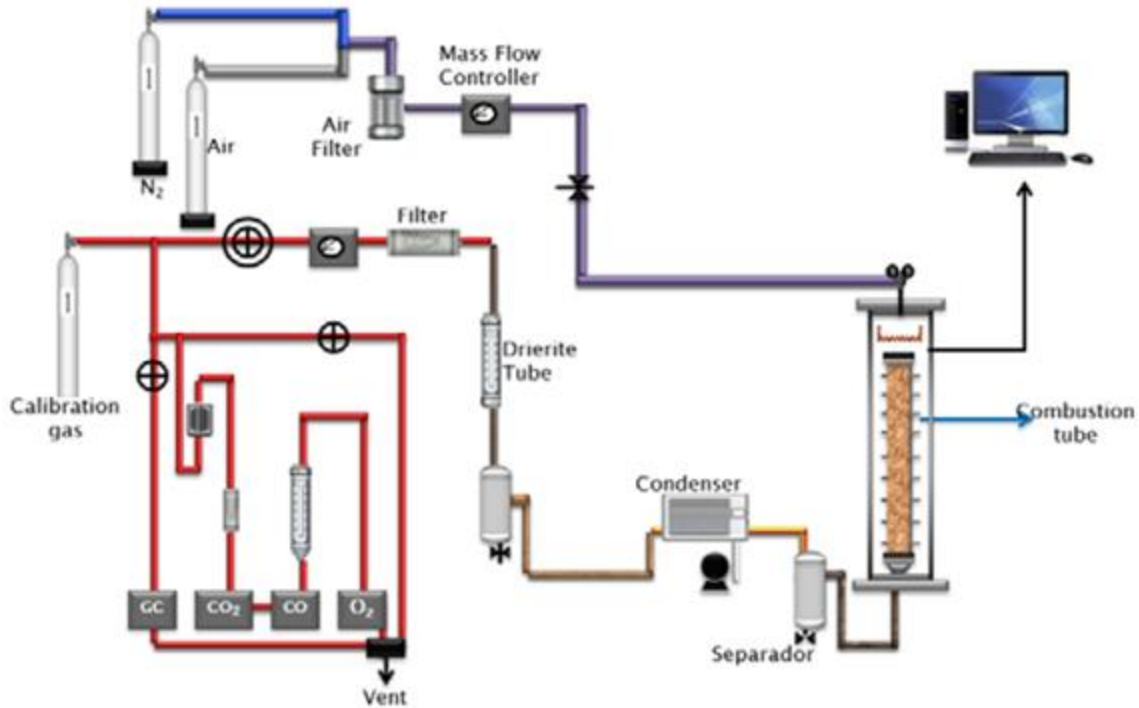
The main reason of performing combustion tube (CT) test is to provide information and parameters to make an appropriate and non-expensive engineering approach about the performance of a field test. These results are also useful for determining the interrelation between different mechanisms affecting the combustion. In this way, combustion tube test is widely accepted as a method with reliable results for the in situ combustion process and can be defined as small scale field test of applicability of combustion.

Different combustion mechanisms are represented with the various combustion front velocity and as the super wet combustion is introduced the operation speed can be increased. The concept of combustion considers dependence of combustion front velocity from O<sub>2</sub> flux and fuel concentration. Velocity of combustion front is slower in comparison with reaction rate during combustion process (Kumar and Garon, 1988). Comparison of the displacement front for different fluid and combustion regime from experiment is represented. Kumar and Garon (1988) studied the air injection in CT experiments and showed the thickness of combustion front is of order of 2.5 cm that can be used as good approximation of grid size during numerical modelling.

**Figure 6** shows the schematic of combustion tube test. The equipment showed in **Figure 6** can be divided into injection gas system, combustion tube, production system, gas analysis system, control system and data logging system. Measurable data are overall burning characteristics of oil, incremental oil production, air fuel requirement, produced gas compositions, properties of the produced fluids; oil and water.

As general there two types of combustion tube (CT) tests which can be carried out to study the combustion behavior of the bitumen under the reservoir condition; dry CT and wet CT tests. Details of these two tests were already published Moore et al (2010) and (2011). The dry CT test is to investigate burning characteristics of the core-bitumen-brine matrix by dry air injection. While, the wet or super wet CT test is to assess the wet combustion behavior of the reservoir bitumen after hot water flooding steam injection.

The super wet CT experiment is a representative test in this study. The representative extra heavy oil is extracted from the bitumen reservoir. Moore et. al (1999) have in detail explained the procedure of how to extract the bitumen from the reservoir (sands).



**Figure 6:** Schematic of combustion tube test (after Oliveros 2013)

The viscosity, density and fractions of the representative bitumen are shown in **Table 2**. The super wet combustion tube test is performed in an elongated cylindrical combustion tube-size of the tube is 102.9 cm length and 5 cm diameter-(Moore et al, 2011).

**Table 2:** The representative bitumen characterization data

<b>Density</b>			
<i>Original oil (g/cc)</i>	<i>Maltenes (g/cc)</i>	<i>Temperature (°C)</i>	
1.0158	0.9888	15	
1.0095	0.9824	25	
1.0002	0.9728	40	
<b>Viscosity</b>			
<i>Original oil (cp)</i>	<i>Temperature (°C)</i>	<i>Maltenes (cp)</i>	<i>Temperature (°C)</i>
482500	25	50080	15
55000	40	13000	25
10000	55	2475	40
<b>Molecular Weight</b>			
<i>Original oil (g/gmol)</i>	<i>Maltenes (g/gmol)</i>	<i>Asphaltene content (wt%)</i>	
556.95	485.97	23.44	

The super wet CT tube is divided into 14 zones and the temperature of each zone is measured by the centerline and wall thermocouples. The wall heaters were set to adiabatic control with a 10°C interval behind the centerline temperature.

However, the operating conditions employed for the super wet in-situ combustion tube tests are shown in **Table 3**.

**Table 3: Operating conditions for super wet CT test**

Parameter	Super wet CT	Unit/Comment
Core Porosity:	42.2	percent
Pressure:	2200	kPa
Ignition Temperature:	240	°C
Feed Gas (normal air):	21.77	mole percent oxygen, balance nitrogen
Injection Air Flux:	30.4	m <sup>3</sup> (ST)/m <sup>2</sup> h
Stable Water/Air Ratio:	5.2	kg/m <sup>3</sup> (ST)
Initial Oil Saturation:	58.2	percent
Initial Water Saturation:	20.1	percent
Initial Gas Saturation:	21.7	percent
<b>The combustion parameters for the overall test:</b>		
Maximum recorded peak temperature	671	°C
An overall air requirement	148	m <sup>3</sup> (ST)/m <sup>3</sup>
An overall oxygen requirement	32.3	m <sup>3</sup> (ST)/m <sup>3</sup>
An overall fuel requirement	15.5	kg/m <sup>3</sup>
An overall apparent atomic H/C ratio	0.88	
An overall air/fuel ratio	9.57	m <sup>3</sup> (ST)/kg
An overall oxygen utilization	98.01	percent
An overall (CO <sub>2</sub> +CO)/CO ratio	4.83	
An overall (CO <sub>2</sub> +CO)/N <sub>2</sub> ratio	0.24	
An oil recovery of the initial oil in the core	97	percent

The combustion tube is filled and packed with core materials and fluids. The core packed is a mix of original rock and described as homogenous media. The core porosity and the initial saturations of oil, water and gas are determined. The packed combustion tube is preheated with hot flood injection. In practical, the distilled water is injected while the core is slowly heated to 90°C from bottom part of the tube. The hot water flooding is continued at higher temperature, until the

steam flood is started at 240°C. Note that significant oil is recovered during the hot water flood and the steam flood. Just before starting air injection, the water injection is stopped. The synthetic air with 21.77 mole % oxygen is injected at a stable injection flux and constant water/air ratio.

## **2.4 Numerical Modeling of Combustion and Current Approaches**

In in-situ combustion processes, many physical changes as well as chemical reactions take place simultaneously or sequentially in the vicinity of the combustion front (Lin et al., 1984). The mechanisms of the physical changes and chemical reactions occurring around the combustion zone can be studied effectively through numerical modeling.

There are a number of numerical simulations of combustion tube experiments to understand the kinetic reactions during the in situ combustion. Among them the Belgrave model is the representative and well-known model developed for bitumen (Belgrave et al., 1993). In our study, the Belgrave's model is used, and a detail description on the model is given as follows.

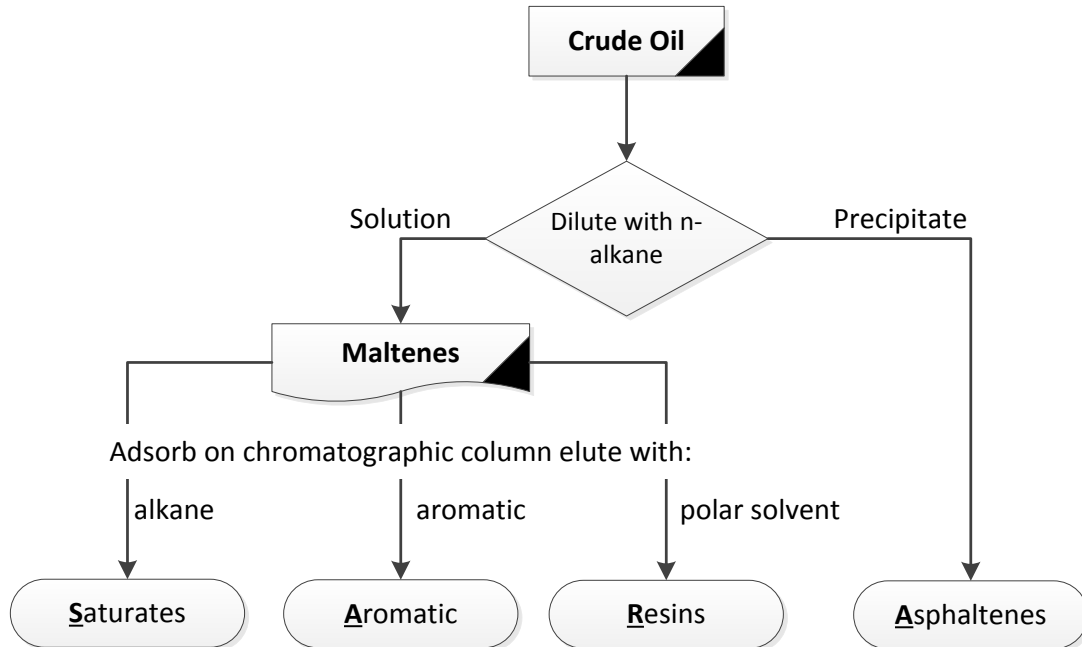
### 2.4.1 Phases and Components

The SARA fractions are introduced as a complex model to represent heavy oil components. In this model, **S** denotes Saturates, **A**: Aromatic, **R**: Resin and **A**: Asphaltenes. Saturates, aromatic and resin are division of the Maltenes which are soluble in pentane while Asphaltenes is insoluble in pentane. **Figure 7** shows the schematic illustration of SARA analysis. If other components are introduced to the model, it will increase the complexity and computation of the model.

However, in our study, the Belgrave's model with considering the SARA fractions is used to represent the heavy oil sample. There are four phases and seven components assumed in the Belgrave's model. The phases are the oil phase, water phase, gas phase and solid phase.

The oil phase is divided into the heavy component of oil phase (Asphaltene) and the light component of the oil phase (Maltenes). By definition, Asphaltenes is insoluble in pentane while Maltenes is soluble in pentane. The solid phase is coke, a remained product of reactions between hydrocarbons. The cock is

separated from oil and it is insoluble in toluene. The water phase is water. It is assumed that water is completely immiscible with the other components in liquid phase but miscible with gas.



**Figure 7:** Schematic illustration of SARA analysis

In addition to other phases, there is the gas phase. Air is injected into to model and due to chemical reactions, carbon oxides is produced. However, with regards to air composition and its chemical products, the remaining components are oxygen, nitrogen and carbon oxides.

#### 2.4.2 Reactions

There are, in general, three main reactions in the Belgrave's model (Belgrave et al. 1993);

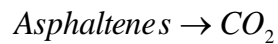
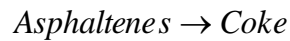
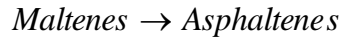
- Thermal cracking
- Oxidation reactions
- Coke combustion

When the heavy oil component is heated, the light oil is evaporated and the remained residuals are Maltenes components. The thermal cracking reaction



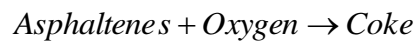
represents the thermolysis of the Matlenes components into coke and gases. In the thermal cracking reaction, the oxygen is absent (Adegbesa 1980).

The general scheme of the thermal cracking reactions is as follows.

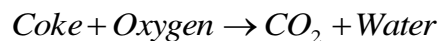


The produced coke by thermal cracking is used as the source of fuel for generating oxidation reactions. The oxidation reactions are subdivided into the low temperature oxidation (LTO) at a relative low temperature, and high temperature oxidation (HTO) at a relatively high temperature. A good definition of the LTO and HTO reactions is found in the paper published by Gutierrez et al. (2009).

However, the form of LTO reactions is as follow;

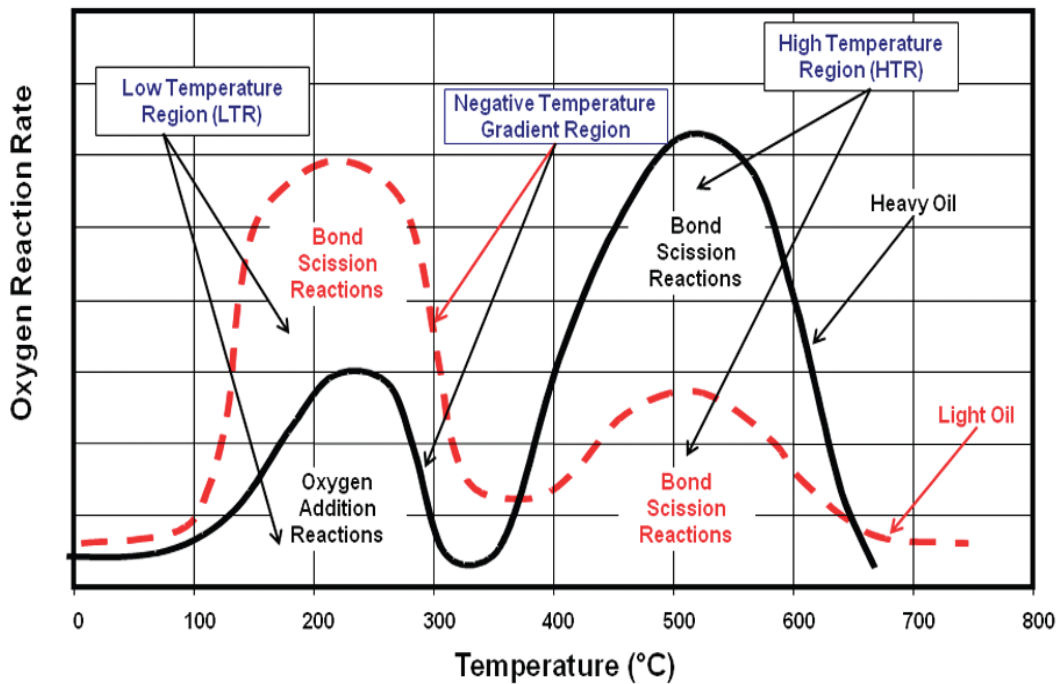


The HTO reaction is of the form:



However, the reaction zones anticipated in the in situ combustion process are complex and interact over relatively small length scales. **Figure 8** shows a schematic of the oxygen consumption rate versus temperature. Depending on the temperature range, there are two regions: The low temperature region (LTR) and high temperature region (HTR). In each region, both reaction types can occur at the same time, but one type of oxidation modes is dominant.

Low temperature oxidations (LTO) take place at temperatures below 300°C (it is dominant between 150 and 300°C) and the range of oxygen consumption is lower, whereas high temperature oxidations (HTO) become the dominant reaction mechanism at temperatures above 350°C with a higher range of oxygen consumption rate.



