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# **DISPERSION DETERMINATION IN VAPEX: EXPERIMENTAL DESIGN, MODELING AND SIMULATION**

by

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Surat, Gujarat, India, 2002

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in partial fulfillment of the  
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## Abstract

### **Dispersion Determination in VAPEX: Experimental Design, Modeling and Simulation**

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The heavy oil and bitumen reservoirs of Canada are one of the largest hydrocarbon sources in the world. Vapor extraction of heavy oil, or VAPEX, has emerged as a very promising recovery process since its inception in 1991. The principal reason is the environmental friendliness of VAPEX together with its cost-effective nature vis à vis other recovery processes. In this work, a review has been done on various factors affecting VAPEX process. Also, a lab-scale VAPEX experimental setup is designed to determine the dispersion coefficients of solvent gases in heavy oil and bitumen. Further, a mathematical model is developed based on earlier reported rectangular physical model of homogenous porous medium saturated with heavy oil and bitumen. The developed mathematical model is simulated to determine gas dispersion along with solubility during the vapor extraction of live oil from a laboratory scale physical model. At a given temperature and pressure, the block is initially exposed on its side to a solvent gas, which diffuses into the medium and gets absorbed. The absorption of gas reduces the viscosity of heavy oil and bitumen causing it to drain under gravity. The low-viscosity "live oil" is produced at the bottom of the porous block. The production of live oil with time is accompanied by the shrinkage of block as well as its increased exposure to gas from top. These phenomena of VAPEX are described by the mathematical model, which is used to calculate live oil production with various values of gas solubility and dispersion. Their optimal values are determined for the vapor extraction of Cold Lake bitumen with butane by matching the calculated live oil production with its experimental values published earlier.

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# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Recovery of Heavy Oil and Bitumen . . . . .	3
1.2	Mechanism of VAPEX . . . . .	5
1.3	Importance of VAPEX . . . . .	8
<b>2</b>	<b>Background</b>	<b>11</b>
2.1	Factors that affect VAPEX . . . . .	11
2.1.1	Viscosity of heavy oil and bitumen . . . . .	11
2.1.2	Diffusion of Solvent Gases in heavy oil and bitumen . . . . .	13
2.1.3	Dispersion of Solvent Gases in Heavy Oil and Bitumen . . . . .	15
2.1.4	Deasphalting of heavy oil and bitumen . . . . .	17
2.1.5	Solvent injection condition and solvent selection . . . . .	19
2.1.6	Geological Factors . . . . .	21
2.1.7	Residual Oil Saturation . . . . .	24
2.1.8	Pore Scale Events . . . . .	26
2.2	Scale-up of VAPEX Production Rates . . . . .	28
2.3	Mathematical model development: . . . . .	29
<b>3</b>	<b>Experimental Setup</b>	<b>32</b>
3.1	Design of Experimental Setup . . . . .	32



## **CONTENTS**

---

3.2	Details of Experimental Setup used to develop the Mathematical Model . . .	39
<b>4</b>	<b>Mathematical Model</b>	<b>43</b>
4.1	Introduction . . . . .	43
4.2	Model Development . . . . .	44
4.3	Solution . . . . .	48
<b>5</b>	<b>Result and Discussion</b>	<b>53</b>
<b>6</b>	<b>Conclusion</b>	<b>61</b>
<b>7</b>	<b>Recommendations for Future Work</b>	<b>62</b>

## List of Tables

1.1	Supply costs of heavy oil and bitumen recovery techniques . . . . .	10
4.1	Various parameters used in this study . . . . .	52
5.1	Percentage root mean square error (in gray cells) between predicted and experimental live oil production . . . . .	54

