CHAPTER-1

GENERAL INTRODUCTION

In this thesis, quite a lot of new developments for simulation of shale gas reservoirs were presented to enable the production from such reservoirs. A new analytical model was developed to simulate shale gas reservoirs by considering normal rectangular hydraulic fractures with constant fracture width and variable fracture porosity and permeability. For simulation of gas production from shale reservoirs, the new analytical model considers the different gas transport mechanism that is prevailing in shale gas reservoirs. This transport mechanism includes gas slippage, gas diffusion, and gas desorption. In addition to this, the analytical model includes different number of hydraulic fractures which makes the model more economical for production. This chapter first introduces the background of shale gas, different models representing shale gas reservoirs and hydraulic fracturing. Then, statement of the problem and the objectives of this study are presented. Finally the organization of the thesis is described.

1.1 BACK GROUND:

1.1.1. SHALE GAS:

Gas in shale reservoir is a natural gas which is extracted from gas shales which acts as both source and reservoir rock. In shale gas reservoirs, gas is stored in two forms: free gas in the pore spaces i.e. in the matrix pores and in the natural fractures and as adsorbed gas on the surface of the matrix blocks containing organic matter. As shale is an unconventional reservoir because of its ultralow permeability (around 10 to 100 Nano-Darcy), the economic production of shale gas is considered as impossible from a very long periods.

Mitchell Energy (1988) completed the first feasible shale gas stimulation work by performing slick water fracturing method. From this year onwards, the shale gas production becomes a main source of natural gas production.

From 2005 to 2015, there is a huge growth in the shale gas production which is because of two main technologies. One of them is hydraulic fracturing technology. The permeability of unconventional gas reservoirs is very low when compared to conventional gas reservoirs, which makes it impossible to produce gas at economical rates with the available technology. Now, with the application of fracturing technology, the permeability of the reservoir can be increased by inducing artificial hydraulic fractures. The Second technology is horizontal well bore technology. Though the problem of lower permeability formation is solved by hydraulic fracturing, the stimulated reservoir volume in case of vertical well is not sufficient to produce gas at economical rates. For producing the gas at economical rates, a horizontal well bore has to be drilled in the pay zone which will increase the contact area of wellbore with the formation, which will further increase the stimulated reservoir volume (SRV). The implementation of horizontal wellbore drilling and multi stage hydraulic fracturing technology will improve both the reservoir permeability and the stimulated reservoir volume.

1.1.2. SHALE GAS RESERVOIRS IN UNITED STATES:

It has been nearly 200 years since the first shale gas well was drilled in Fredonia. In the last few decades only the increase in exploration and production of shale gas is started.

As per the prediction made by the U.S. Energy Information Administration (EIA) (Figure 1.1 and Figure 1.2), the production of natural gas will increase from 23.0 trillion cubic feet (Tcf) to 33.1 trillion cubic feet (Tcf) from year 2011 to 2040. This increase in production will contribute around 38% of the total natural gas demand in the country, as shown in Figure 1.1. As shown in Figure 2, almost all of this increase is due to the growth in shale gas production from 7.8 Tcf in 2011 to 16.7 Tcf in 2040.