**Figure 8:** Crude oil oxidation regions (after Moore et al. 2009)

The LTO reactions are very ineffective at mobilizing oil because the production of heavier hydrocarbons (oxygenated oil components) and coke during the LTO results in more viscous or immobile oil. On the other hand, the HTO reactions are extremely effective at mobilizing oil, particularly for heavy oil combustion. However, the most important key is to start and maintain the oxidation process in the HTO mode. Once a high temperature combustion zone is created, a sufficient supply of oxygen is required to maintain the oxidation reactions in the temperature range where the HTO reactions are dominant.

In general, as a chemical reaction occurs and the first substance reacts with second substance to produce the third part, a reaction rate quantifies the speed of the chemical reaction, and depends on temperature (Fogler 2006). The Arrhenius equation gives the dependence of the rate constant of chemical reactions on the temperature (T) and activation energy (Ea). The rates of reaction are given on a general form as,

$$r_i = FF_i \exp\left(-\frac{E_{a,i}}{RT}\right) \prod_{j=1}^n C_j^{e_{ij}}$$

Where, FF is the frequency factor of that reaction, Ea is the activation energy of that reaction, T is absolute temperature, Cj is the concentration factor of component j for liquid and solid phases measured as mass per total volume, eij is the reaction order of component j in reaction i and R is the universal gas constant and is expressed as:

$$R = 8.3145 \frac{J}{mol K}$$

In addition there is the enthalpy of reaction (Hr). The positive Hr means the energy released and negative Hr for adsorption. Only reactants are assumed to control the rates.



# 3 NUMERICAL MODEL OF SUPER WET COMBUSTION

This part contains the main body of this study. It is the numerical modeling on the experiment. The goal of modeling is of better understanding of the kinetic reactions in the experiment.

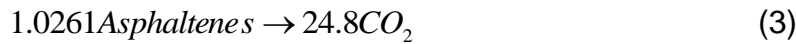
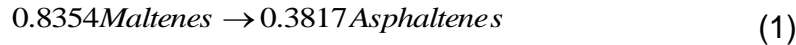
The package from STARS (CMG Manual User, 2010) is used for modeling the experiment. The Module CMG BUILDER is used for making models, CMG STARS for performing calculations on the model, CMG RESULTS GRAPH and RESULTS 3D for visualizing the results and CMG CMOST for optimizing parameters in the model.

## **3.1 Kinetic Reactions**

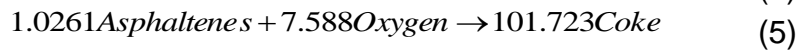
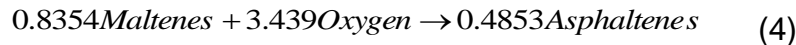
As mentioned earlier, the low temperature oxidation (LTO) and high temperature oxidation (HTO) reactions are qualitative and introduced in general forms. The stoichiometric coefficients for these reactions are therefore determined from the representative heavy oil (or bitumen). The ratios of the molecular weights of

reactants and products are counted to revise the reactions on the molar basis for the representative bitumen. Therefore, the six reactions are rewritten as follows according to the model in Belgrave's study (Belgrave et al. 1993).

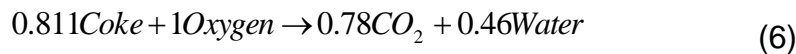
Thermal cracking:



Low temperature oxidation:



High temperature oxidation:



However, the Belgrave's model assumes first order reaction of all hydrocarbons components. Parameters for the rate expressions are given in **Table 4**.

**Table 4:** Reaction parameters for the representative bitumen

Reaction	FF	(variable unit)	Ea (1e5 J/gmol)	Hr (1e6 J/gmol)	Rate
1	7.86e17	ay-1	2.347	0	$r = FF \exp\left(-\frac{E_a}{RT}\right) C_{\text{malt}}^{-1}$
2	3.51e14	ay-1	1.772	0	$r = FF \exp\left(-\frac{E_a}{RT}\right) C_{\text{asph}}^{-1}$
3	1.18e14	ay-1	1.763	0	$r = FF \exp\left(-\frac{E_a}{RT}\right) C_{\text{asph}}^{-1}$
4	1.11e10	ay-1 kPa-0.4246	0.8673	1.296	$r = FF \exp\left(-\frac{E_a}{RT}\right) C_{\text{malt}}^{-1} P_{O_2}^{0.4246}$
5	3.58e9	ay-1 kPa-4.7627	1.85	2.857	$r = FF \exp\left(-\frac{E_a}{RT}\right) C_{\text{asph}}^{-1} P_{O_2}^{4.7627}$
6	150.2	ay-1 kPa-1	0.3476	0.35	$r = FF \exp\left(-\frac{E_a}{RT}\right) C_{\text{coke}}^{-1} P_{O_2}^{-1}$

There are totally nine components and three phases which are introduced in the CMG model. Phases are H<sub>2</sub>O, Asphaltene, Maltenes, CO<sub>2</sub>, H<sub>2</sub>S, CO, N<sub>2</sub>, O<sub>2</sub> and coke identified based on their PVT properties. Some components are converted into other components under the six Belgrave kinetic reactions.

In practical, the DATA file is modified to implement the reactions into CMG. The modification of the data file is shown in **Figure 9**.

```

**COMPNAME 'H2O' 'Asphalt' 'Maltenes' 'CO2' 'H2S' 'CO' 'N2' 'O2' 'coke'
** O2 + Coke --> H2O + CO2
STOREAC
0      0      0      0      0      0      0      1      0.811
STOPROD
0.46  0      0      0.78  0      0      0      0      0
FREQFAC 150.2
RENTH 3.5e5
EACT 3.476e4

```

**Figure 9:** Programming a kinetic reaction dataset

There is a delay to form the coke. Sequera et al. (2010) explain that the coke is formed from Asphaltenes in the oil phase. It means that first the Asphaltenes is oversaturated in the oil phase and partially precipitated as solid phase. Xequil specifies the critical mole fraction of Asphaltenes in the oil phase. As the Xequil exceeds over an optimal fraction (0.11 or 32 wt%), the coke is precipitated.

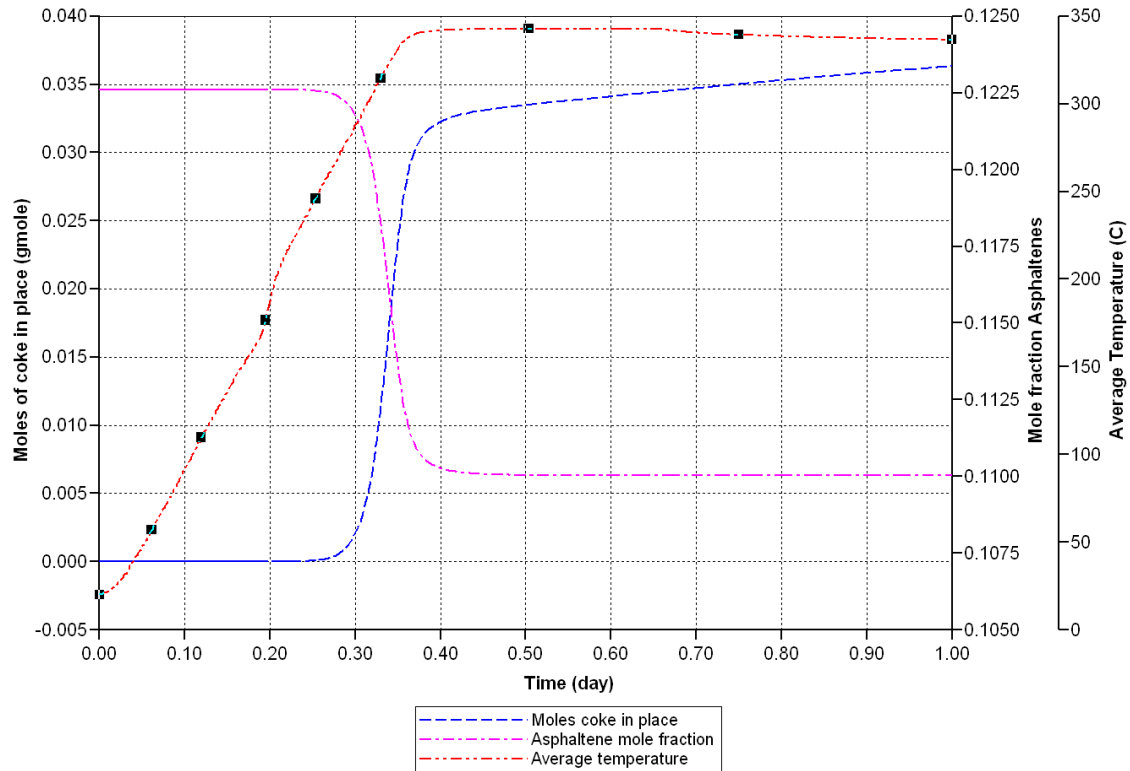
This effect is observed within cracking reactions. However, in our model, this effect is included in the Partial Equilibrium Reaction option in CMG by using this Keyword.

```

RXEQFOR 'Asphalt' 0 0 9.091 0 -273

```

**Figure 10** illustrates the partial equilibrium reactions for coke delay. The initial mole fraction is about 0.12 so the oil is oversaturated. At the temperature about 280°C, the mole fraction of Asphaltene declines and the coke fraction increases. The mole fraction of Asphaltenes is stable at the critical fraction (0.11) in which the rate of coke formation slows down. Since Maltenes vaporizes continuously after the equilibrium in Asphaltene, there is still some production of coke. It is noted that all of Asphatenes are not consumed by reactions and there is a nonreactive part. Only when the mole fraction reaches a certain level do the Asphaltenes begin to react.



**Figure 10:** Illustration of the partial equilibrium reactions function for coke delay.

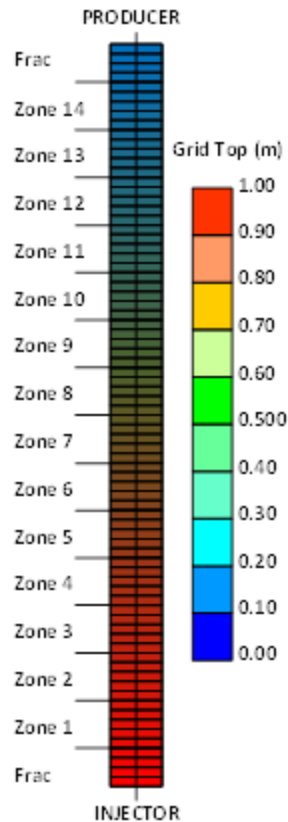
### 3.2 Super Wet CT Experiment Model

The super wet combustion tube (CT) is built based on the parameters extracted from the experimental parameters. The model is one dimension (1D) model in the Cartesian grid system and it is an elongated cube in the Z direction. In fact, the model is vertically oriented in which the injection point is in the bottom and the producer is in the top and the air flows up at a constant rate in the vertical direction. The **Figure 11** shows a schematic geometry of the 1-D super wet model.

The model has a total of 168 grid cells in which each cell has 6.125 mm length which is able to capture with a good accuracy the combustion front movements (combustion front is approximately 2.5 cm wide). The total length of the tube is 102.9 cm. The diameter of the tube is 50mm. The model is divided into 14 zones. The heat losses are not included in the model. The PVT data and information related to the components and reactions are taken from the Belgrave kinetic reactions.



For the super wet CT, the initial saturations are 61.8, 21.3 and 16.9 in volume percent. The permeability is 4500 mD and the model is a homogenous medium and the porosity is 42.1% for the super wet CT.



**Figure 11:** Schematic geometry of 1-D super wet model

In the super wet CT model, water is injected together with air injection. There are hot water flooding and steam injection before air injection, therefore the simulation steps are changed. Even normally in operation dry combustion initiated prior the wet combustion operation, in the experiment is set up as a post SAGD operation.

First, the helium gas is injected to pressurize the system to the initial pressure. The temperature is increased and water injection is performed at 90°C with different injection rates to reach the initial condition as experiment was carried out with hot water flooding.

Second, the temperature is increased to 200°C and hot water flooding is converted to the steam flooding. Significant oil is produced during the hot water

flooding and steam flooding. Afterward, the temperature in the Zone 1 near to the injection point is increased to 240°C.

Third, the temperature reaches to the point at the Zone 1 where the ignition occurs. Subsequently air injection starts and pushes the produced heat into the zones ahead, and the combustion reactions happen. The heaters turn off and water is co-injected with air. Due the combustion process the temperature is increased to its maximum value. At the stage of simulation, the helium is injected to purge the combustion tube.

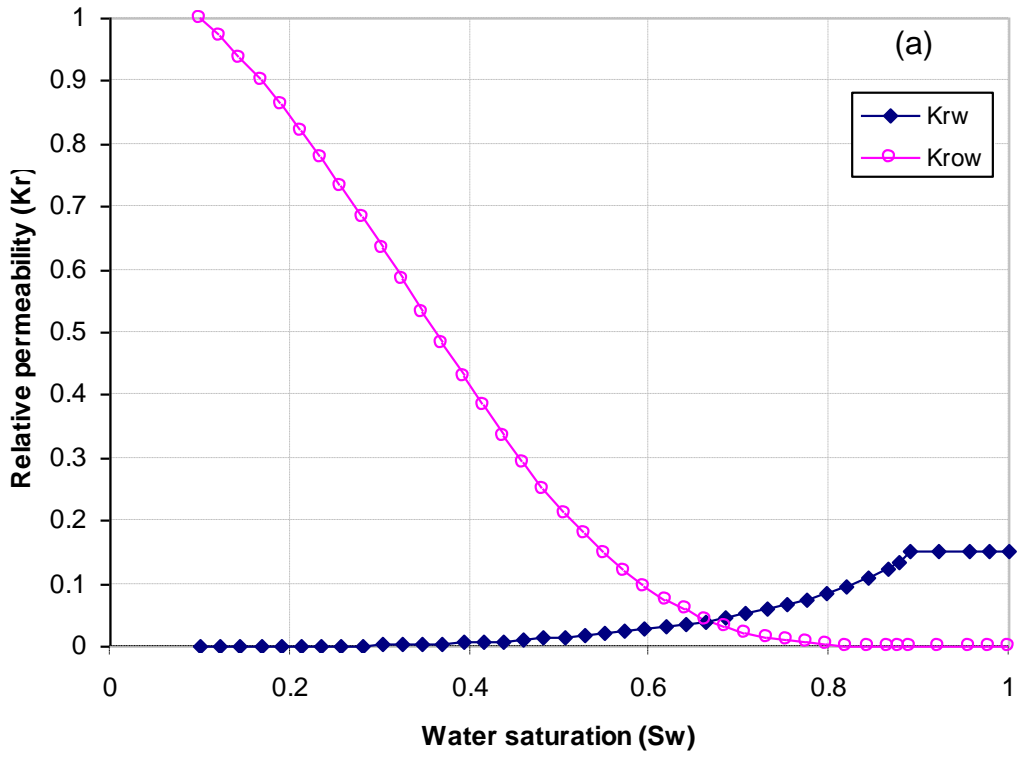
The temperature history and the components produced and their properties are logged in report files. The normalized water-oil relative permeability and the gas-oil relative permeability curves are shown in **Figure 12**.

To initialize the rock and fluid properties, the data of the experiments are used. For instance, initial saturations, pressure, temperature, and rock properties are similar to the experimental condition. Some parameters such as relative permeability curves, mole fraction and information related to the components and reactions are taken from the Belgrave study (Belgrave, 1993).