# List of Figures

1.1	Schematic of the VAPEX process . . . . .	6
1.2	Mechanism of the VAPEX process, Source: Alberta Research Council . . . . .	7
2.1	Model Configuration for Layered System, Oduntan et al. . . . .	23
2.2	Residual Oil Saturation Profile in a Layered System after Extraction, Oduntan et al. . . . .	25
2.3	Butane Vapor/Heavy oil interface at Pore Scale, Oduntan et al. . . . .	27
2.4	Different Stages of Solvent Chamber Growth in a Sintered Glass Bead Micro-model ( $L=31$ cm, $W=2.4$ cm, $h_c=5$ cm), Oduntan et al. . . . .	28
3.1	Schematic diagram of experimental Setup . . . . .	33
3.2	Details of the Pressure Vessel . . . . .	34
3.3	Data Acquisition System Loop . . . . .	38
3.4	Schematic diagram of experimental Setup, Oduntan et al. . . . .	40
3.5	The details of rectangular channel, Oduntan et al. . . . .	41
4.1	Lateral cross section of the physical model with the arrangement of grid points at the onset of VAPEX . . . . .	45
5.1	RMS% error versus Dispersion Coefficient for 0.87 saturation mass fraction . . . . .	55
5.2	Experimental and model predicted production of live oil versus time . . . . .	56
5.3	The height of block versus its width at different times . . . . .	57
5.4	The variation of mass fraction in the block at 1.2 hrs . . . . .	58
5.5	The variation of mass fraction in the block at 4.0 hrs . . . . .	59

# Nomenclature

$b_1, b_2$	constants in Equation (2.3)
$d_0, d_1$	constants in Equation (2.9)
$c$	limits of integration in Equation (2.16)
$C$	solvent/heavy oil concentration
$D$	diffusivity, $\text{cm}^2/\text{s}$
$\mathcal{D}$	dispersion coefficient of gas in heavy oil and bitumen, $\text{cm}^2/\text{s}$
$\mathcal{D}_0$	$\mathcal{D}$ when $\omega = 1$ , $\text{cm}^2/\text{s}$
$e$	root mean square error given by Equation (4.27)
$f$	weighted volume fraction in Equation (2.1)
$g$	gravity, $\text{cm}/\text{s}^2$
$h$	reservoir height, cm
$K$	permeability of physical model, $\text{cm}^2$
$K_r$	relative permeability of physical model
$L$	length of model or reservoir pay zone, cm
$N$	number of experimental data points
$N_i$	number of grid points along $x$ -direction
$N_j$	number of grid points along $y$ -direction
$Q$	drainage or production rate, $\text{m}^3/\text{h.m}$
$t$	time, s
$t_f$	operation time, h
$T$	temperature, $^{\circ}\text{C}$
$v$	Darcy velocity given by Equation (4.5), $\text{cm}/\text{s}$
$V_{\text{cal}}$	predicted volume of produced live oil, $\text{cm}^3$
$V_{\text{exp}}$	experimental volume of produced live oil, $\text{cm}^3$
$X$	width of physical model, cm

## Nomenclature

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$x$	direction along $X$ , cm
$Y$	height of physical model, cm
$Y_0$	initial $Y$ , cm
$y$	direction along $Y$ , cm
$Z$	thickness of physical model, cm

## Subscripts

av	average
$B$	heavy oil/bitumen or liquid
$f$	field
$m$	model
max	maximum
min	minimum
mix	mixture
$pz$	pay zone
$S$	solvent

## Greek Symbols

$\alpha, \beta$	constants in Equations (2.6)
$\theta$	angle between the base of physical model and the horizontal, rad
$\mu$	viscosity of live oil, g/cm-s
$\Delta x$	distance between grids along $x$ -direction
$\Delta y_i$	distance between grids along $y$ -direction for a given $x$ -location, $i$
$\mu_0$	viscosity coefficient of heavy oil and bitumen, g/cm-s
$\rho$	density of live oil, g/cm <sup>3</sup>
$\delta$	volume expansion coefficient in Equation (4.15)
$\omega$	mass fraction of gas in heavy oil and bitumen
$\omega_{sat}$	equilibrium saturation value of $\omega$ , or gas solubility
$\phi$	porosity of physical model

# 1 Introduction

VAPEX is the process of recovery of heavy oil and bitumen in a horizontal well configuration inside their reservoir using vaporized solvents. These solvents diffuse and dissolve into the highly viscous natural reserves, and reduce their viscosity so that the live oil can be easily pumped out. VAPEX was proposed by Butler and Mokrys [1991], who investigated the recovery of Tangleflags North oil from its lab scale reservoir model using hot water and propane gas. Their experimental results showed that oil recovery was higher than that with hot water alone. In a subsequent development of VAPEX, Butler and Mokrys [1993] found that oil recovery was even higher with the use of propane gas alone close to its dew point under reservoir conditions. These results revealed the suitability of VAPEX for the effective oil recovery from thick as well as frequently occurring thin reservoirs with much smaller heat losses than a conventional thermal process such as Steam Assisted Gravity Drainage (SAGD). Since that development, VAPEX has undergone substantial advancement from laboratory scale studies to pilot plant investigations, and commercial projects.