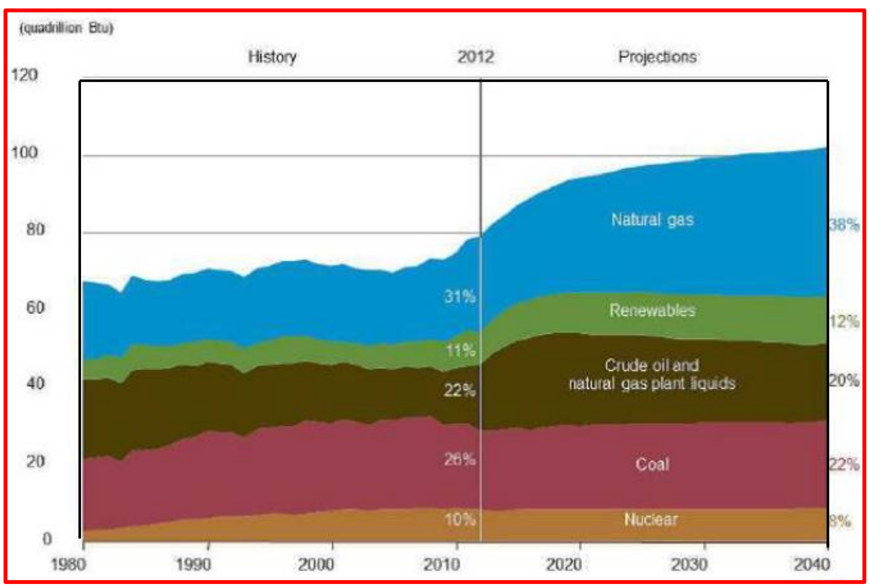

Figure 1.1: U.S. Energy Production by Fuel, 1980-2040 (EIA, 2013).

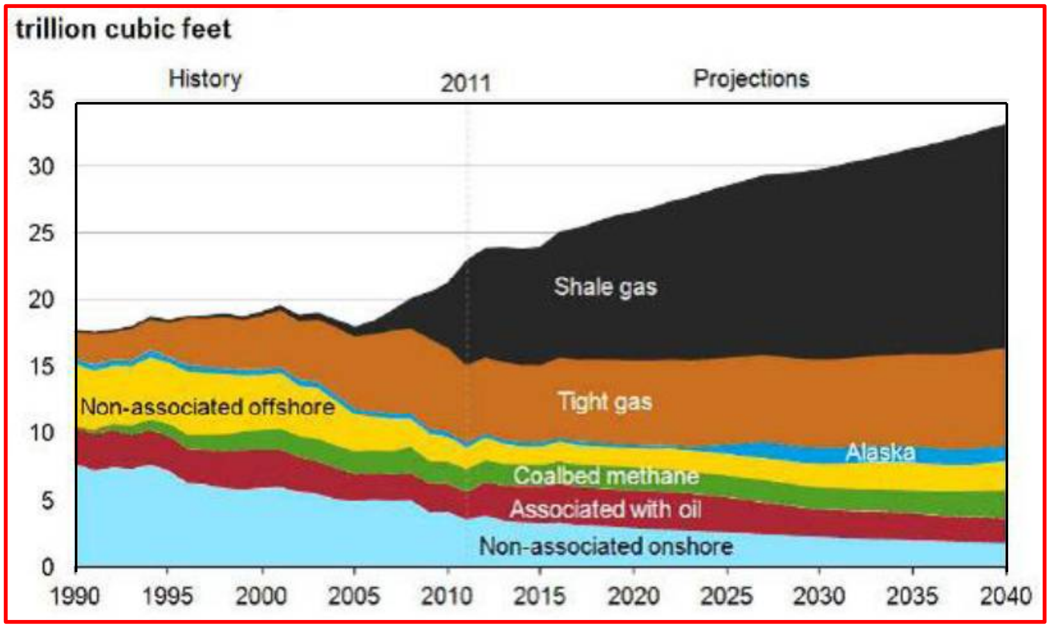

Figure 1.2: U.S. Dry Natural Gas Production (EIA, 2013).

From the lower 48 states of U.S., production of shale gas is mainly concentrated in five most important reservoirs: Barnett, Woodford, Fayetteville, Marcellus, and Haynesville as shown in Figure 1.3. Among these five reservoirs, Barnett shale is one of the most effective shale reservoirs for gas production at economical rates.