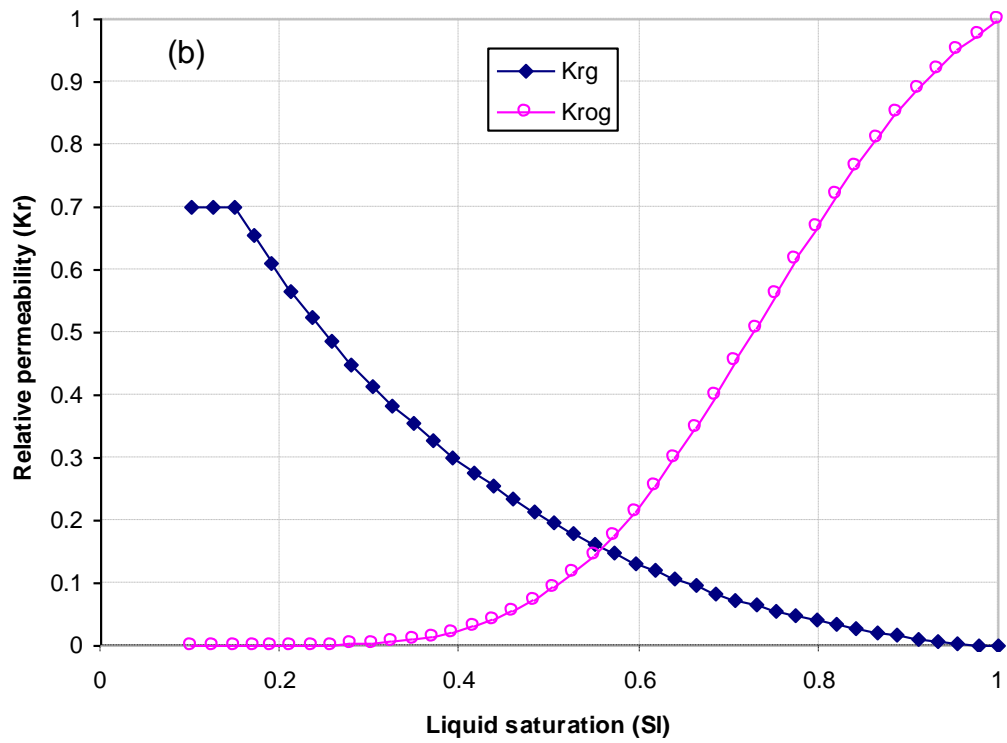
Nine components and three phases have been used. The components are H<sub>2</sub>O, Ashaltene, Maltenes, CO<sub>2</sub>, H<sub>2</sub>S, CO, N<sub>2</sub>, O<sub>2</sub> and coke. The phases are gas, water and solid. The density, viscosity and molecular weight from Table 2 are used for constructing the simulation model. There is no capillary pressure in the model.

The data file showing the model in details is presented in Appendix to this study.

**Oil-water relative permeability curve**



**Oil-gas relative permeability curve**



**Figure 12: Relative permeability curves, a) oil-water, b) gas-oil**

### **3.3 Manual History Matching of Super Wet Model**

The history matching (HM) study is performed on the modeling results to get best fits with the results from an experiment.

Various criteria are being studied for matching. The modeling results can be shown in temperature profiles at different zones of the core, the residual coke and oil after the end of experiment, the pressure versus time profiles at different zones of the core, the produced gas composition versus time and the cumulative production of oil. Those experimental data are selected as matching parameters (observation data) with the highest weight on temperature profile to mimic. Injected gas rates, activation energy and frequency factor are become history matching variables that have to be changed in order to perform the history matching. Gas rate is studied for sensibility analysis.

The manual history matching (HM) is the term that the parameters are manually changed for history matching. The goal of manual history matching is to understand the effect of changing of parameters to have the best match fitting to the real curves obtained from the experiment. Usually those steps of history matching workflow validate the range for assumed variables used next during automated history matching.

In the super wet CT experiment, the test is started with low temperature until the hot water flooding is established. Then, the experiment is continued with a relatively high temperature to conduct the steam flooding. At the high given temperature, the ignition is performed and the air injection is present.

The temperature profiles are plotted and the modeling on the super wet CT experiment is performed. In many cases, the temperature profiles from modeling and super wet CT experiment are not matched. Therefore, the history matching can fit the results of the simulation and experiment closely.

The procedure for the manual history matching is that parameters are first being manually changed in the data file to low, medium and high values, and then their effects on the temperature profiles of the simulation are evaluated and compared with the experimental temperature profiles to achieve best fit. The best match

obtained from different cases is evaluated for interpretation. This process is repeated until a good convergence is obtained.

### **3.4 History Matching of Super Wet Model with BASRA**

The manual history matching is a long process, because all values of parameters should be manually changed. The history matching with BASRA tools gives a solution to reduce the run time increasing accuracy of the output results prevent of finding only local solution for the system, and in general, estimates accurately values of parameters which are used for the kinetic model. The operating system of computer has to be on UNIX system in order to use the BASRA tools.

The BASRA tool is applied to get a best value to variables affecting the super wet model to the best match with the experimental parameters. The temperature profiles obtained from the super wet test present the maximum temperature occurred in each zone which provides clear understanding of the regime during combustion. The numerical modeling of super wet test gives a temperature profile which maximum temperature of each zone from the model is different from the maximum temperature in the experiment. To get best match between the temperature profile of model and experiment, variables of kinetic parameters and injection rate in the super wet model have to be updated. The temperature profile obtained from the model depends on reaction parameters. These parameters, for instance in our super wet model, are the frequency factor, activation energy and coke precipitation which can vary. The BASRA tool is used to optimize the value for these variables. There are some files defined in the BASRA tools. These files are summarized as follows.

-The BASRA data file is the STARS data file without having the section which is going to history matching. The reaction section is separately defined as the reaction definition (\*.def) file.

-The reaction definition file includes the variables of frequency factor and coke precipitation (RXEi). There are six reactions including six frequency factors and two coke precipitation factors (RXE1 and RXE2). The variables for frequency

factors are introduced as 1freqfac11, 1freqfac22, ...1freqfac66. Each variable is corresponding to each reaction.

-The template file includes the maximum temperatures obtained at a given time during the super wet test. There are 14 zones defined in the super wet test. The file contains the maximum experimental temperature of each zone and the time that the temperature occurs.

-The Preproc file defines only the times that maximum temperature occurred during each zone.

In practical, as the BASRA window is opened, a new project file is created. The parameterization is done and the data file and preproc file are loaded as the input files. The maximum run time is set according to the simulation time. The maximum and minimum values for variables including RXE1 and RXE2, and all six frequency factors are inset under Manipulate Prior Probability window in BASRA tools. There are shown in the **Table 5**.

**Table 5:** The range of values for the frequency factors, activation energy and coke precipitation variables

Parameter name	Minimum value	Maximum value
RXE1	0.1	0.5
RXE2	0.1	0.5
Ea	1E+5	1E+10
1freqfac11	1	2
1freqfac22	5	10
1freqfac33	5	10
1freqfac44	5	10
1freqfac55	5	10
1freqfac66	5	10

The minimum and maximum values are taken from the experimental parameters. The variable RXE1 is referring to the precipitation of Asphaltene during the reactions. The variable 1freqfrac is defining the frequency factor and has a logarithmic value. Different min and max values for frefrac11 depend on the cracking reaction which occurs prior to the combustion reactions.

After the adjustments are completed, the simulation is run. The BASRA tool is taking a value, for instance, for the frequency factor variable. The temperature of each zone is obtained at the given time that the maximum temperature occurred

at the test, then the next value of frequency factor is randomly selected within the minimum and maximum values and the temperature of each zone is determined. The total number of selections depends on the decision defined in the BASRA model. However, this algorithm process is repeated until the calculated temperature of each zone at the given time from the simulation is approached close as possible to the maximum temperature in the test. A similar procedure is performed for the coke precipitation variable. Optimized values of the frequency factors, activation energy and coke precipitation are listed as the BASRA results.





# 4 RESULTS AND DISCUSSION

The aim of this study is to perform history matching of experiment carried out on combustion tube for super wet combustion conditions. The experimental procedure was presented in the previous chapter. In the following, due to the confidentiality of some experimental results, this chapter will focus of history matching work and methodology without disclosure some of the experimental results in the work.

## **4.1 Experimental Results**

### 4.1.1 Super Wet CT Experiment

In the super wet CT experiment on the representative bitumen, the hot water flooding and steam injection are established before the air injection is started. Therefore, the super wet experiment was divided into three periods; the hot water flood (-8.45 h to -2.52 h), the steam flood (-2.52 h to 0.00 h) and the combustion (0.35 h to 4.70 h). The maximum temperature observed in hot water flood was less than 200°C. The saturated steam temperature at the given pressure was

219°C which is higher than the maximum temperature during the hot water flooding. The third section was the combustion.

The temperatures of the tube wall are generally lower than the centerline temperatures due to heat losses via the wall. Normally after the temperature of any zone peaks, the wall heaters were set to adiabatic control with a 20°C lag behind the centerline temperature. This is the reason for the slope change during cooling. The heaters in a given zone were placed on set point control at 600°C whenever the peak temperature in that zone exceeded this value. **Table 6** includes the maximum or "peak" temperature observed in each zone and the time at which they occurred. That data is one of the central interests for history matching.

The highest peak temperature at Zone 2 is 671°C which vaporizes liquid hydrocarbons. The vapors are being consumed as fuel. The combustion front progresses until the air injection is stopped at zone 12 at 496°C. Subsequently, the highest temperature in Zone 13 and 14 reaches at 480°C and 401°C respectively. The combustion front velocity at 350°C is 0.193 m/h.

**Table 6:** Peak temperature summary of super wet combustion test

<b>Zone</b>	<b>Location (m)</b>	<b>Time (hrs)</b>	<b>Peak Temperature (°C)</b>
1	0.038	1.26	570
2	0.114	2.07	671
3	0.190	2.71	638
4	0.267	3.09	579
5	0.343	3.66	535
6	0.419	4.38	515
7	0.495	4.98	522
8	0.572	5.69	406
9	0.648	6.40	508
10	0.724	6.95	499
11	0.800	7.38	494
12	0.876	7.96	496
13	0.952	8.77	480
14	1.029	8.41	401

As seen from the results, the data represent super wet combustion conditions only on the part of the experiment when the lower temperature is detected. That part indicates that combustion front and evaporation front has the same velocity which eventually transfers to much lower peak of temperature during experiment. That part means in the majority of the test, can be classified as normal wet combustion.

Velocity of steam front can be compared with evaporation front velocity during combustion. During the wet combustion, evaporation front is present where water is converted to steam from the heat of combustion. Usually this evaporation front is in behind of the combustion front, meanwhile it provides additional heat upfront and reduce viscosity in front of combustion front and provides support during displacement process-combustion front starts moving faster and does not used as much fuel as during the normal dry run. In front of combustion front, there is condensation front which represents the condensation of the steam of evaporation front. The size of the condensation front depends on how much heat is in the reservoir and difference between the speed of evaporation front and combustion front.

#### ***4.2 History Matching Results on Super Wet CT Experiment***

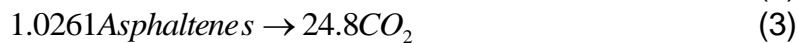
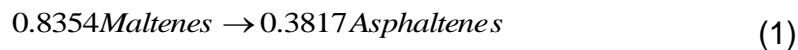
The data file was built based on the experimental parameters. The prepared data file was run in STARS simulator and the simulation results were plotted. The temperature profile during each experiment is the main result in this study. The temperature profile from simulation has shown that maximum temperatures have not reached to the maximum temperature occurred in each zone in the experiments. In any thermal flooding, the kinetic reactions are of important. In our model, there might be variables related to the kinetic reactions that can be changed. The manual history matching has been performed to change the variables to get the best match between the modelling and experimental temperature profiles.

The variables which have been changed for manual history matching are frequency factor (FF), and activation energy (Ea), saturations, gas rates, and relative permeability. The details of each history matching are discussed in the following and the effect on each variable changed for improving the temperature profile is presented.

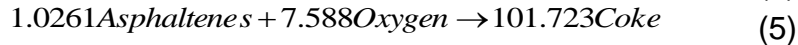
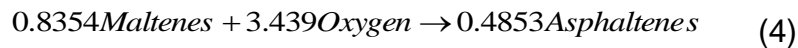
#### 4.2.1 Effect of FF and Ea

Kinetic plays a central role in combustion mechanism, detailed reaction mechanism of the combustion was presented in the previous chapter. In our model, Belgrave model was implemented. The reactions are;

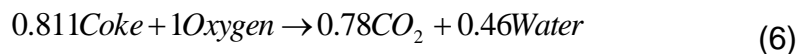
Thermal cracking:



Low temperature oxidation:



High temperature oxidation:



However, the Belgrave's model assumes first order

From Arrhenius equation, reaction rate is dependent parameter from frequency factor, activation energy and subchapter provides sensitivity study results.

The procedure to change the frequency factor (FF) variable is changing them in a particular range. The FF or Ea parameters for each of reactions are fixed while the rest of other parameters in the kinetic reaction model are removed. By this modification, the effect of FF and Ea parameters have shown that they have significant influence on reaction no.4. Basically, that seen the domination of the low temperature oxidation reaction.

The reaction no. 4 in the low temperature oxidation process shows that the Maltenes is converted to Asphaltene (see Eq 4 in the section 3.1), that means

oil become more viscous. It reflects on amount of fuel left after combustion front eventually this reaction is responsible to reduce air requirements during the process. As it is obvious at zone 1, for instance, when keeping the FF or Ea for reaction no.4 and then eliminating these parameters for the rest of reactions, a significant of combustion and temperature response is achieved.

The next attempt is to change FF or Ea to low, medium and high values only for reaction no.4 while keeping the same values for the other reactions. The similar procedure is applied to change the Ea values. The result has shown that changing FF and Ea have much influence only on the reaction no. 4.

Based on the analysis provided in above chapter, in our discussion, focus will be on the reaction no 4. Initial estimate from Belgrave model is that the frequency factor (FF) is  $5.68E+5$  and the activation energy (Ea) is  $8.673E+4$ . The FF has been changed to the low value ( $10E+2$ ), medium value ( $6E+6$ ) and high value ( $10E+10$ ) as a part of the sensitivity study. The similar changes have been applied to the Ea variable. It is observed that the best match is obtained with the high values chosen for FF and Ea ( $10E+10$ ).