A number of researchers have investigated VAPEX through its lab scale physical model at University of Calgary [Butler and Mokrys, 1991, 1993, Das and Butler, 1994a, Butler and Mokrys, 1998, Das and Butler, 1998, Butler and Jiang, 2000, Boustani and Maini, 2001], University of Waterloo [Jin, 1999, Oduntan et al., Ramakrishnan, 2003, James et al., 2003] and Alberta Research Council [Cuthiell et al., 2003].

At the industrial level, about 23 Canadian oil companies have actively participated in development of VAPEX, which is rapidly advancing toward its commercialization. Nexen Inc.'s Plover Lake VAPEX field pilot project (Alberta) is generating positive results. Imperial Oil Resources at Cold Lake (Alberta), Baytex Energy Ltd. in Saskatchewan and Suncor Energy Inc. at Firebag (Alberta) have implemented VAPEX field pilot plant. Several VAPEX field pilot plants are under construction, which include EnCana Corp.'s field pilot at Foster Creek (Alberta), DOVAP field pilot at Dover site (Fort McMurray, Alberta) [Das, 2002], and Soda

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Lake field pilot plant in Saskatchewan [Turta and Singhal, 2004].

The rapid development of VAPEX has been propelled by a variety of factors, which include (a) our increasingly high demands for energy and petroleum products, (b) the decline of conventional light oil reservoirs, (c) the advantages of VAPEX over other recovery processes, and most important, (d) the abundance of heavy oil and bitumen resources around the world.

In particular, the heavy oil and bitumen reservoirs of Canada are one of the largest hydrocarbon sources in the world. Canadian reserves are held in the sand and carbonate sedimentary formations of Athabasca, Cold Lake, Peace River and Wabasca regions as well as in Carbonate Triangle [Allen, 1981]. The estimated original oil-in-place of these reserves is more than 400 billion  $\text{m}^3$ , which is about twice that of the total conventional oil reserves of all Gulf nations [Janisch, 1981]. According to National Energy Board [Board], Canadian oil sands production will be about 160,000  $\text{m}^3/\text{d}$  in 2004, and it is expected to increase more than double by 2015. In 2001, the heavy oil and bitumen reserves of Canada met the largest demand of oil to the United States, supplied one out of every ten barrels of oil consumed there, and stood ahead of Saudi Arabia in terms of the supply [Luhning, 2003]. This fact indicates that heavy oil and bitumen reserves have tremendous potential to meet the ever-increasing demands of energy and useful petroleum products. This is particularly important at present when conventional oil reserves are declining all over the world. New oil discoveries have become rare. Oil explorations are very expensive, and the development of offshore and field facilities require huge capital investments. These phenomena have imparted a significant thrust to the research and development aimed at effective recovery of heavy oil and bitumen reserves. According to Alberta Energy and Utilities Board, about 80% of the total recoverable bitumen will be with in-situ techniques. Mostly, in-situ production is used in the Cold Lake, south Athabasca and Peace River deposits. VAPEX is a significant outcome of that endeavor in the last 13 years.

### 1.1 Recovery of Heavy Oil and Bitumen

Conventional crude oil flows at reservoir temperature, and pumped from the ground, but oil sands must be mined or recovered in-situ. The recovery of natural heavy oil and bitumen reserves is a difficult task. Although abundant, more than 90% of these reserves lie deep inside the earth's crust and are not easily recoverable owing to their very high viscosity. The viscosity of bitumen in their natural state is typically in the range, 100 to 1000 Pa·s. For instance, the viscosity of Athabasca, Peace River, Cold Lake and Lloydminster reservoirs are 265 000, 126 500, 65 000 and 7 000 mPa·s respectively [Das, 1995]. With state-of-the-art surface mining technology, such as that used by Suncor and Syncrude, the economic excavation and transportation of heavy oil and reserves lie close to the surface, generally limited to the depth of 75 meters or less. The majority of heavy oil and bitumen lie below the surface of 400 meters or more, and can be extracted through in-situ techniques. Consequently, the objective of all in-situ recovery processes is to reduce the viscosity, or equivalently, to increase the mobility of heavy oil and bitumen reserves. This objective is achieved by providing additional energy or materials to heavy oil and bitumen reserves [Latil, 1980]. In general, recovery processes can be categorized into three types—displacement, thermal and chemical. VAPEX falls into the third category of recovery processes.