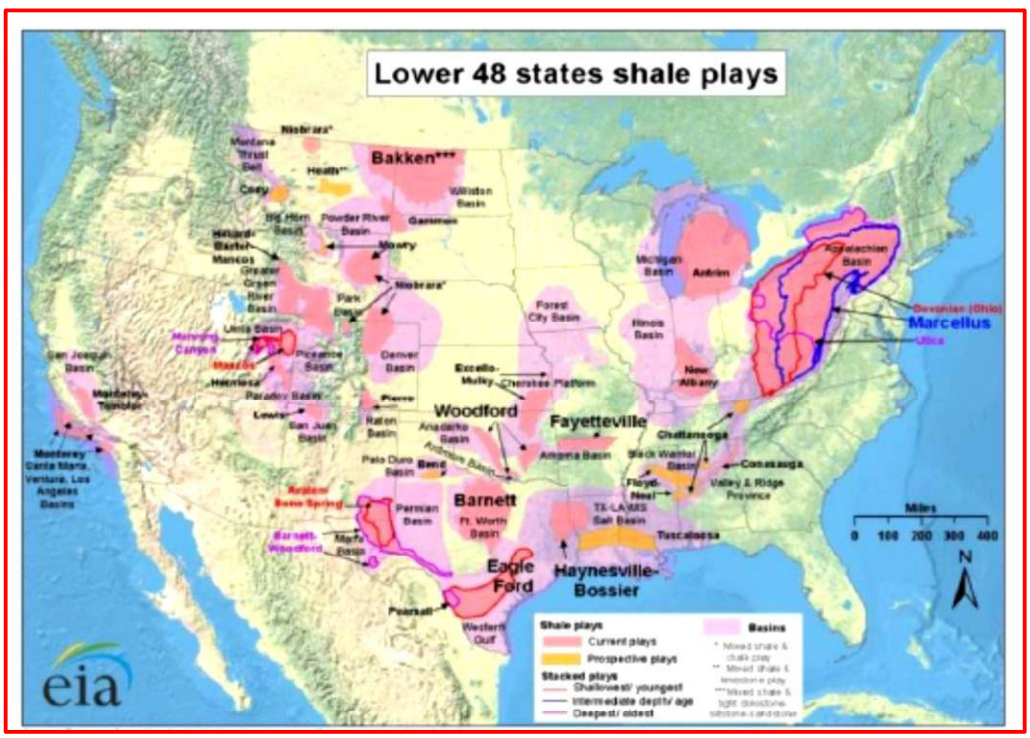

Figure 1.3: Shale Reservoirs in Lower 48 states (EIA, 2011).

Mitchell Energy and Development co. started producing gas from the Barnett shale in the early 1980's, but the production really started to rise up by the end of the 1990's, when they started implementing horizontal drilling combined with multi-stage hydraulic fracturing. Figure 1.4 shows the increase in production of shale gas from Barnett shale with increase in number of horizontal wells drilled.

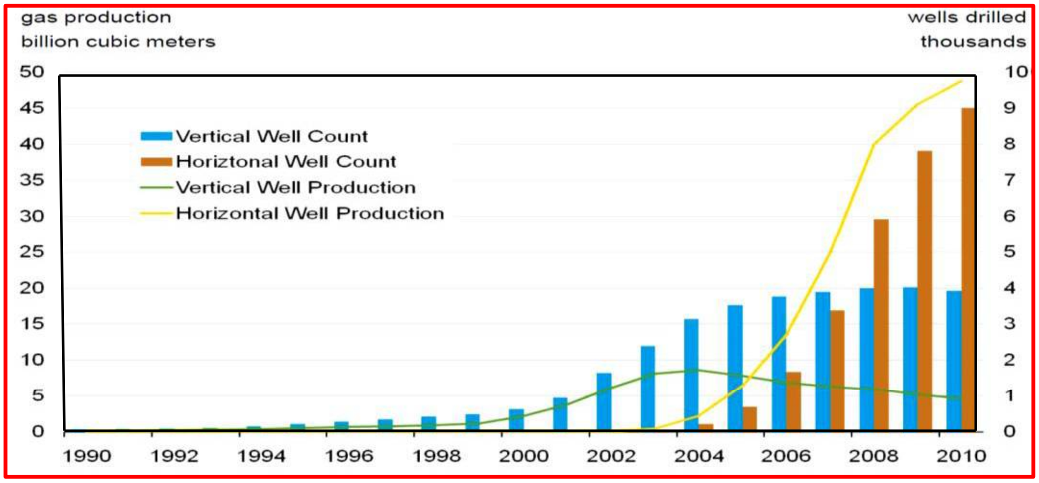

Figure 1.4: Increase in production and well count in the Barnett shale from 1990 to 2010 (Newell, 2010).