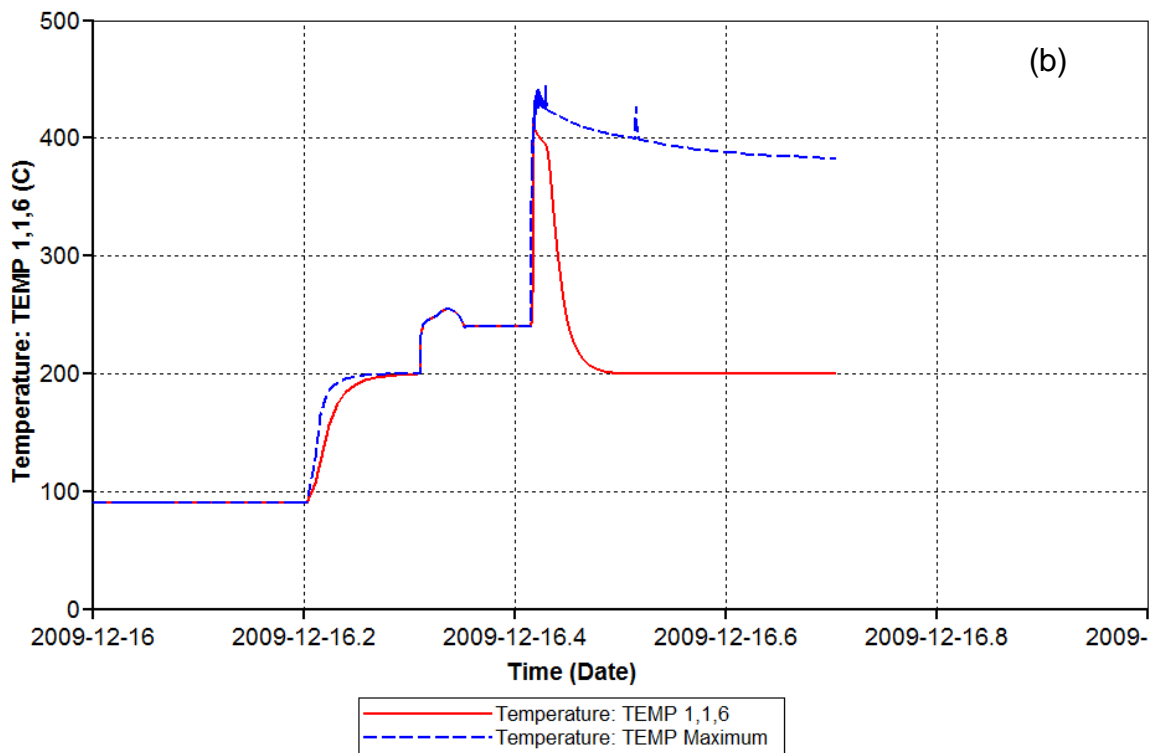
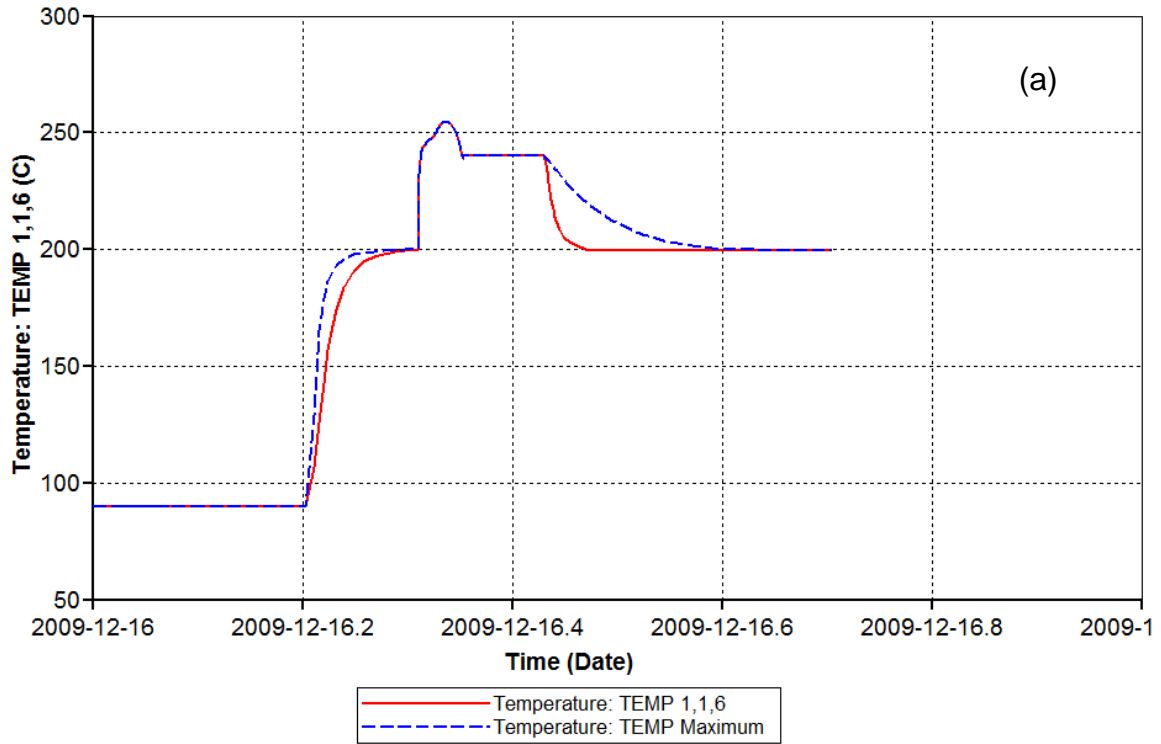
**Figure 13** shows the temperature profiles of super wet combustion tube at zone 1 (1, 1, 6). **Figure 13** (a) shows the temperature profiles with the original FF value while **Figure 13** (b) presents the temperature profiles when the FF was changed to the its high value. In each plot, there are two temperature profiles. The red curve shows the temperature profile in the zone 1 and the blue curve presents the maximum temperature profile that might be in another zone.

The result in **Figure 13** (a) presenting the temperature profile at zone 1 and the maximum temperature profile indicates that the temperature is not enough for the super wet combustion (see comparison with the maximum peak of temperature in **Table 6**. The maximum temperature either in the Zone 1 or in another zone is below to that temperature which is required for the super wet combustion obtained during the experiment. Thus, the temperature profile from simulation does not represent super wet combustion process. This plot was obtained with

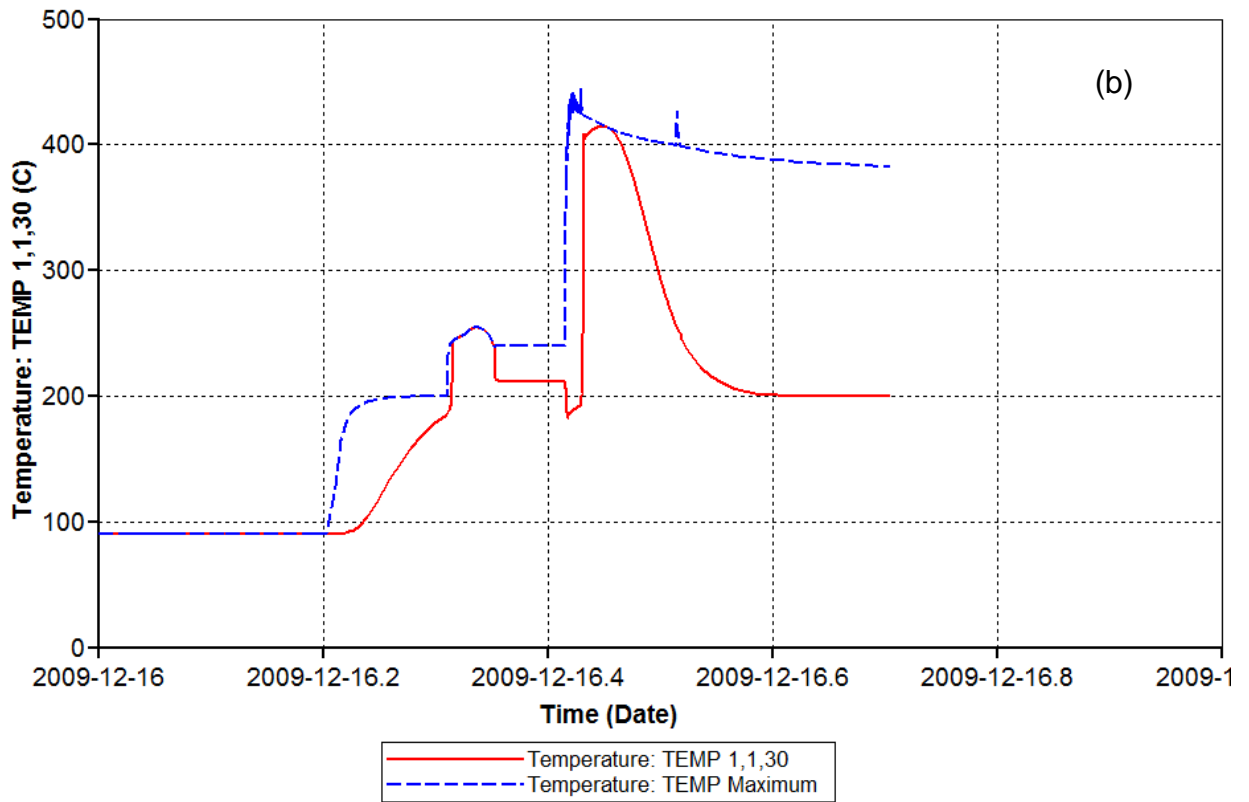
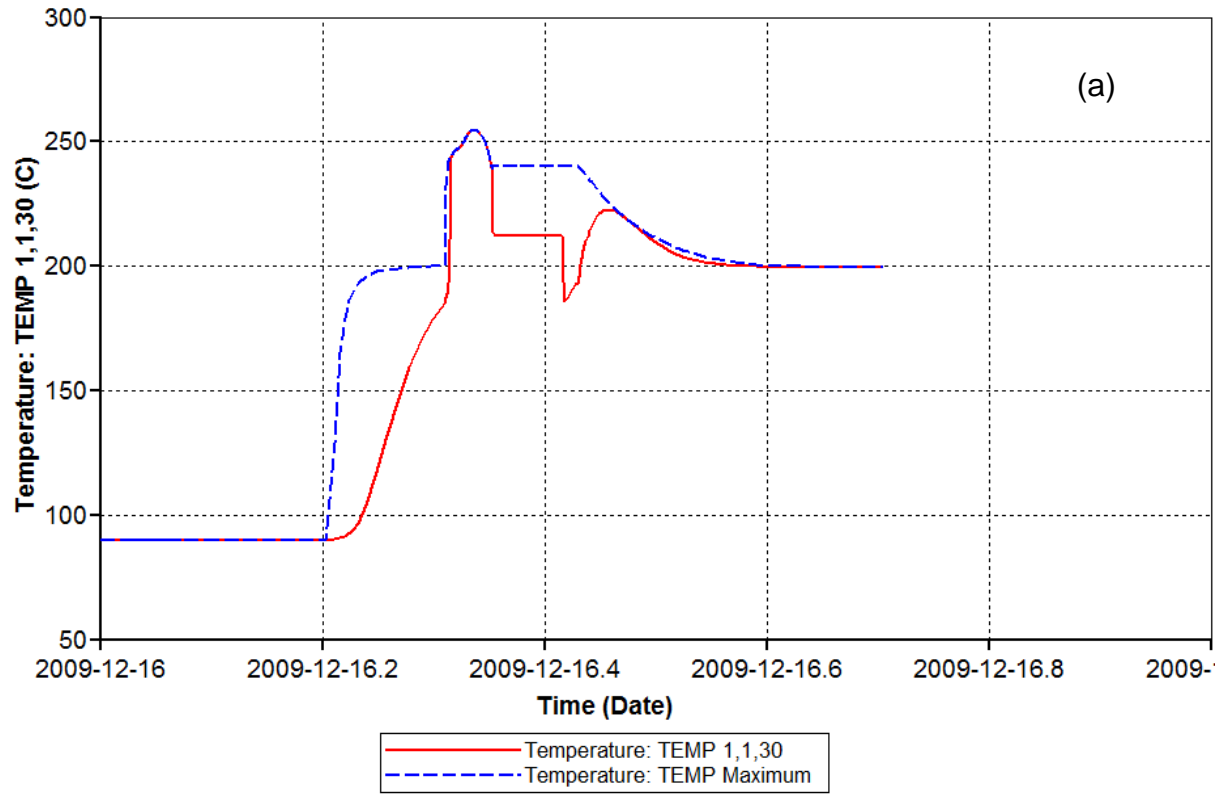
the original FF value ( $5.68E+5$ ). When the FF value is changed to its maximum value ( $10E+10$ ), the temperature has increased towards the experimental values.

The shape of temperature profiles shown in **Figure 13** (b) illustrates that the wet CT experiment has established. It starts at low temperature and progresses to high and then reaches to a maximum temperature at  $400^{\circ}\text{C}$  which is above the combustion front temperature at  $350^{\circ}\text{C}$ .

Similar results have been obtained when the Ea variable is varied. The results of such sensitivity are shown in **Figure 14**. The plot on **Figure 14** represents for the original Ea while **Figure 14** presents the results with high value of Ea.



**Figure 13:** Effect of FF variable on the temperature profile (reaction no. 4) - (a) original FF value and (b) high FF value



**Figure 14:** Effect of Ea variable on the temperature profile (reaction no. 4) - (a) original Ea value and (b) high Ea value



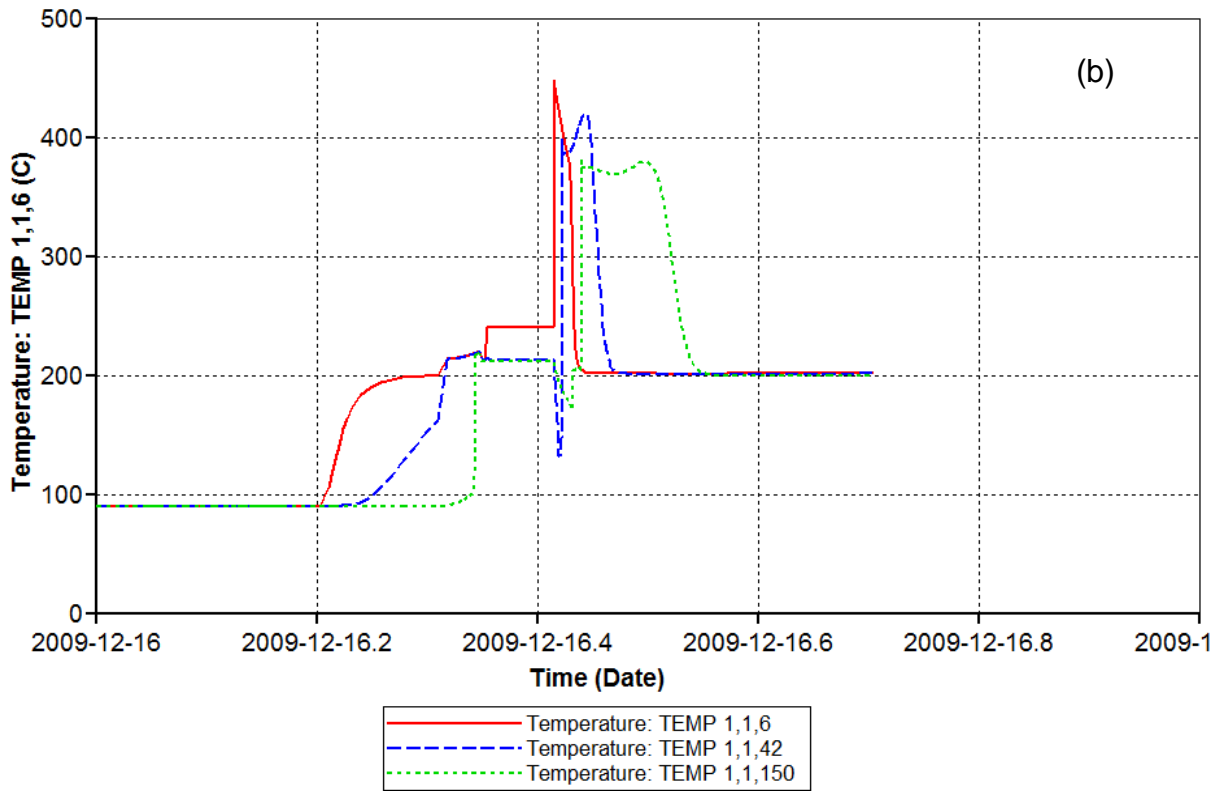
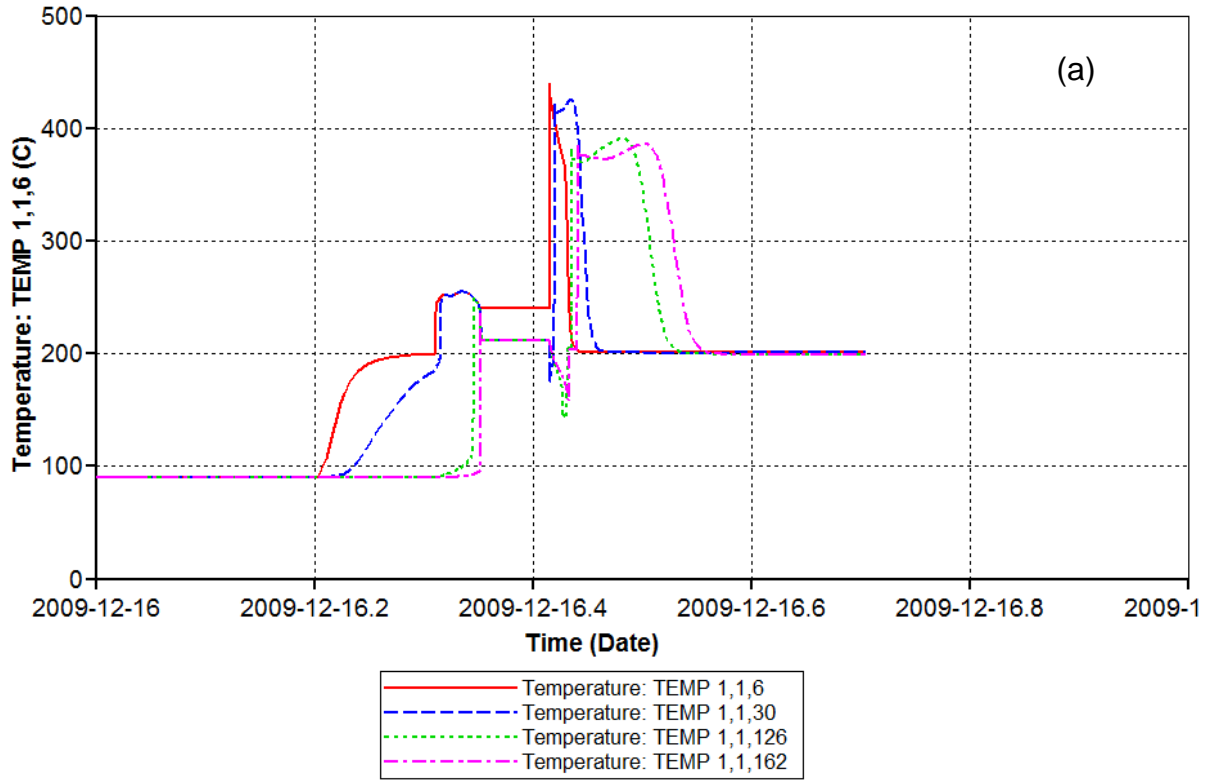
#### 4.2.2 Effect of Saturations

Amount of fuel effects significantly on the temperature achieved during combustion, since during normal combustion all air is used on burning the fuel (oil) and that heat is stored in the reservoir. Combination of the combustion and injection of water which utilize that heat reflects significantly on the temperature profile. That was the reason to analyze saturation effect.