The first category, displacement recovery processes use the injection of water and immiscible gases into heavy oil and bitumen reservoirs to displace and drive out the reserves. However, the effectiveness of displacement processes is severely limited due to the high viscosity of heavy oil and bitumen reserves. Moreover, injected fluids often get wasted in a bottom water saturation zone having the least resistance to flow. Such an occurrence is frequent in Peace River, Cold Lake, and Wabasca formations, and results in low recoveries and poor sweep efficiencies [Butler and Mokrys, 1998].

The second category of thermal recovery processes includes Cyclic Steam Injection, Steam Drive, Hot Water Drive, In Situ Combustion, and Steam Assisted Gravity Drainage (SAGD)



### 1.1 Recovery of Heavy Oil and Bitumen

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[Butler, 1982]. These processes raise the temperature of a reservoir to reduce the viscosity of its reserves. For example, in SAGD, steam is continuously injected through an upper horizontal well in a reservoir to create a steam chamber at high temperatures. As a result, the heated heavy oil and bitumen reserves of reduced viscosity flow by gravity along the walls of the well into a lower well. Although accounting for more than 80% share in heavy oil and bitumen recovery [Mokrys and Butler, 1993b], thermal processes are often not economical. They cause large heat losses, require huge amounts of water and vast surface facilities, and are inefficient for the frequently encountered thin reservoirs [Mokrys and Butler, 1993a, Das and Butler, 1994a].

The third category, chemical recovery processes such as VAPEX use chemicals such as pure or mixed solvent gases to reduce the viscosity of heavy oil and bitumen upon gas absorption. Before the invention of VAPEX, many chemical recovery processes were proposed in the 1970s. These processes were based on the absorption of solvent gases in a vertical well or a group of vertical wells inside a heavy oil and bitumen reserve [Allen, 1973, 1974, Allen and Redford, Brown et al., 1977, Nenniger, 1979]. For example, Allen [1974] proposed Huff and Puff recovery utilizing butane or propane as solvent. Allen and Redford proposed the injection of liquid solvent, and a non-condensable gas at reservoir temperature and pressure. Some researchers [Brown et al., 1977, Allen, 1973] even proposed chemical recovery in combination with heating. Nenniger [1979] suggested a chemical recovery process utilizing pure gases or gas mixtures at pressures slightly less than or equal to saturated vapor pressure. Dunn et al. [1989] suggested the process of heavy oil and bitumen recovery by gravity drainage using carbon dioxide and ethane at pressure slightly less than their dew point pressures. However, these chemical recovery processes were not feasible as oil recovery was poor due to the slow diffusion of solvents in vertical wells [Das and Butler, 1998].

The limitations of the early chemical recovery processes was addressed by Butler and Mokrys [1991], who proposed the use of horizontal wells instead of vertical ones for the absorption of solvents, and the subsequent recovery of heavy oil and bitumen. This process was

## 1.2 Mechanism of VAPEX

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named VAPEX. Their lab scale VAPEX recovery of Tangleflags North oil with hot water and propane gas was found to be higher than that with hot water alone. Soon they found that the recovery was even higher with the use of propane gas alone [Butler and Mokrys, 1993]. Since then, VAPEX has undergone considerable development from lab scale experiments to pilot plant and commercial project implementations.