Gas shales have low permeability and low porosity with significant amounts of total organic content (TOC). The permeability in shale reservoirs is in the range of nano-Darcy, as shown in Figure 1.5. A sample of Barnett shale core sample is shown in Figure 1.6

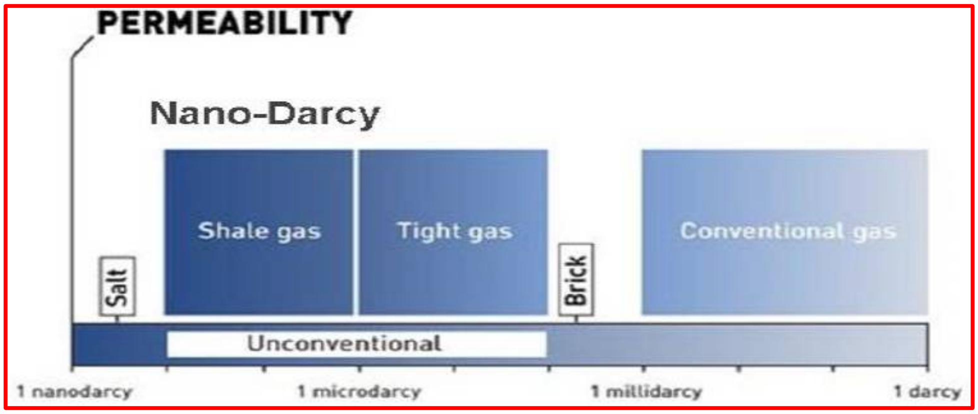

Figure 1.5: Permeability of Nano-Darcy for shale gas reservoirs. (http://www.total.com).

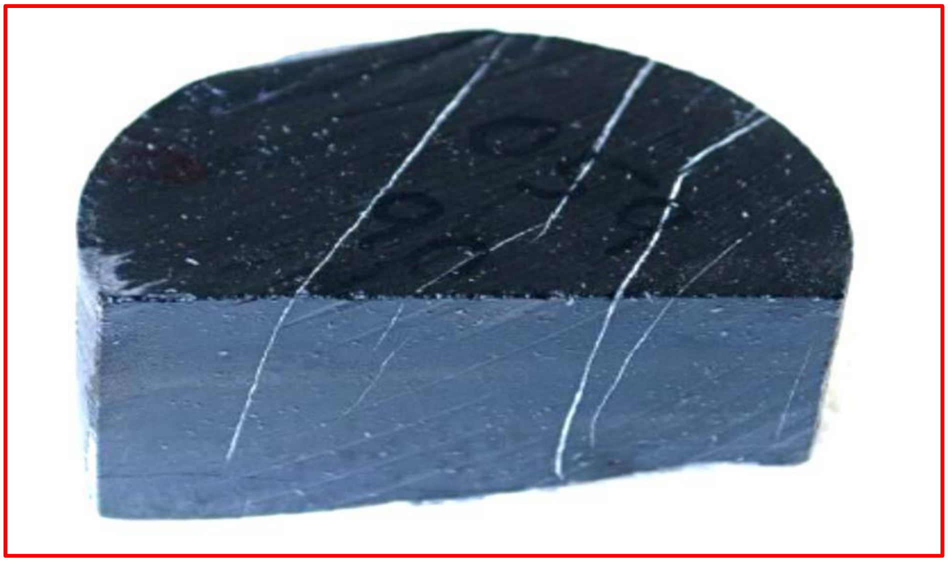

Figure 1.6: Core Sample from Barnett Shale (Bowker, 2013).

1.1.3. SHALE GAS DISTRIBUTION IN THE WORLD:

From the past decade, due to the invention of two new technologies for hydraulic fracturing and horizontal wellbore drilling, larger reserves of unconventional shale gas reserves which are untapped till now are under exploitation. Table 1.1 represents the distribution of shale gas reserves around the world; most of the reserves are located in North American and Asian basins with an estimated recovery of 16,000 Tcf (W. Fazelipour 2010).

Table 1.1: Estimation of Technically Recoverable Shale Gas Resources in the World.