According to the methodology applied in for kinetic parameters study, saturations have been manually changed in current sensitivity as well. The procedure is that the oil saturation ( $S_o$ ), for instance, is kept constant and the gas saturation is manually changed to low and high values, obviously the water saturation is determined depending on the gas saturation. The original saturations in the super wet model are 0.618 ( $S_o$ ), 0.213 ( $S_w$ ) and 0.169 ( $S_g$ ). For example, the gas saturation is changed to low value (0.05) and high value (0.5), while the water saturation is kept constant and the oil saturations are determined to be 0.737 and 0.287 respectively.

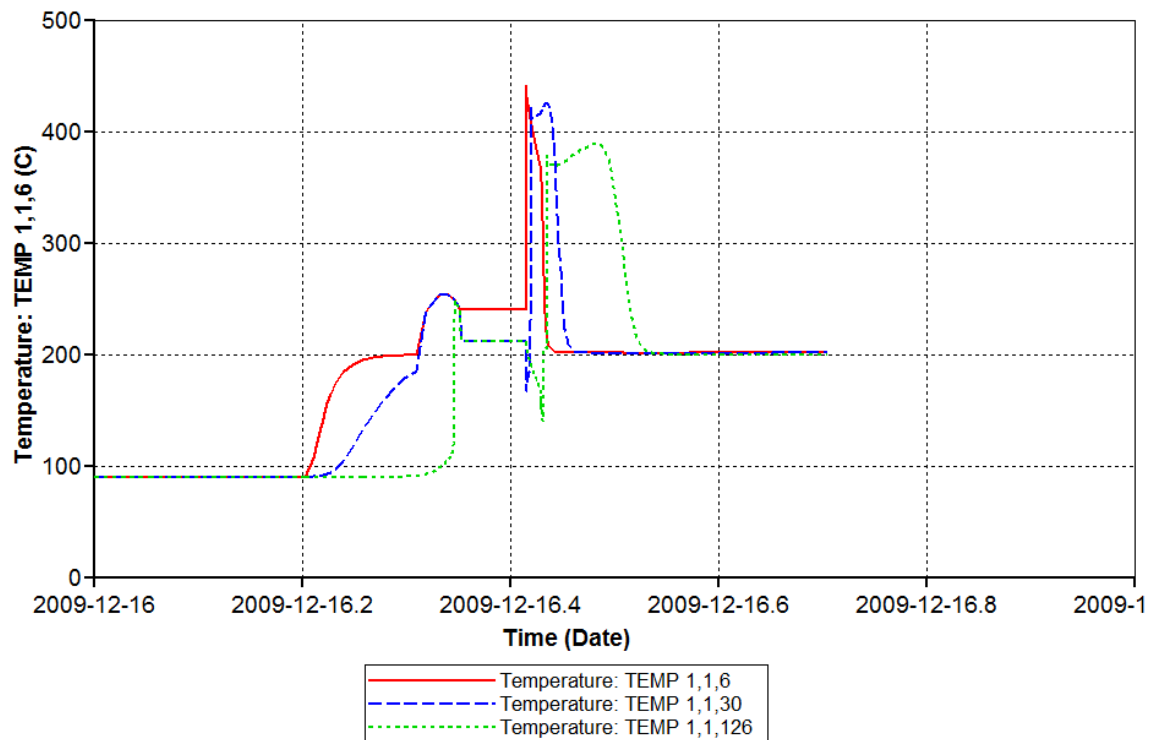
**Figure 15** shows how the temperature profiles are changed in different zones for the super wet combustion test. **Figure 15-a** presents the temperature profile when the gas saturation (as variable) has its low value (0.05) and the **Figure 15-b** shows the temperature as the high value (0.5) is set to the gas saturation. The original gas saturation is 0.169. However, the results indicate that the changing in gas saturation does not have a significant effect on the temperature profiles.

In the next step, the oil saturation (0.618) is kept constant while the gas saturation (0.169) is manually changed to low (0.05) value and the water saturation (0.332) is determined properly. The high gas saturation (0.5) is not considered because the summation of high gas saturation (0.5) and the original oil saturation (0.618) will exceed 1. However, the water saturation will be 0.332 when the constant oil saturation is 0.619 and the gas saturation is changed to 0.05.



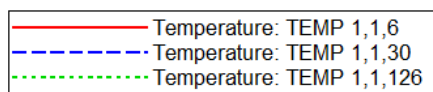
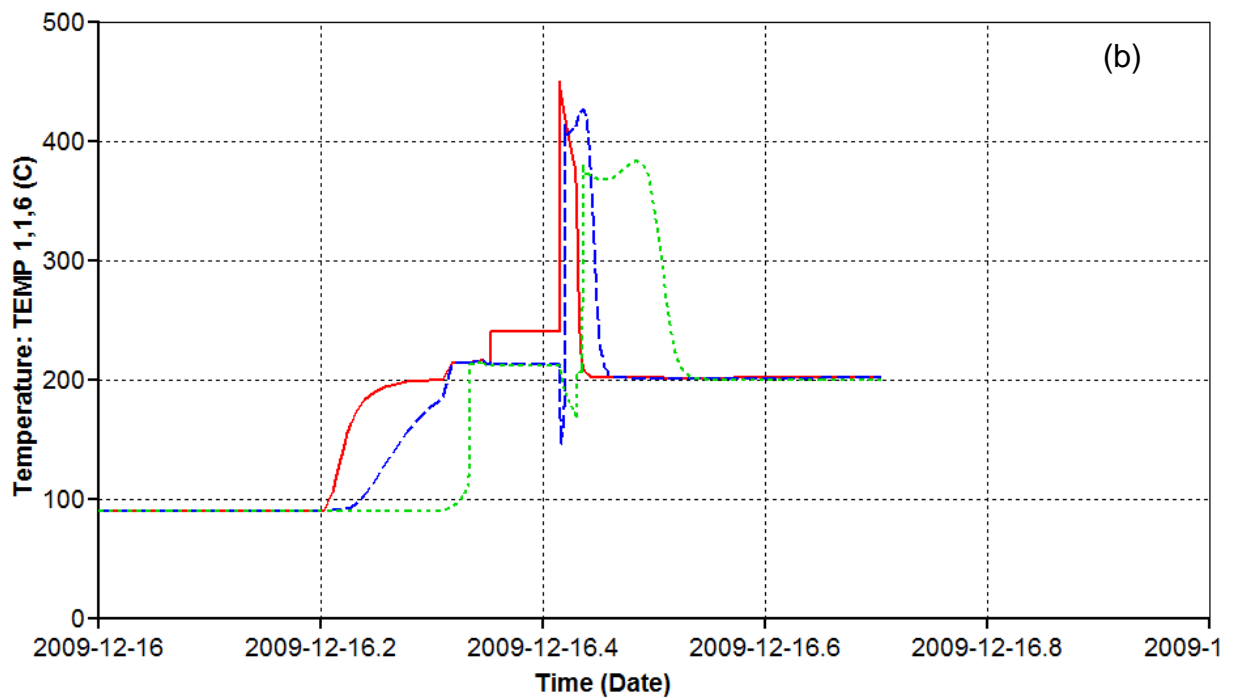
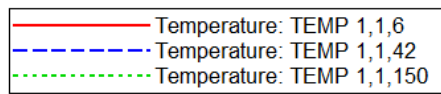
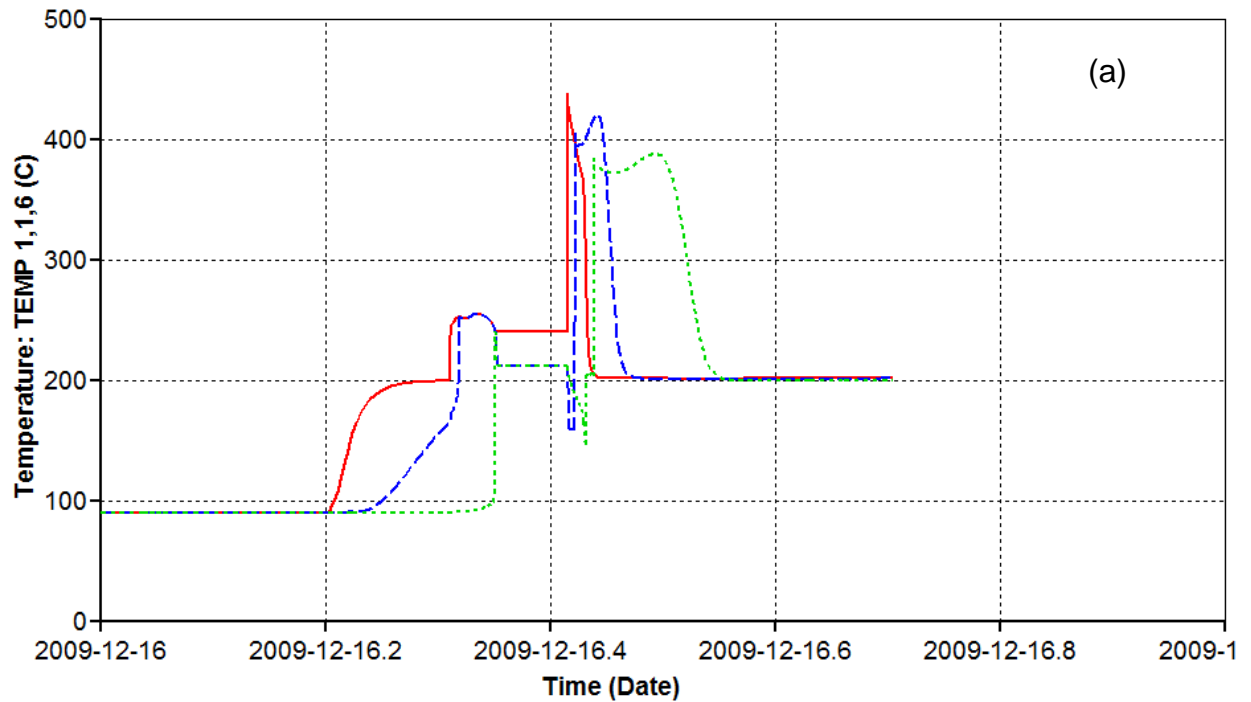
**Figure 15:** Effect of gas saturation on the temperature profile- low Sg at 0.05 (a), high Sg at 0.5(b), Sw at 0.213 (constant)

**Figure 16** shows the temperature profile in different zones when the oil saturation is fixed and the gas saturation is changed to the value of 0.05. The results indicate that the changing in gas saturation does not have significant effect on the temperature profiles obtained in different zones. In the final step, the gas saturation (0.169) is kept constant and the water saturation is manually changed to low value (0.05) and high value (0.5). The calculated oil saturations are 0.781 and 0.331.



**Figure 16:** Effect of gas saturation on the temperature profile- low  $S_g$  (0.05),  $S_o$  (0.618; constant)

**Figure 17** shows the temperature profile in different zone and indicates that the changing in water saturation does not have a major effect on the temperature profile in the super wet combustion. Comparison of the results with the different saturation (oil, water and gas) provide a conclusion that this not significant effect in our case of changing the saturation data which effect combustion behavior. However, it can be seen that the distribution of heat differ case to case and increase in oil saturation translates to more heated reservoir. Increase of water saturation almost does not affect the speed of combustion and evaporation front, even supposed to produce more steam.



**Figure 17:** Effect of water saturation on the temperature profile- low Sw at 0.05 (a), high Sw at 0.5(b), So at 0.618 (constant)

#### 4.2.3 Effect of Gas Rate

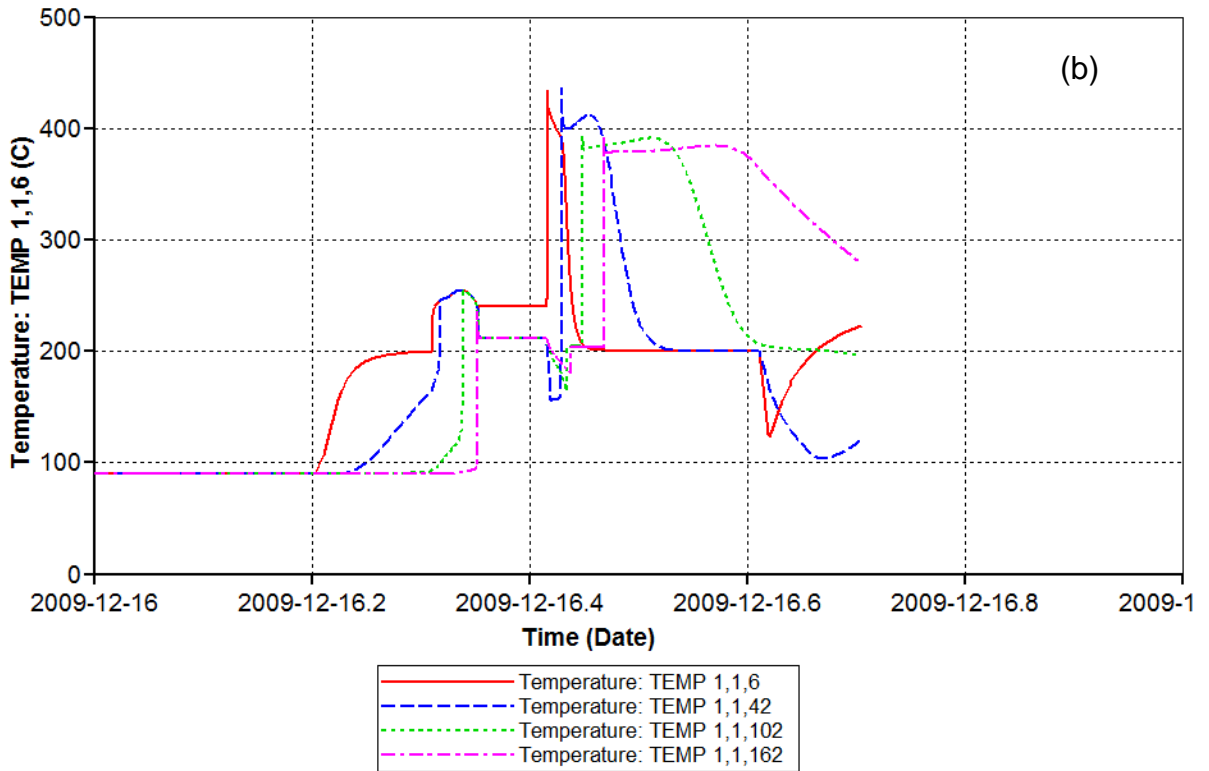
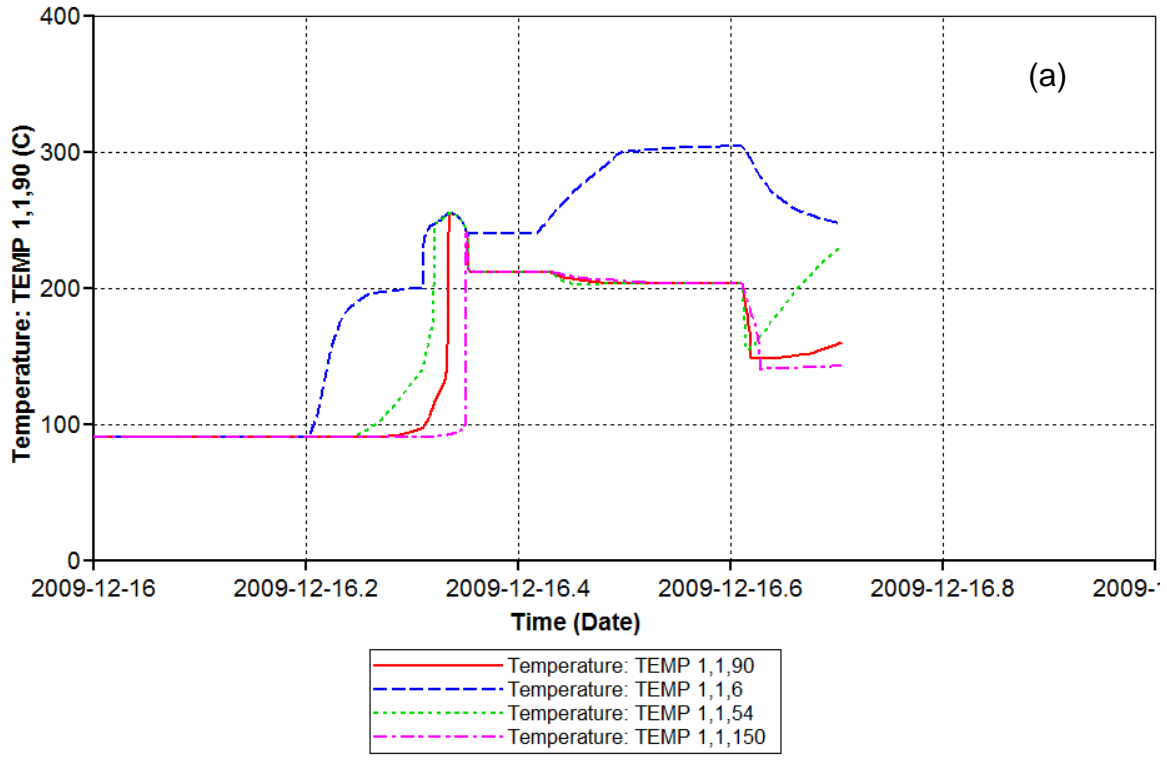
Air requirement is the major parameter during combustion, as it has been discussed in the previous chapters, wet combustion allows to reduce gas rate and utilize more that heat left behind in the reservoir.