## 1.2 Mechanism of VAPEX

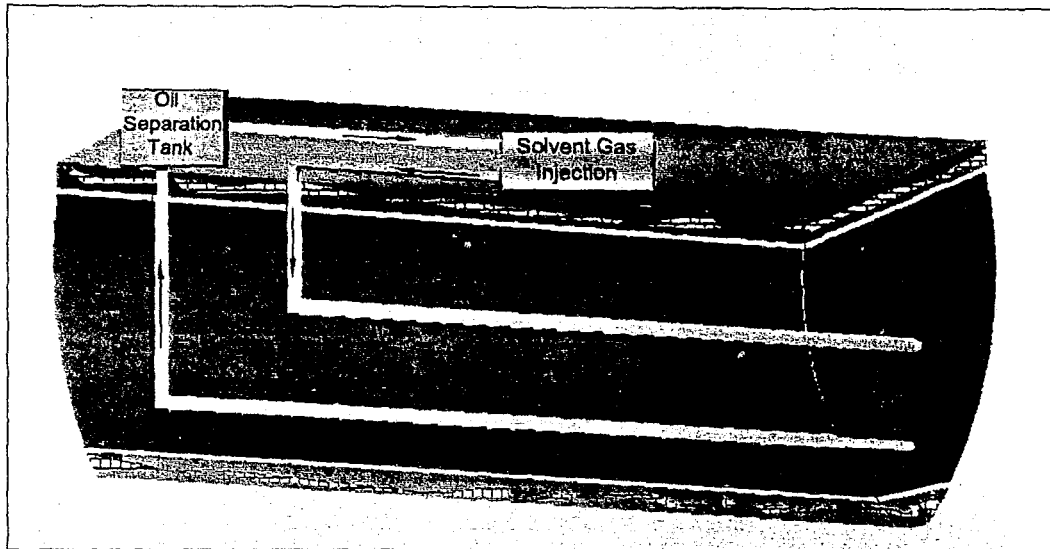
The mechanism of VAPEX is simple, and is based on the phenomenon of viscosity reduction of heavy oil and bitumen in the presence of absorbed solvents [Butler and Mokrys, 1991, Das and Butler, 1998]. As shown in Figure 1.1, VAPEX is typically implemented in a horizontal configuration of an injection well on top of a production well inside a heavy oil and bitumen reservoir. Figure 1.2 shows the vertical cross section of the reservoir, which explains the mechanism of VAPEX.

A vaporized solvent is injected to the injection well at pressures slightly less than or equal to its saturation vapor pressure. A mixture of vaporized solvents can also be used. Solvent diffusion and absorption inside the well reduces the viscosity of its heavy oil and bitumen reserves, and also causes some deasphalting, i. e. the precipitation of asphaltene contents. As a result, the heavy oil and bitumen reserves become mobile and flow under gravity to the underlying production well from where they are easily recovered. The presence of a dissolved gas in heavy oil and bitumen enhances the recovery of heavy oil and bitumen by (i) generating a saturated displacement front by swelling oil in reservoir pores [Welker and Dunlop, 1963, Simon and Graue, 1965], and (ii) reducing adhesive forces between oil globules, films and connate water [Beecher and Parkhurst, 1926, Rosman and Zana, 1977]. In VAPEX, a solvent gas mixes with the bitumen phase through combined phenomena of molecular diffusion, viscosity reduction, capillary action, gravitational flow, and surface renewal. The net effect is dispersion, which can not be described by solvent diffusivity alone.

## 1.2 Mechanism of VAPEX

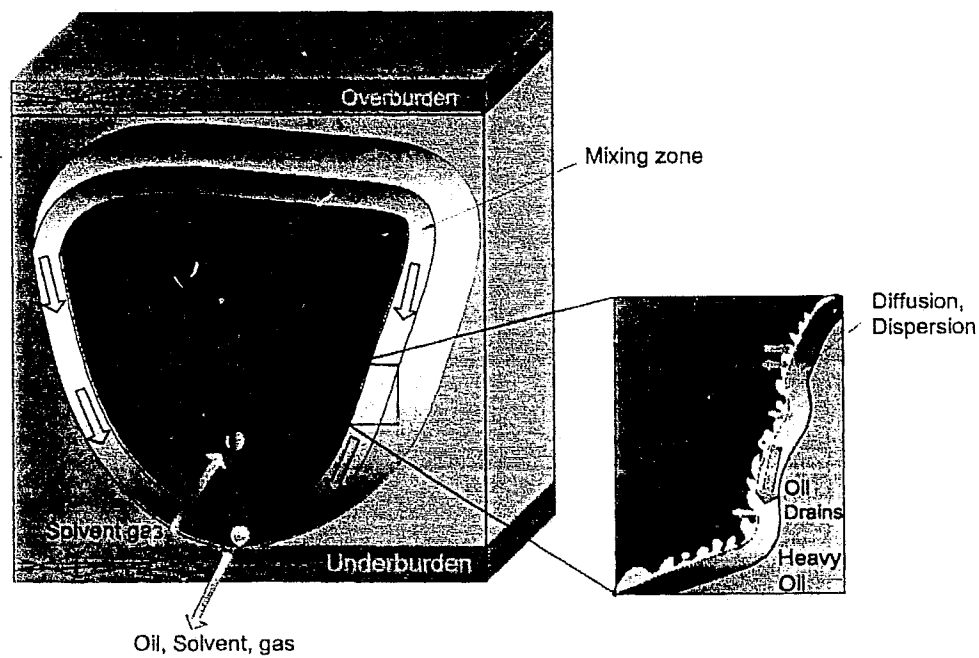
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Figure 1.1 Schematic of the VAPEX process