(Source: www.energy.cr.usqc.gov, acquired on 15/11/2013).

Region	**Tight Gas Sands (Tcf)**	**Coalbed Methane (Tcf)**	**Shale Gas (Tcf)**
North America	1,371	3,107	3,840
Latin America	1,293	39	2,116
Western Europe	353	157	509
Central and Eastern Europe	78	118	39
Former Soviet Union	901	3,957	627
Middle East and North Africa	823	0	2,547

Sub-Saharan Africa	784	39	274
Asia and China Pacific	705	470	2,312
Other Asia Pacific	549	0	313
South Asia	196	39	0
World	7,406	9,051	16,103

As per the data estimated by EIA, the strictly recoverable shale gas in the world is around 7,299 trillion cubic feet (Tcf). Table 1.2 shows the total technically recoverable shale gas from different countries. In almost all the countries, the technically recoverable shale gas is higher than proven natural gas reserves.

Table 1.2: Shale Gas Reserves in the World (EIA, 2013).

S.No.	Country	Estimated technically recoverable shale gas (Tcf)	Proven natural gas reserves of all types (Tcf)
1	China	1,115	124
2	Argentina	802	12
3	Algeria	707	159
4	United Sates	665	318
5	Canada	573	68
6	Mexico	545	17
7	South Africa	485	-
8	Australia	437	43
9	Russia	285	1688
10	Brazil	245	14

1.1.4. SHALE GAS SCENARIO IN INDIA:

India has huge shale deposits across the Gangetic plain, Assam, Gujarat, Rajasthan, and many coastal areas. Gas has long been found in shale across the world, but its extraction has been viewed as uneconomic because of shale‘s low permeability gas does not flow easily through this rock. Exploration for oil and gas has traditionally focused on limestone and sandstone, which have high permeability.

India contains a number of basins with organic-rich shales, mainly the Cambay, Krishna Godavari, Cauvery, and Damodar Valley basins. There are some other potential reserves such as the Upper Assam, Vindhyan, Parinhita- Godavari, and South Rewa, but it has been found that either the shales were thermally too immature for gas or the data with which to conduct a resource assessment are not available.

Shale basins in India are geologically highly complex. Many of the basins, such as the Cambay and the Cauvery, have horst and graben structures and are extensively faulted. The prospective area for shale gas in these basins is restricted to a series of isolated basin depressions (sub-basins). While the shales in these basins are thick, considerable uncertainty exists as to whether (and what interval of) the shale is sufficiently mature for gas generation.

ONGC has stuck the first shale gas in a pilot project of Ichhapur in Buurdwan, West Bengal. It's drilling started on October 27, 2013 with Conocophillips. In addition ONGC has spudded one more well for shale gas and oil exploration in Gandhar area of Cambay Basin. Identified shale gas formations are spread over several sedimentary basins of the country, such as Cambay, Gondwanra, Krishna Godavari Onland and Cauvery. Shale Gas exploration has started from 2010. In January 2011, Schlumberger made an initial gas in place estimate of 300-2100 Tcf, under shale gas project for ONGC in Damodar Valley basin. In April 2011, Energy Information Administration (EIA)-USA assessed risked gas in place of 290 Tcf with technically estimated 63 Tcf recoverable resources from 4 (Cambay Onland, Damodar, K-G Onland and Cauvery Onland) out of 26 basins in India, which was upgraded to 584 Tcf in 2013.In a study conducted by United States Geological Survey (USGS) in 2011/2012, technically recoverable resource of 6.1 Tcf has been estimated in 3-sedimentary Basins (Cambay Onland, Krishna Godavari Onland and Cauvery Onland). In 2013, ONGC has estimated shale gas prospects as 187.5 Tcf from 5 basins namely Cambay, Krishna Godavari, Cauvery, Ganga & Assam, Assam-Arkan. Soon after these estimates were calculated the government of India on October 14, 2013 announced "Policy Guidelines" allowing two National Oil Companies (NOCs) and Oil India Limited (OIL) to carry out shale gas exploration in 56 blocks respectively in the first phase. Out of 56 Petroleum Exploration lease (PEL)/ Petroleum Mining Lease (PML) blocks are located in the states of Assam (7 Blocks), Arunachal Pradesh (1 Block), Gujarat (28 Blocks), Rajasthan (1