The effect of gas injection rate has been evaluated on the super wet combustion test. The gas injection rate variable (stg) is changed to low values (0.05 and 2.5) and high values (20 and 40). **Figure 18** shows the effect of low gas injection rates (0.05 and 2.5) on the temperature profile.

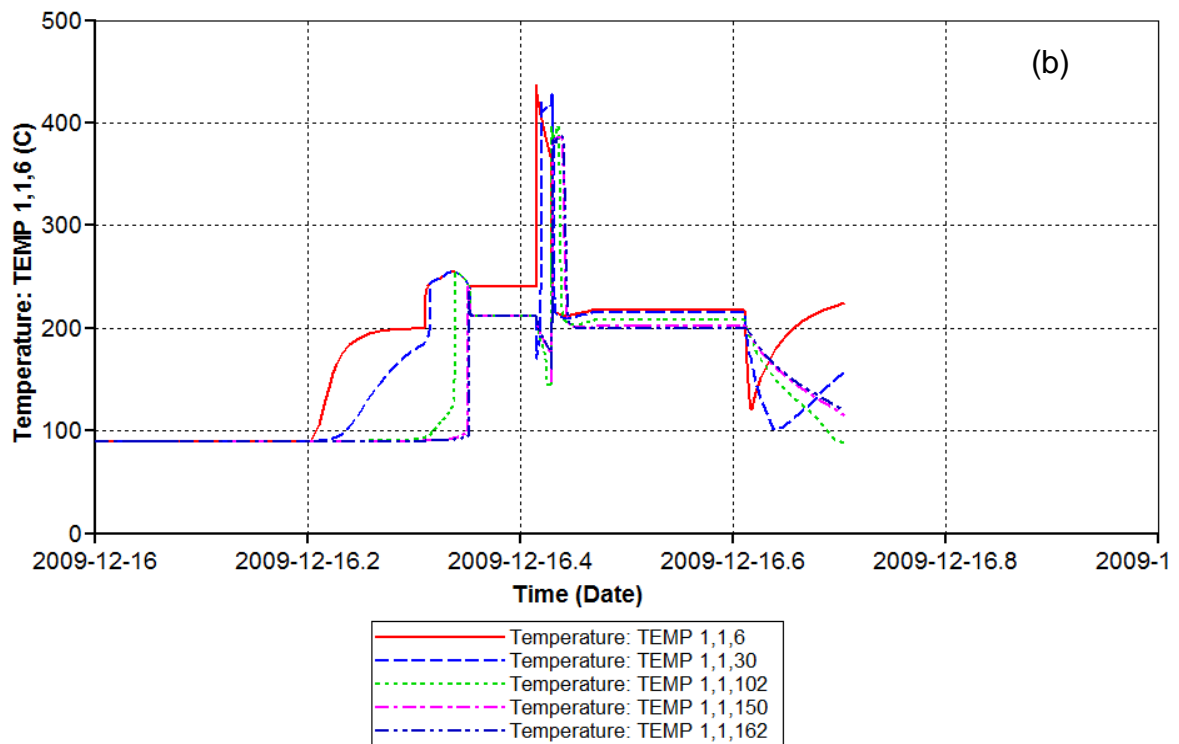
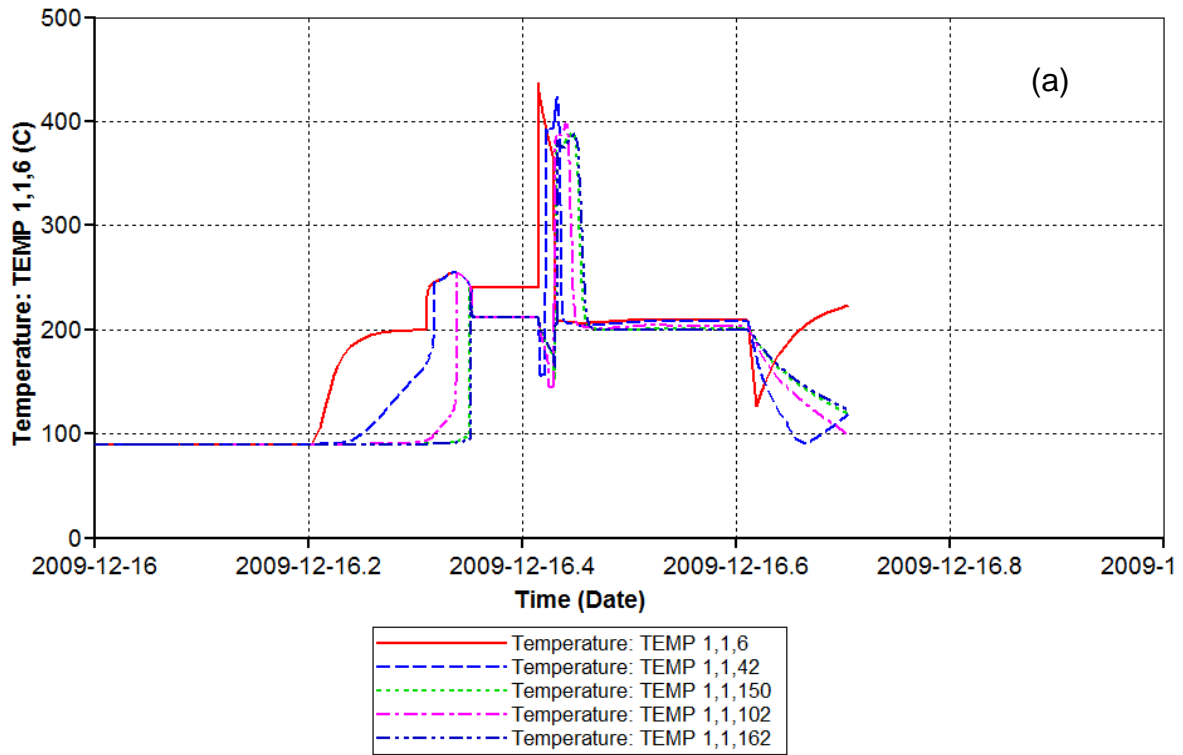
The temperature profiles presented in **Figure 18** (a) show when the gas injection rate is too low (0.05), the condition for reaching the maximum temperature for the super wet combustion is not established. That means not enough heat is produced to create evaporation front, and confirms the theory developed for wet combustion process.

As the gas injection rate is increased to higher value (e.g. 2.5), the temperature profile (**Figure 18-b**) indicates that the wet combustion can be established.

Next plot on **Figure 19** presents the temperature profile for the super wet combustion test at the relatively high gas injection (20 and 40). Theoretically, high water air ratio provides ideal conditions to establish super wet combustion. Meanwhile, as it can be noted from the very high air rates in our sensitivities, combustion is obtained locally at the one moment (see almost immediate peak in all zones) and moved very fast towards the end of tube. Afterwards, displacement is characterized as normal gas injection which is not effective for bitumen conditions.



**Figure 18:** Effect of low gas injection rate (stg) on the temperature profile- stg: 0.05 (a) and 2.5 (b)

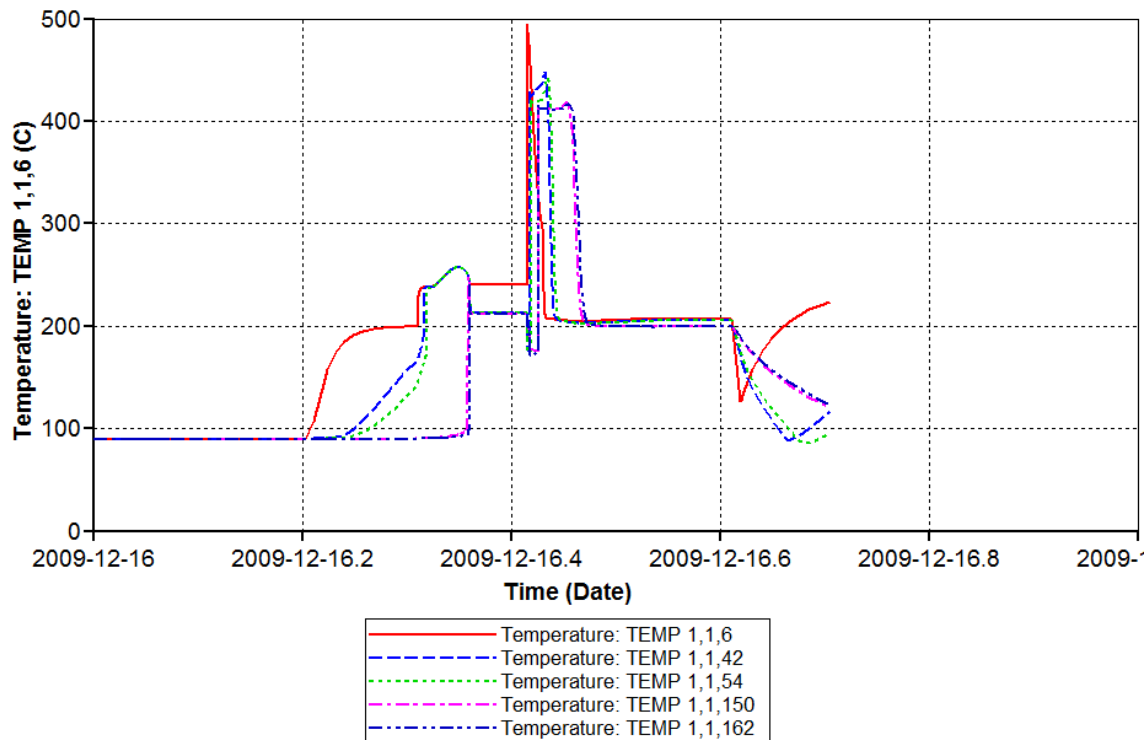


**Figure 19:** Effect of high gas injection rate (stg) on the temperature profile- stg: 20 (a) and 40 (b)

#### 4.2.4 Effect of Relative Permeability

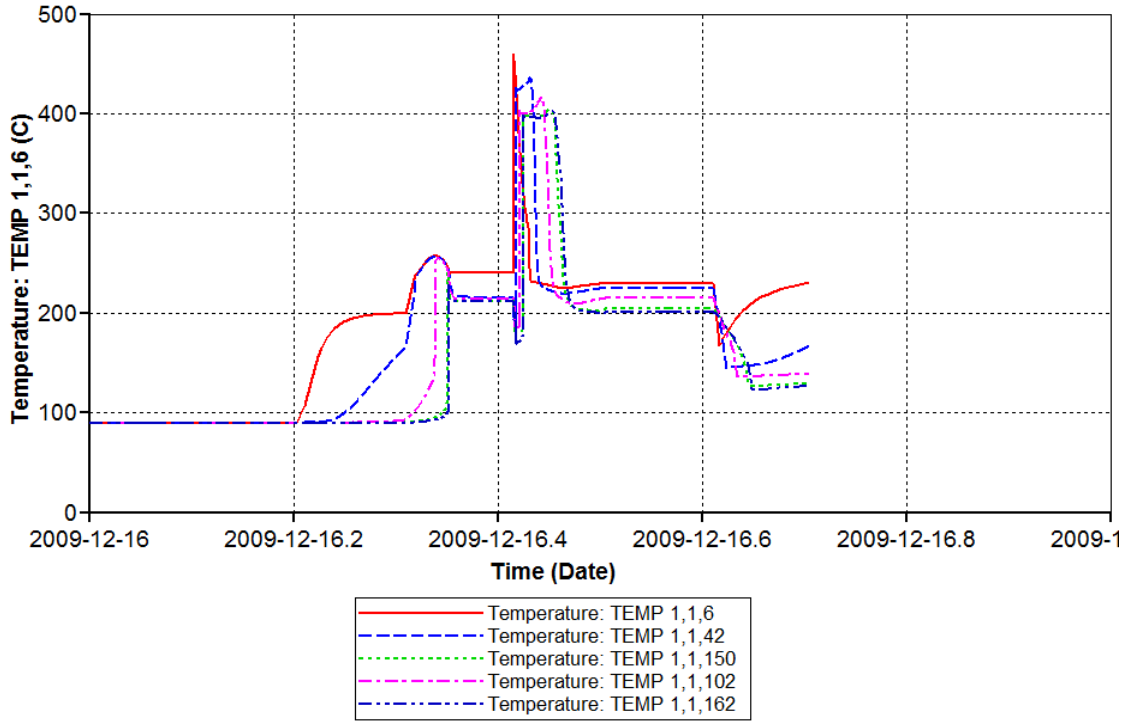
One of the large uncertainties during heat simulation is connected with relative permeability curves being temperature dependent parameters. Industrial experience provides an indication of active use of that parameter during history matching.

In our simulation model, the relative permeability curve as shown in **Figure 12** are normalized data, therefore the end points of  $K_{rog}$  and  $K_{row}$  before normalizing the relative permeability curves are changed. The normalization is subsequently performed in order to use the proper data for the history matching. The end point of  $K_{row}$  or  $K_{rg}$  has been changed between 0 and 1, for example, it set to 0.2. The effect of different end points on the temperature profiles are given in **Figure 20**, **Figure 21** and **Figure 22**.