## 1.2 Mechanism of VAPEX

Figure 1.2 Mechanism of the VAPEX process, Source: Alberta Research Council



### 1.3 Importance of VAPEX

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VAPEX was proposed with the horizontal configuration of reservoir wells [Butler and Mokrys, 1991] for increased heavy oil and bitumen recovery, which was not achievable with the chemical recovery processes utilizing vertical wells. The horizontal wells are especially superior in the reservoir where heavy oil and bitumen reserves are present in a thin flat zone. These wells enable a greater coverage of the reserves, thereby offering a cost-effective recovery operation. For many heavy oil and bitumen reservoirs, the use of horizontal wells over short distances is a popular choice so as to avoid high injection pressures and channeling of solvents [Turta and Singhal, 2004]. However, instead of the use of horizontal well pairs, several other configurations are also possible in VAPEX process [Das and Butler, 1998].

### 1.3 Importance of VAPEX

Canadian oil industry is facing challenges associated with environmental impact, capital costs, energy requirements and water requirements with currently used (SAGD) heavy oil and bitumen recovery techniques. VAPEX has a number of advantages over other heavy oil and bitumen recovery processes. The advantages of VAPEX range from its cost-effectiveness to environmental compatibility, and have been verified in a recent investigation carried out by Luhning et al. [2003]. Their study examines the full project engineering and economics of a commercial scale VAPEX process based on heavy oil and bitumen production from Athabasca oil sands, Cold Lake oil sands, and Southeast Alberta heavy oil.

To begin with, environmental concerns are among the major concern. A larger threat to Canadian oil industry is Kyoto Protocol [Williams, 2003]. On 21<sup>st</sup> November 2002, the Government of Canada announced the *Climate Change Plan for Canada*, which include oil sands producers in the Large Industrial Emitters category (companies emitting 8000 tonnes of CO<sub>2</sub> equivalent or more per year) [Board]. Oil producers have to modify technologies to reduce the greenhouse gas emission. To do so, VAPEX is the best alternative, as the implementation of VAPEX cuts down greenhouse gas emission by 80% compared to other

### 1.3 Importance of VAPEX

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thermal processes [Das, 2002]. Hence, VAPEX is a very environmental friendly process for heavy oil and bitumen recovery.

VAPEX has low capital costs as the injection of vaporized solvents does not require extensive surface facilities. Since solvent injection does not involve the energy losses that are characteristic of thermal recovery processes, VAPEX is very economical. For same production rate, VAPEX uses approximately 3% of the energy consumed by SAGD [Singhal et al., 1997]. Compared to liquid solvents, vaporized solvents provide a higher driving force for the gravity drainage of heavy oil and bitumen, and are easily recoverable. Laboratory results show that 90% of injected solvents can be retrieved and recycled in VAPEX [Singhal et al., 1997].

It is noteworthy that VAPEX has a positive bearing on the quality and cost effectiveness of recovered heavy oil and bitumen. VAPEX carried out at pressures close to the saturated vapor pressure of solvent results in deasphalted, and upgraded heavy oil and bitumen. As a consequence, subsequent heavy oil and bitumen treatment is minimized. Table 1.1 indicates the supply costs of currently used heavy oil and bitumen production techniques [Board]. According to Das [2002], Athabasca bitumen extracted with VAPEX, will have the estimated supply costs of CDN\$9 per barrel. The supply costs include all costs associated with production, including operating costs, capital costs, taxes, royalties and a rate of return on investment. This result is a major motivation to oil industry which is actively participating in the research, development and commercialization of VAPEX.