Block), Andhra Pradesh (10 Blocks) and Tamil Nadu (9 Blocks). ONGC has decided to drill 17 wells out of 50 wells. As per the contract with government of India ONGC will have to drill at least one (two in blocks having area more than 200 sq. km) well for assessment of shale gas and oil in each of these blocks by 2017.ONGC has drilled two shale gas R&D wells, first near Durgapur in Bengal Basin in 2011 and second near Jambusar in Cambay basin in 2013. Both these wells show the presence of shale gas.

Natural Gas Production for the year 2014-2015 is 33.656 Billion Cubic Meters (BCM) which is 4.94% lower than production of 35.407 BCM in 2013-2014. Consumption of Natural Gas for the year 2014-2015 is 46.95 Billion Cubic Meters (BCM). Imports of LNG for the financial year 2014-2015 is 15.47 Billion Cubic Meters (BCM) which has increased from the previous year 2013-2014 import of 13.03 Billion Cubic Meters (Source-www.dghindia.org, Directorate General of Hydrocarbons, India 2014-2015).

1.2. HYDRAULIC FRACTURING:

In order to produce shale gas at economical rates the two important technologies like horizontal drilling and multi-stage hydraulic fracturing are required, as shown in Figure 1.7. The stimulation process includes pumping huge volumes of fluids, which are helpful in creating fractures, large quantities of proppants, which keeps the induced fractures open. During stimulation treatments, different fracture networks will be generated and the interaction of induced fractures with the natural fractures will impact the complexity of the fracture network (Daniels et al., 2007; Maxwell et al., 2013). This fracture network will create a huge impact on the contact area between the formation and the horizontal wellbore (Cipolla and Wallace, 2014). The efficiency of the stimulation treatment will play an important role in economic production of the unconventional reservoirs (Weng., 2014). As the number of perforations will increase the contact area between the formation and horizontal wellbore, usually 3-6 perforation clusters per fracturing stage are mostly used in most horizontal wells (Cipolla et al., 2010). Recently U.S. Energy Information Administration (EIA, 2015) states that four countries are producing shale gas in economical rates, among these four countries United States is the dominant producer (Figure 1.8).

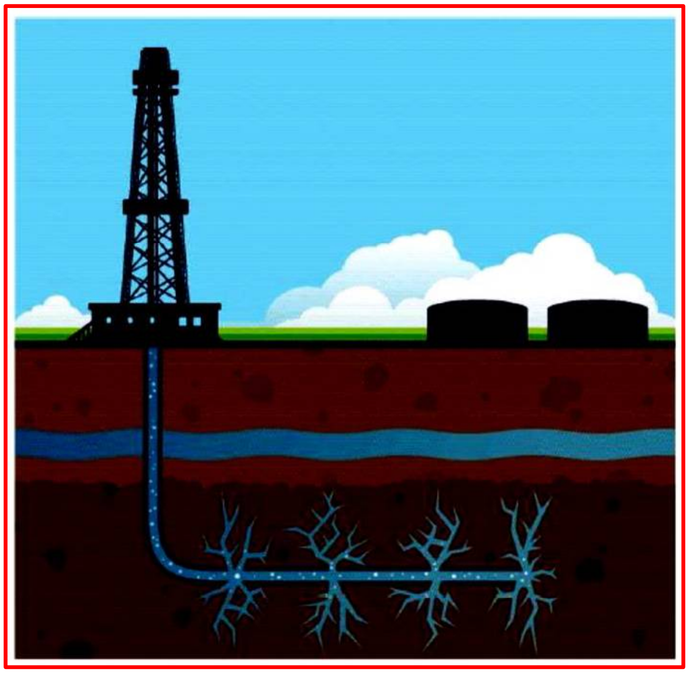

Figure 1.7: Horizontal drilling and multi-stage hydraulic fracturing (Web Page)