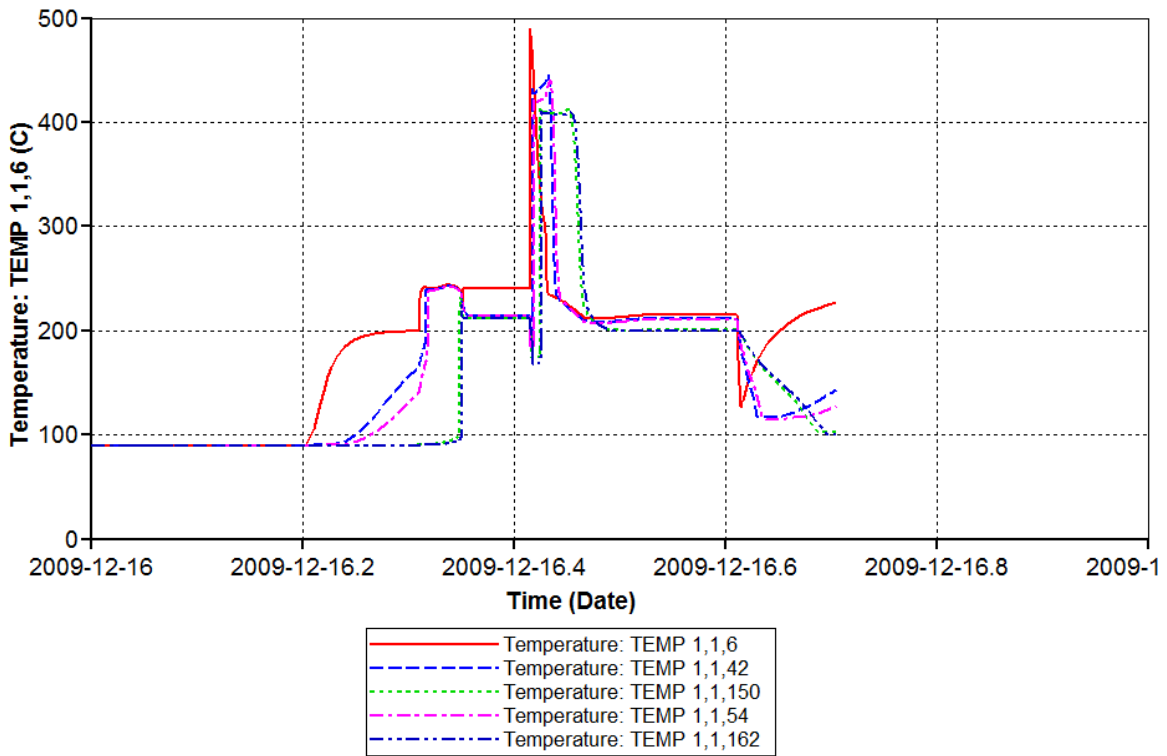


**Figure 20:** Effect of relative permeability end point ( $K_r$ : 0.4) on temperature profile





**Figure 21:** Effect of relative permeability end point ( $K_r$ : 0.7) on temperature profile



**Figure 22:** Effect of relative permeability end point ( $K_r$ : 0.9) on temperature profile

#### 4.2.5 Automated HM Methodology with BASRA and Its Testing Results

The manual history matching is a time consuming process with limitation on accuracy of the output product. The history matching with BASRA tools aims to increase the accuracy and speed up the history matching process.

This chapter provides an example of BASRA application for our experimental data. In our study, only the frequency factor (FF), activation energy (Ea) and coke precipitation (RXE) have been used as variables with the BASRA tools for the wet CT test history matching manually. During the testing process, it has been created two steps methodology for combustion tube history matching in order to match temperature profiles.

The first step; the maximum temperature obtained from the experiment is set as a matching parameter to the model. That means that all kinetic factors (FF, Ea and RXE) should be adjusted until the maximum temperature will correspond to experimental value with the certain defined range. This step ensures the validity of the maximum peak of temperature with respect to effective temperature for combustion process.

The second step; the temperature at all zones are variables will be entered as matching parameters to increase accuracy of the match.

In our study, focus is on the match of the temperature profiles as a main representation of the movement of combustion front, however based on the number of parameters the methodology can be revised and increased number of steps (pressure data, combustion composition coke layout and etc). The same data set as for manual history matching has been used for BASRA study. Additional specific files have been created for setting the target matching parameters (step one – peak of temperature, step two – set of temperatures for all zones).

BASRA is required to range of initial values of variable (FF, Ea and RXE) which been provide in Table 5. One of the advantages of BASRA is lack of predefined range of parameters, which eliminate identification of local solution, algorithm applied determinate the surface with multiple solution for the particular

conditions. The best fit for the FF, Ea and RXE variables for the super wet test is given in **Table 7**.

**Table 7:** The best fit of FF and RXE variables for the CT tests

<b>Parameter name</b>	<b>Best Fit for Super wet CT</b>
RXE1	0.2967
RXE2	0.1570
1freqfac11	5.1184
1freqfac22	6.4757
1freqfac33	12.2136
1freqfac44	5
1freqfac55	6.2539
1freqfac66	5.2114
1eact11	10.5545
1eact22	7.6109
1eact33	7.7701
1eact44	10
1eact55	5.5344
1eact66	1.3347

It is noted that the FF of reaction no1, for instance, is expressed as  $10E+(1freqfac11)$  and so on. The activation energy is written as  $10E+(1eact11)$  for the first reaction for example. The best fit values are reimported into the numerical model of super wet test and the model is run to get the temperature profile.

The obtained solution represents an illustration of two step HM approaches for replication of super wet combustion condition with main focus on temperature match. As it mentioned before, the approach proposed can be extended for pressure, compositional gages and other initial data in respect with aim of the study.



## 5 CONCLUSION

The super wet combustion tube test has been carried out at UoC laboratory. A numerical modeling and history matching has been performed based on the experimental parameters obtained with particular focus on the temperature profiles.

Extended sensitivity study with further manual history matching has been performed. At the later stage it has been tested a two-step approach for automated HM by BASRA. The results have been discussed and most of parameters influencing the temperature profiles have been evaluated. The main conclusions given for this study are following:

1-The numerical model has been successfully created according to experiment setup for combustion tube. The model represents bitumen composition and their characterization, Belgrave kinetic model is used as a base. The model assumes no radial heat losses, since convective heat losses are believed to be dominant. Effective representation of hot water injection and steam injection is an important

part of initialization of the model and replication of further combustion process (see data file in Appendix).

2-Sensitivity study allowed ranking the domination of the parameters on the behavior of the combustion. During the test it has been selected kinetic parameters, bitumen compositional, air injection rates and relative permeability parameters. Analyze clearly distinguished the major effect of kinetic parameters (frequency factors, activation energy and coke precipitation) on the combustion behavior. In simplified condition, e.g. one model, kinetic model can be applied (low temperature oxidation reaction).

3-The results from history matching show that the parameters for the frequency factor, activation energy, and coke precipitation are determined better with the BASRA tools rather than the manual work. The best fit for each parameter has been obtained. The effect of relative permeability end point and saturation do not have much influence on the temperature profile while the gas injection rate does significant effect on the temperature profiles.

4- Simulations and experiments suggest that the low temperature oxidation (LTO) process occurs when the temperature is below 300°C and the high temperature oxidation (HTO) process is dominant at the temperature above 350°C.

5-The two-steps automated history matching methodology has been tested by using BASRA. It could provide comparable results with the manual history matching with additional advantages in speed of matching and accuracy of the obtained output results.

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# 7 APPENDIX

## 7.1 Appendix A: Data files

\*\* OVERVIEW

\*\* =====

\*\* Super wet combustion in a 1-d vertical tube is simulated for BITUMEN - 11 August 2009.

\*\* Air is injected at a constant rate. Fluids are produced at constant back-pressure.

\*\* Model is in Field units due to PVT model has taken from CMG template

\*\* Heat losses are not included in the model

\*\* Fuel requested for combustion is 21.95 kg/m<sup>3</sup>

\*\* Major events during CT experiment

\*\* -3.65 Begin pressure-up of annulus and tube with helium

\*\* -3.58 Start-up heaters (set T to 35°C)

\*\* -3.23 Heaters set to 90°C (initial test temperature)  
 \*\* -3.10 First sign of gas breakthrough (back pressure rising)  
 \*\* -3.10 Start inert gas (He) flood at 233 slph  
 \*\* -2.53 Start ignition heating  
 \*\* 0.00 Start air injection at 233 slph; Zone 1 core at 350°C  
 \*\* 1.06 First sign of liquid production (mostly water)  
 \*\* 1.42 First sign of oil production  
 \*\* 9.64 Switch to helium at 233 slph for purging  
 \*\* 10.72 End of helium purge; start to depressurize tube  
 \*\* HM is done in main respect with a peak temperature table in the different zones

** Location (m)	Time (h)	Peak Temp (°C)	Peak Temp (°F)	
** ZONE 1	0.076	0.49	383	721
** ZONE 2	0.229	1.29	532	990
** ZONE 3	0.381	2.69	657	1215
** ZONE 4	0.533	3.55	630	1167
** ZONE 5	0.686	4.47/(4.71)*	599 (609)*	1111 (1127) **max temp in brackets
** ZONE 6	0.838	5.47	605	1120
** ZONE 7	0.991	6.31	567	1053
** ZONE 8	1.143	7.30	561	1042
** ZONE 9	1.295	8.51(10.97)*	543 (577)*	1009 (1070)*
** ZONE 10	1.448	9.51	568	1054
** ZONE 11	1.600	10.97	234	452
** ZONE 12	1.753	10.06	156	313

RESULTS SIMULATOR STARS 200900

\*\*RANGECHECK ON

TITLE1 'STARS Air Injection Course'

TITLE2 'Combustion Tube simulation'

\*INUNIT \*SI

\*\*OUTUNIT \*SI except 1 1 \*\* hrs instead of days

```

** =====
** INPUT/OUTPUT CONTROL
** =====

INTERRUPT STOP
**RESTART 99
WRST 3
WPRN GRID 0
WPRN SECTOR 1
WSRF WELL 1
WSRF GRID 1 **TIME
WSRF SECTOR 1
**WPRN ITER 300
OUTPRN WELL ALL
**OUTPRN GRID OBHLOSS PRES SG SO SOLCONC SW TEMP VISG
VISO VISW X Y
OUTPRN RES ALLSMALL
OUTPRN ITER BRIEF
OUTSRF  GRID  CCHLOSS  CMPDENO  CMPDENW  CMPVISG
CMPVISO CMPVISW KRG KRO KRW KVALYW KVALYX
      MASDENG MASDENO MASDENW OBHLOSS PCOG PCOW
PRES SG SO SOLCONC SW
      TEMP VISG VISO VISW W X Y
OUTSRF SPECIAL BLOCKVAR TEMP 1,1,6
      BLOCKVAR TEMP 1,1,18
      BLOCKVAR TEMP 1,1,30
      BLOCKVAR TEMP 1,1,42
      BLOCKVAR TEMP 1,1,54
      BLOCKVAR TEMP 1,1,66
      BLOCKVAR TEMP 1,1,78
      BLOCKVAR TEMP 1,1,90
      BLOCKVAR TEMP 1,1,102

```

BLOCKVAR TEMP 1,1,114  
 BLOCKVAR TEMP 1,1,126  
 BLOCKVAR TEMP 1,1,138  
 BLOCKVAR TEMP 1,1,150  
 BLOCKVAR TEMP 1,1,162  
 MOLEFRAC 'PRODUCER' 'O2' GAS  
 MOLEFRAC 'PRODUCER' 'N2' GAS  
 MOLEFRAC 'PRODUCER' 'CO2' GAS  
 MOLEFRAC 'PRODUCER' 'Asphalt' OIL  
 MAXVAR TEMP  
 MATBAL REACTION 'Asphalt'  
 MATBAL REACTION 'Maltenes'  
 MATBAL REACTION 'coke'  
 MATBAL REACTION 'H2O'  
 MATBAL REACTION 'O2'  
 MATBAL REACTION ENERGY  
 MATBAL CURRENT 'Asphalt'  
 MATBAL CURRENT 'Maltenes'  
 MATBAL CURRENT 'coke'  
 MATBAL CURRENT 'H2O'  
 MATBAL CURRENT ENERGY  
 DELP 'INJECTOR' 'PRODUCER'  
 MAXVAR MASS SOLCONC 'coke'

\*MAXERROR 40

\*SR2PREC \*DOUBLE

\*\*\$ Distance units: m

RESULTS XOFFSET 0.0000

RESULTS YOFFSET 0.0000

RESULTS ROTATION 0.0000 \*\*\$ (DEGREES)

RESULTS AXES-DIRECTIONS 1.0 -1.0 1.0

\*\*\$ \*\*\*\*\*

```

**$ Definition of fundamental Cartesian grid
**$ *****
GRID VARI 1 1 168 ***the number of cells=1.029*14
KDIR DOWN **UP
** Diameter is 5 cm
DI IVAR
0.05
DJ JVAR
0.05
*** Length of the tube is 1.029
DK ALL
168*0.006125
DTOP
0
**$ Property: NULL Blocks Max: 1 Min: 1
**$ 0 = null block. 1 = active block
NULL CON      1
**$ Property: Porosity Max: 0.439 Min: 0.439 *** 0.45 for the BITUMEN?
POR CON      0.421
**$ Property: Permeability I (md) Max: 4500 Min: 4500
PERMI CON     4500
PERMJ EQUALSI
PERMK EQUALSI
**$ Property: Pinchout Array Max: 1 Min: 1
**$ 0 = pinched block. 1 = active block
PINCHOUTARRAY CON      1
END-GRID
ROCKTYPE 1 ***compare with Belgrave data
ROCKCP 1.25522E+06 2.428E+03
THCONR 1.40832E+05 **1.40832E+05
THCONW 5.85686E+04 **5.85686E+04

```

THCONO 1.20874E+04 \*\*1.20874E+04

THCONG 2679.183 \*\*2679.183\*\*

\*\*=====

\*\* FLUID PROPERTIES

\*\* =====

\*\*\$ Model and number of components

MODEL 9 8 3 1

COMPNAME 'H2O' 'Asphalt' 'Maltenes' 'CO2' 'H2S' 'CO' 'N2' 'O2' 'coke'

CMM

0 1.0928 0.406 0.04401 0.03408 0.02801 0.028013 0.031999 0.01313

PCRIT

0 792 3394 7376 8937 3496 3394 5046

TCRIT

0 904 -146.95 31.05 100.05 -140.25 -146.95 -118.55

KV1

0 0 1.888e7

KV2

0 0 0

KV3

0 0 0

KV4

0 0 -6562.3

KV5

0 -79.98 0

CPG1

0 0 992 0 0 0 0 0

CPG2

0 0 0 0 0 0 0 0

CPG3

0 0 0 0 0 0 0 0

CPG4



```

0 0 0 0 0 0 0 0
HVR
0 0 10300
SOLID_DEN 'coke' 917 0 0
MASSDEN
0 1149.63 978.46
CP
0 9.46e-7 9.53e-7
CT1
0 4.5e-4 5.85e-4
AVISC
0 4.89e-25 0.19359e-4 **0.0007573
BVISC
0 33147 5369.2

** 'H2O' 'Asphalt' 'Maltenes' 'CO2' 'H2S' 'CO' 'N2' 'O2' 'coke'
** CRACKING
** Maltenes --> asphaltenes
**$ Reaction specification
STOREAC
0 0 0.835442517 0 0 0 0 0 0
**0 0 1 0 0 0 0 0
STOPROD
0 0.31169967 0 0 0 0 0 0
**0 0.372 0 0 0 0 0 0
FREQFAC 160378.858670087
RENTH 0
EACT 2.347E5
** Asphaltene --> Coke
**$ Reaction specification
STOREAC

```

```

0 1.026074383 0 0 0 0 0 0
**0 1 0 0 0 0 0 0
STOPROD
0 0 0 0 0 0 0 83.223
**0 0 0 0 0 0 0 83.223
FREQFAC 9268011422115.23
RENTH 0
EACT 1.772e5
**O2PP 'Maltenes'
**RXEQFOR comp_name rxk1 rxk2 rxk3 rxk4 rxk5
RXEQFOR 'Asphalt' 0 0 0.126242884216199 0 -273
** Asphaltene --> Gas (CO2)
**$ Reaction specification
STOREAC
0 1.016074383 0 0 0 0 0 0
**0 1 0 0 0 0 0 0
STOPROD
0 0 0 24.8 0 0 0 0
**0 0 0 24.8 0 0 0 0
**RPHASE
**0 2 0 0 0 0 0 0
FREQFAC 11730880613321.2
RENTH 0
EACT 1.763e5
** LOW TEMPERATURE OXIDATION
** Maltenes + O2 --> Asphaltenes
**$ Reaction specification
STOREAC
0 0 0.835442517 0 0 0 0 3.439 0
**0 0 1 0 0 0 0 3.439 0
STOPROD