Finally, VAPEX is very suitable for the heavy oil and bitumen reservoirs, which have high water content, thin pay zones, low thermal conductivities of rock formations, and underlying aquifers [Singhal et al., 1997, James et al., 2003]. The occurrence of such reservoirs is frequent, and heavy oil and bitumen recovery from them with displacement and thermal recovery processes is neither economical nor environmental friendly.

One limitation with VAPEX is the slow mixing of solvent with the heavy oil and bitumen reserves resulting in long start-up times, and low initial rates of heavy oil and bitumen

### 1.3 Importance of VAPEX

**Table 1.1** Supply costs of heavy oil and bitumen recovery techniques

Heavy oil and bitumen recovery technique	Crude Type	Supply Cost, CDN\$ per barrel
Cold Production - Wabasca, Seal	Bitumen	10 to 14
Cold Heavy Oil Production with Sand (CHOPS)	Bitumen	12 to 16
Cyclic Steam Stimulation (CSS)	Bitumen	13 to 19
Steam Assisted Gravity Drainage (SAGD)	Bitumen	11 to 17
Mining/Extraction	Bitumen	12 to 16
Integrated Mining/Upgrading	Synthetic	22 to 28

production. To address this limitation, a VAPEX configuration of laterally separated parallel injector and producer wells was successfully tested recently by using Atlee Buffalo reservoir sample [Butler and Yee, 2002]. This configuration augments the mass transfer area for solvent injection. With this approach, satisfactory time-averaged production rates of 70 m<sup>3</sup>/day were obtained with more than 50% heavy oil and bitumen recovery.

## 2 Background

Since the pioneering works done by Butler and Mokrys [1991, 1993], considerable effort has been devoted to study the various factors concern with VAPEX process in lab-scale using the physical models of heavy oil and bitumen reservoirs. The important factors which influence VAPEX are viscosity of heavy oil and bitumen, deasphalting of heavy oil and bitumen, diffusion of solvent into heavy oil and bitumen, dispersion of solvent with heavy oil and bitumen, solvent selection for VAPEX and geological factors of reservoir. In the following sections, details are presented to show how each factor influences the VAPEX process.

### 2.1 Factors that affect VAPEX

#### 2.1.1 Viscosity of heavy oil and bitumen

Evidently, it is the high viscosity of heavy oil and bitumen that is the major obstacle in their recovery. The reduction in the viscosity of heavy oil and bitumen, and the increase in their mobility are the objectives of all recovery processes. In VAPEX, the gaseous solvent injection results in viscosity reduction. The viscosity of heavy oil and bitumen is a strong function of temperature for natural sample in comparison with pressure; but while gases are dissolved into heavy oil and bitumen, pressure can effectively influence the viscosity [Strausz, 1989]. In general, heavy oil viscosity is the function of temperature, concentration of dissolved gases, pressure and asphaltene content. For example, the mean viscosity of Athabasca bitumen, based on some twenty sets of data, decreases by five orders of magnitude from 900 Pa-s at 20°C to 0.01 Pa-s at 200°C [Seyer and Gyte, 1989]. The effect of dissolved gases can be even stronger. Several gases like carbon dioxide, ethane, methane, carbon monoxide, and nitrogen reduce the viscosity of bitumen remarkably [Svrcek and Mehrotra, 1982, Mehrotra and Svrcek, 1985a,b,c]. For example, the viscosity of carbon dioxide-saturated bitumen at



## 2.1 Factors that affect VAPEX

25°C decreases from about 50 Pa·s to about 0.5 Pa·s when the pressure is increased from 0.1 MPa to about 5 MPa [Mehrotra and Svrcek, 1988]. Based on the number of moles of gas absorbed in bitumen, the most effective gas for viscosity reduction among these gases is ethane which is followed by (in the decreasing order of effect) carbon dioxide, methane, carbon monoxide, and nitrogen.

The crude oil is classified by its high viscosities and low API gravities [Singhal et al., 1997]. If the crude oil has the viscosity lower than 10,000 cP with API gravity of 20° or less, it is known as heavy oil, and if the viscosity greater than 10,000 cP, with API gravity of 10° or less, it is known as bitumen [Seyer and Gyte, 1989].