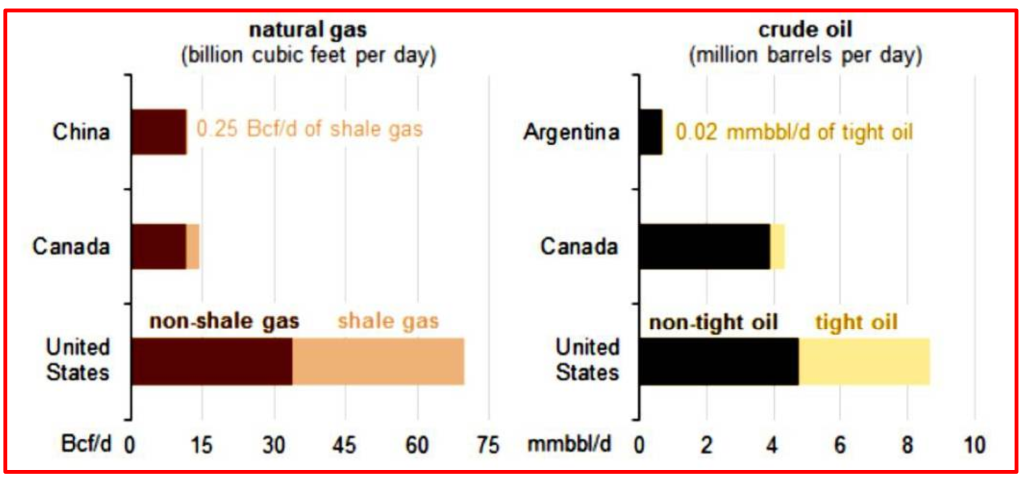

Figure 1.8: Four Countries producing commercial volumes of shale gas and tight oil reservoirs (EIA, 2015).(Web Page)

1.3 <u>STATEMENT OF THE PROBLEM:</u>

In shale gas reservoirs, the gas transport mechanism is entirely different from the conventional gas reservoirs, which includes not only gas advection, but also gas slippage, gas diffusion, and gas desorption. This type of gas transport mechanisms occurs due to different pore size distributions in unconventional and conventional gas reservoirs. The number of Nano pores in shale gas reservoirs is relatively higher than conventional gas reservoirs (Javadpour et al., 2007; Civan et al., 2010; Sakhaee-Pour and Bryant, 2012; Shi et al., 2013; Rezaveisi et al., 2014; Wu et al., 2014; Wu et al., 2015a, 2015b). The diffusivity equation of conventional gas reservoir is not acceptable to describe the gas flow in shale reservoirs. Moreover, due to large variations of permeability in matrix and hydraulic fractures, the gas velocity also changes. In hydraulic fractures the gas flow velocity is so high where the non-Darcy flow has to be considered. Furthermore, multiple hydraulic fractures, uniform distribution of proppants and fracture conductivity will play an important role in producing gas at economical rates (Gu and Mohanty, 2014; Gu et al., 2014, 2015); The effect of stress dependent fracture conductivity has to be considered because it is very stimulating to maintain that conductivity due to proppant settlement, generation and migration of fine proppants in the fracture, embedment of proppants in softer rock, and crushing of proppants in harder rocks (Darin and Huitt, 1960; Pope et al., 2009; LaFollette and Carman, 2010; Fan et al., 2010). Therefore, a complete model by considering the significant mechanisms for gas flow in shale and the effects of the rectangular fractures, non-Darcy flow and compressibility of fractures and fracture conductivity is highly essential.

In general, the hydraulic fracturing process will create complex non-planar hydraulic fractures. This complex fractures will be in bi-wing fractures and orthogonal fracture networks. Though there are many numerical models which will deal with complex fracture network, most of them are time expensive. Mainly, the effects of fracture width and permeability are not considered in the current models. So, an efficient model which will describe the effects of fracture width, fracture permeability and other parameters is highly recommendable.