```

```

0 0.405333183 0 0 0 0 0 0
**0 0.473 0 0 0 0 0 0
RORDER
0 0 1 0 0 0 0 0.425 0
FREQFAC 5688838.75031045
RENTH 1.296e6
EACT 8.673e4
O2PP 'O2'
** Asphaltenes + O2 ----> Coke
**$ Reaction specification
STOREAC
0 1.016074383 0 0 0 0 0 7.588 0
**0 1 0 0 0 0 0 7.588 0
STOPROD
0 0 0 0 0 0 0 101.723
**0 0 0 0 0 0 0 101.723
RORDER
0 1 0 0 0 0 0 4.7627 0
FREQFAC 473425.859501808
RENTH 2.857e6
EACT 1.85e5
O2PP 'O2'
**RXEQFOR comp_name rxk1 rxk2 rxk3 rxk4 rxk5
RXEQFOR 'Asphalt' 0 0 0.151459830428514 0 -273
** COKE COMBUSTION
** O2 + Coke --> H2O + CO2
**$ Reaction specification
STOREAC
0 0 0 0 0 0 0 1 0.811
**0 0 0 0 0 0 0 1 0.811
STOPROD

```

0.46 0 0 0.78 0 0 0 0 0  
FREQFAC 170077076.535231  
RENTH 3.5e5  
EACT 3.476e4

\*\* =====

\*\* ROCK-FLUID PROPERTIES

\*\* =====

\*\* BITUMEN Rock-fluid data

\*\* Capillary pressure is set to 0

ROCKFLUID

RPT 1 LININTERP WATWET

SWT SMOOTHEND CUBIC

\*\* SW krw krow

0.100000 0.000000 1.000000

0.122500 0.000008 0.970086

0.145000 0.000044 0.937268

0.167500 0.000121 0.901525

0.190000 0.000252 0.862902

0.212500 0.000446 0.821511

0.235000 0.000715 0.777545

0.257500 0.001070 0.731283

0.280000 0.001523 0.683088

0.302500 0.002086 0.633408

0.325000 0.002773 0.582761

0.347500 0.003598 0.531721

0.370000 0.004576 0.480898

0.392500 0.005722 0.430912

0.415000 0.007054 0.382368

0.437500 0.008591 0.335826

0.460000 0.010351 0.291782

0.482500 0.012356 0.250646  
0.505000 0.014628 0.212735  
0.527500 0.017192 0.178259  
0.550000 0.020075 0.147330  
0.572500 0.023303 0.119964  
0.595000 0.026910 0.096092  
0.617500 0.030929 0.075575  
0.640000 0.035397 0.058217  
0.662500 0.040360 0.043781  
0.685000 0.045866 0.032004  
0.707500 0.051974 0.022602  
0.730000 0.058756 0.015292  
0.752500 0.066305 0.009787  
0.775000 0.074741 0.005811  
0.797500 0.084238 0.003099  
0.820000 0.095063 0.001397  
0.842500 0.107682 0.000467  
0.865000 0.123093 0.000078  
0.877500 0.133850 0.000011  
0.890000 0.149992 0.000000  
0.922500 0.149992 0.000000  
0.955000 0.149992 0.000000  
0.977500 0.149992 0.000000  
1.000000 0.149992 0.000000  
SLT SMOOTHEND CUBIC  
\*\*\$SL krg krog  
0.100000 0.699998 0.000000  
0.125000 0.699998 0.000000  
0.150000 0.699998 0.000000  
0.170000 0.653869 0.000003  
0.190000 0.610820 0.000030

0.212500 0.565747 0.000145  
0.235000 0.523915 0.000439  
0.257500 0.485032 0.001028  
0.280000 0.448845 0.002060  
0.302500 0.415125 0.003712  
0.325000 0.383671 0.006194  
0.347500 0.354303 0.009750  
0.370000 0.326859 0.014659  
0.392500 0.301195 0.021232  
0.415000 0.277180 0.029814  
0.437500 0.254696 0.040775  
0.460000 0.233639 0.054500  
0.482500 0.213911 0.071378  
0.505000 0.195424 0.091781  
0.527500 0.178101 0.116040  
0.550000 0.161868 0.144419  
0.572500 0.146659 0.177084  
0.595000 0.132416 0.214069  
0.617500 0.119083 0.255256  
0.640000 0.106611 0.300351  
0.662500 0.094954 0.348883  
0.685000 0.084071 0.400212  
0.707500 0.073925 0.453562  
0.730000 0.064483 0.508058  
0.752500 0.055714 0.562780  
0.775000 0.047591 0.616824  
0.797500 0.040093 0.669347  
0.820000 0.033200 0.719619  
0.842500 0.026896 0.767047  
0.865000 0.021172 0.811192  
0.887500 0.016022 0.851768

0.910000 0.011452 0.888634  
0.932500 0.007478 0.921771  
0.955000 0.004141 0.951263  
0.977500 0.001532 0.977268  
1.000000 0.000000 1.000000

\*\* =====

\*\* INITIAL CONDITIONS

\*\* =====

\*initial

VERTICAL OFF

INITREGION 1

    \*\* high initial pressure

\*\*\* Changed from 2000

\*\*\$ Property: Pressure (kPa) Max: 2000 Min: 2000

PRES CON    2000

\*\*\$ Property: Water Saturation Max: 0.222 Min: 0.222

SW CON    0.201

\*\*\$ Property: Oil Saturation Max: 0.458 Min: 0.458

SO CON  0.582

SG CON 0.217

\*\*\$ Property: Oil Mole Fraction(Maltenes) Max: 0.8 Min: 0.8

MFRAC\_OIL 'Maltenes' CON    0.9151

\*\*\$ Property: Oil Mole Fraction(Asphalt) Max: 0.2 Min: 0.2

MFRAC\_OIL 'Asphalt' CON    0.0849

\*\*\$ Property: Gas Mole Fraction(N2) Max: 0.9649 Min: 0.9649

MFRAC\_GAS 'N2' CON    0.9649

\*\*\$ Property: Temperature (C) Max: 90 Min: 90

TEMP CON    90

\*\* =====NUMERICAL CONTROL =====

```

*NUMERICAL
*DTMAX 0.01
***PRECC 0.00000001
*NORTH 100
*ITERMAX 100
*SDEGREE 2
*CONVERGE *TOTRES *TIGHTER
** ===== RECURRENT DATA =====
RUN
DATE 2009 12 16.0000
DTWELL 0.005
**$
WELL 'PRODUCER'
PRODUCER 'PRODUCER'
    operate MIN bhp 2000
** maximum temp during test
            ** i j k
**$      rad geofac wfrac skin
GEOMETRY K 1. 1. 1. 0.
PERF TUBE-END 'PRODUCER'
**$ UBA  ff Status Connection
    1 1 168 1. OPEN  FLOW-TO 'SURFACE'

DATE 2009 12 16.0007
**starting pressurize the system with injecting of helium
**injection of helium is continued with water to bring and maintain the
back pressure to 2.2Mpa which is the initial test pressure.
***water injection at 90c WITH THE RATE 50 ML/H from -9.15h to -9.11h
WELL 'INJECTOR'
INJECTOR MOBWEIGHT 'INJECTOR'
INCOMP WATER 1. 0. 0.

```



TINJW 90

OPERATE MAX STW 0.0012 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.0333

\*\*continuing the water injection from -9.11h to -9.10h with the rate of 500ml/h at 90C

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER 1. 0. 0.

TINJW 90

OPERATE MAX STW 0.012 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.0347

\*\*continuing the water injection from -9.10h to -8.68h with the rate of 200ml/h at 90C

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER 1. 0. 0.

TINJW 90

OPERATE MAX STW 0.0048 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.  
PERF WI 'INJECTOR'  
\*\*\$ UBA wi Status Connection  
1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.0528

\*\*continuing the water injection from -8.680h to -8.20h with the rate of  
100ml/h at 90C

WELL 'INJECTOR'  
INJECTOR MOBWEIGHT 'INJECTOR'  
INCOMP WATER 1. 0. 0.

TINJW 90

OPERATE MAX STW 0.0024 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.  
PERF WI 'INJECTOR'  
\*\*\$ UBA wi Status Connection  
1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.0729

\*\*continuing the water injection from -8.20h to -7.80h with the rate of  
75ml/h at 90C

WELL 'INJECTOR'  
INJECTOR MOBWEIGHT 'INJECTOR'  
INCOMP WATER 1. 0. 0.

TINJW 90

OPERATE MAX STW 0.0018 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.  
PERF WI 'INJECTOR'  
\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.0896

\*\*continuing the water injection from -7.80 to -7.48h with the rate of  
100ml/h at 90C

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER 1. 0. 0.

TINJW 90

OPERATE MAX STW 0.0024 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.1028

\*\*continuing the water injection from -7.48 to -7.01h with the rate of  
125ml/h at 90C

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER 1. 0. 0.

TINJW 90

OPERATE MAX STW 0.003 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.1222

\*\*continuing the water injection from -7.01 to -6.89h with the rate of 150ml/h at 90C

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER 1. 0. 0.

TINJW 90

OPERATE MAX STW 0.0036 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.1271

\*\*continuing the water injection from -6.89 to -6.59h with the rate of 175ml/h at 90C

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER 1. 0. 0.

TINJW 90

OPERATE MAX STW 0.0042 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.1396

\*\*\*water injection at 90C WITH THE RATE 200 ML/H from -6.59 to -6.06h

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'      \*\*starting water injection  
INCOMP WATER 1. 0. 0.  
TINJW 90  
OPERATE MAX STW 0.0048 CONT  
\*\*\$      rad geofac wfrac skin  
GEOMETRY K 0.086 0.249 1. 0.  
PERF WI 'INJECTOR'  
\*\*\$ UBA    wi      Status Connection  
    1 1 1 0.615556 OPEN    FLOW-FROM 'SURFACE'

DATE 2009 12 16.1618

\*\* continuing hot water flooding with he rate of 200ml/h at 200C from -  
6.06 to -5.09h... no helium injection directly during pressure up, hot water  
flooding and steam floods.

\*\*starting recovering of significant oil from production end, because the  
temperature is now enough to start to production.

WELL 'INJECTOR'  
INJECTOR MOBWEIGHT 'INJECTOR'  
INCOMP WATER 1. 0. 0.  
TINJW 90  
OPERATE MAX STW 0.0048 CONT  
\*\*\$      rad geofac wfrac skin  
GEOMETRY K 0.086 0.249 1. 0.  
PERF WI 'INJECTOR'  
\*\*\$ UBA    wi      Status Connection  
    1 1 1 0.615556 OPEN    FLOW-FROM 'SURFACE'

DATE 2009 12 16.2021

\*\* continuing hot water flooding with he rate of 200ml/h at 200C from -  
5.09 to -4.8h

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'  
INCOMP WATER 1. 0. 0.  
TINJW 150  
OPERATE MAX STW 0.0048 CONT  
\*\*\$ rad geofac wfrac skin  
GEOMETRY K 0.086 0.249 1. 0.  
PERF WI 'INJECTOR'  
\*\*\$ UBA wi Status Connection  
1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.2104

\*\* continuing hot water flooding with the rate of 200ml/h at 200C from -  
4.08 to -3.50h

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER 1. 0. 0.

TINJW 200

OPERATE MAX STW 0.0048 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.2681

\*\* continuing hot water flooding with he rate of 200ml/h at 200C from -  
3.50 to -2.52h

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER 1. 0. 0.

TINJW 200

OPERATE MAX STW 0.0048 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.2722

DATE 2009 12 16.2806

DATE 2009 12 16.3021

DATE 2009 12 16.3090

\*\*starting steam injection at 240C with the rate of 200ml/h at -2.52h to -  
0.02.

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER 1. 0. 0.

TINJW 240

QUAL 0.95

OPERATE MAX STW 0.0048 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.3188

DATE 2009 12 16.3299

DATE 2009 12 16.3514

\*\* zone 1 is at 240 C for ignition

\*\*240C is ignition temperature.

AUTOHEATER ON 1:1 1:1 1:12 \*\*preparing the condition of ignition

\*HEATR IJK

1 1 1:12 1E8

\*UHTR \*IJK

1:1 1:1 1:12 1E7

TMPSET \*IJK 1:1 1:1 1:12 240 \*\*at zone 1 from the first cell up to 12th cell.

\*\* zone 2 is at 200 C for ignition

AUTOHEATER ON 1:1 1:1 13:24

\*HEATR IJK

1 1 13:24 1E8

\*UHTR \*IJK

1:1 1:1 13:24 1E7

TMPSET \*IJK 1:1 1:1 13:24 200 \*\*\*Zone 2 starts from 13th cell up to 24th cell

DATE 2009 12 16.4132

\*\*helium injection at the rate of 56.6l/h was continued to maintain back pressure to 2.2Mpa.

\*\*the system should be exceeded to the temp of 219C and a pressure of 2.2Mpa to reach to the steam condition

\*\*continuing with super-heated steam flooding from -0.02h to 0h with the rate of 200ml/h at 240C.

\*\*recovering of significant oil during this stage.

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER 1. 0. 0.

TINJW 240

QUAL 0.95



OPERATE MAX STW 0.0048 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.4146

\*\*starting injection of syntetic air at 0.00h to 0.35h with the rate of 56.7l/h

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP GAS 0. 0. 0. 0. 0. 0. 0.79 0.21

TINJW 240

OPERATE MAX STG 1.36 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

\*HEATR IJK \*\*\*\*Switch off the heaters from the first cell up to 24th cells, including 2 zones.

1 1 1:24 0

\*UHTR \*IJK

1:1 1:1 1:24 0

DATE 2009 12 16.4164

DATE 2009 12 16.4174

DATE 2009 12 16.4215

DATE 2009 12 16.4292

\*\*starting gas and water injection, it means co-injection of water and air at 0.35h to 4.71h with the rate of 300ml/h at temp of 467C.

\*\*467C is the temperature of zone 1 which is the temp of starting of co-injection.

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER-GAS 0.002877318 0. 0. 0. 0. 0. 0.787726919  
0.209395763

TINJW 240 \*\*467

OPERATE MAX STF 1.36 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

DATE 2009 12 16.4333

DATE 2009 12 16.4417

DATE 2009 12 16.5556

DATE 2009 12 16.5569

DATE 2009 12 16.6104

\*\*switching to helium injection at the rate of 56.7l/h at 4.71h to 6.88h  
purge the combustion tube.

WELL 'INJECTOR'

INJECTOR MOBWEIGHT 'INJECTOR'

INCOMP WATER-GAS 0.002877318 0. 0. 0. 0. 0. 0.997122682 0.

TINJW 240

OPERATE MAX STF 1.36 CONT

\*\*\$ rad geofac wfrac skin

GEOMETRY K 0.086 0.249 1. 0.

PERF WI 'INJECTOR'

\*\*\$ UBA wi Status Connection

1 1 1 0.615556 OPEN FLOW-FROM 'SURFACE'

\*\*SHUTIN 'INJECTOR'

DATE 2009 12 16.7042 \*\*\*End of helium purge

STOP

RESULTS SPEC 'Permeability J'

RESULTS SPEC SPECNOTCALCVAL -99999

RESULTS SPEC REGION 'All Layers (Whole Grid)'

RESULTS SPEC REGIONTYPE 'REGION\_WHOLEGRID'

RESULTS SPEC LAYERNUMB 0

RESULTS SPEC PORTYPE 1

RESULTS SPEC EQUALSI 0 1

RESULTS SPEC STOP

RESULTS SPEC 'Permeability K'

RESULTS SPEC SPECNOTCALCVAL -99999

RESULTS SPEC REGION 'All Layers (Whole Grid)'

RESULTS SPEC REGIONTYPE 'REGION\_WHOLEGRID'

RESULTS SPEC LAYERNUMB 0

RESULTS SPEC PORTYPE 1

RESULTS SPEC EQUALSI 0 1

RESULTS SPEC STOP