The reservoir properties of shale reservoirs are highly uncertain, which has a crucial effect on shale gas production. In general, the permeability of shale gas reservoirs are in the range of Nano-Darcy. The range of thickness for a typical shale gas reservoir is 50 to 600 ft, porosity of 2-8%, TOC of 1-14% and is available at depth ranging from 1,000 to 13,000 ft (Cipolla et al., 2010). Further, the induced fracture parameters like fracture spacing, fracture half-length, fracture porosity, fracture permeability and number of fractures are also uncertain which will affect the well performance. As the cost of hydraulic fracturing is expensive, the optimization of hydraulic fracture treatment design is necessary to obtain the most economical gas production rates. So, performing of sensitivity analysis for optimizing the shale gas production in an efficient way is highly desirable.

1.4 RESEARCH GAP:

Many authors have addressed the issue of the different flow mechanism of gas in shale gas formations. Most of the authors has considered a specific region for their study and developed equations for the flow of gas in that region like the flow of gas in Nano pores, in matrix, natural fractures, induced fractures. In present thesis, dual porosity model has been considered i.e. the flow of gas from matrix to fractures (Induced fractures or hydraulic fractures) and then flow of gas from induced or hydraulic fractures into the wellbore. Single phase flow (only gas) within the matrix and multiphase flow within the hydraulic fracture i.e. water and gas flow (two phase flow) has been assumed in the present work.

1.5 RESEARCH OBJECTIVES:

The main objectives of current research problem are to develop simulation tools for production of gas from shale gas reservoirs. Hence, we develop an analytical model which describes the matrix blocks alignment, the gas flow behavior inside the reservoir and also the hydraulic fractures alignment. Moreover, a sensitivity analysis is also performed to optimize hydraulic fracture treatment design for shale gas reservoirs. The specific objectives of this dissertation include:

1) Developing a mathematical model, representing the flow behavior in shale gas reservoir.
2) Generating non-linear partial differential equations for the flow of gas from matrix to fracture and for the gas flow from fracture to the wellbore.
3) The developed nonlinear PDE's are then complied using JAVA to develop a simulator for calculating the shale gas production, by considering the matrix as a source term.
4) Numerically simulating the flow behavior with the help of developed system of PDE's and validating the results with commercial CMG-IMEX simulator.
5) Sensitivity analysis of the developed model and comparison with the result of commercial CMG-GEM simulator results.

Thesis Outline:

There are **9 chapters** in this thesis and their brief details are as follows:

Chapter-1 provides the information about the flow behavior of shale gas in the reservoir. A brief overview of shale gas reserves is discussed and a brief introduction is provided about the storage mechanisms of shale gas in shale reservoirs i.e. gas storage as free gas and in adsorbed gas.

Chapter-2 provides the literature review on different modeling techniques from fractured horizontal wellbore and their application to gas production from shale reservoirs. It also discusses different reservoir simulation models like dual porosity model, triple porosity model etc.

Chapter-3 details the new 3D developed model and developing a nonlinear partial differential equation for representing the gas flow in the matrix. It also details about the discretization method and the compilation of nonlinear PDE with JAVA programming.

Chapter-4 details the 2D developed model for gas flow in the hydraulic fracture. The nonlinear PDE for the flow of gas in the hydraulic fracture and a nonlinear PDE for flow of water in the hydraulic fracture is discussed. It also details about the discretization method and the compilation of nonlinear PDE with JAVA programming.

Chapter-5 details about the gas flow from the hydraulic fracture to the horizontal wellbore. It also includes the pressure variation of the entire matrix block and the pressure variation of all hydraulically fractured blocks.

Chapter-6 discusses about the commercial software **CMG-IMEX** for validating the new developed 3D shale gas reservoir model.

Chapter-7 provides the sensitivity analysis (using **CMG-GEM simulator**) of different reservoir parameters and hydraulic fracture parameters. The chapter also provides the ranges of all the parameters and also their effect on the average reservoir pressure, cumulative gas production and rate of gas production from shale reservoir.

Chapter-8 discusses about the obtained model results and the results of commercial CMG-IMEX Simulator for various cases, like shale reservoir with only horizontal wellbore and no hydraulic fracture, shale reservoir with 2 hydraulic fractures and shale reservoir with 3 hydraulic fractures etc.

Chapter-9 includes the conclusions and recommendations for future work in the area of shale gas reservoir modeling and simulation.