Lederer has reported the correlation for dependence of viscosity on the solvent concentration as:

$$\mu_{\text{mix}} = \mu_s^{f_s} \mu_B^{f_B} \quad (2.1)$$

where,

$$f_B = \frac{\gamma C_B}{\gamma C_B + C_S}; \quad f_S = 1 - f_B$$

where  $\gamma$  is a weighing factor having a value between zero and unity,  $f_B$  is a weighted fraction of the more viscous component,  $\mu_B$  and  $\mu_S$  are the viscosities of bitumen and solvents respectively (Pa·s), and  $C_B$  and  $C_S$  are the volume fraction of bitumen and solvent, respectively.

Shu [1984] has reported a correlation for  $\gamma$  for mixtures of heavy oils or bitumen with light petroleum fractions as shown below:

$$\gamma = \frac{17.04 \Delta \rho^{0.5237} \rho_B^{3.2745} \rho_S^{1.6316}}{\ln\left(\frac{\mu_B}{\mu_S}\right)}; \quad \text{where } \Delta \rho = \rho_B - \rho_S \quad (2.2)$$

Das and Butler [1996] used the two parameter viscosity temperature correlation as given below:

$$\log_{10} \log_{10}(\mu + 0.7) = b_1 + b_2 \log_{10} T \quad (2.3)$$

where  $\mu$  is the viscosity of Peace River bitumen (Pa·s),  $T$  is the absolute temperature (°K), and  $b_1$  and  $b_2$  values are 9.523535 and - 3.57231, respectively.

## 2.1 Factors that affect VAPEX

Jin [1999] also developed the empirical correlation between the viscosity of produced oil with butane solvent concentration and the correlation was:

$$\mu(C_s) = 16609 C_s^{-2.12} \quad (2.4)$$

$$\mu(\omega_s) = 0.0094655 \omega_s^{-2.12} \quad (2.5)$$

where  $\mu$  is the heavy oil or bitumen viscosity in poise,  $C_s$  is the volume fraction of butane in heavy oil, and  $\omega_s$  is the mass fraction of butane in heavy oil. For the case of butane mass fraction in live oil equal to zero tends to infinite viscosity, this correlation does not valid. The work showed that at room temperature of  $23 \pm 2^\circ\text{C}$ , with the increment of butane concentration from 10% to 17% by weight, the bitumen viscosity decreased sharply from 150 cP to 40 cP and it decreased fairly with increased butane concentration.

### 2.1.2 Diffusion of Solvent Gases in heavy oil and bitumen

Solvent gas diffusion in the heavy oil and bitumen is the primary reason for viscosity reduction and hence it affects the production rate [Das and Butler, 1996], which makes diffusion phenomenon most important in VAPEX process. Diffusivity of gas in liquid can be determined by either experimental methods or by empirical correlations [Upreti and Mehrotra, 2000]. The experimental methods are classified under direct method and indirect method. The direct method involves the compositional analysis of liquid samples extracted at different time. Indirect methods are classified under two categories, (i) based on property change such as, volume, pressure, solute volatilization rate, position of gas-liquid interface etc., and (ii) diffusivity measurement from self-diffusion coefficients which are measured by NMR spectroscopy [Upreti and Mehrotra, 2000]. Several authors have made an effort to investigate the diffusion and to understand the concept of mass transfer of various solvents in heavy oil and bitumen by using direct method [Schmidt et al., 1982, 1986, Nguyen and Farouq-Ali, 1998], indirect method [Renner, 1988, Riazi, 1996, Fu and Philips, 1979, Das and Butler, 1996, Yu, 1984, Woessner et al., 1969, Grogan et al., 1988, Denoyelle and Bardon, 1984, Zhang et al.,

## 2.1 Factors that affect VAPEX

2000, Upreti, 2000, Upreti and Mehrotra, 2000, 2002] and empirical correlations [Mokrys and Butler, 1993b, Boustani and Maini, 2001, Upreti and Mehrotra, 2000, 2002].

Hayduk and Cheng [1971] gave a relationship between diffusivity and solvent viscosity:

$$D = \alpha \mu^{-\beta} \quad (2.6)$$

where  $\alpha$  and  $\beta$  are constants for each diffusive substance.

The diffusivity of propane and butane in the Peace River bitumen were estimated using an indirect method by Das and Butler [1996], based on VAPEX experiment. A Hele-Shaw cell was used to study the vapor extraction of bitumen with propane and butane. They empirically correlate the motion of vapor-bitumen interface with the gas diffusivity as well as the corresponding bitumen viscosity. They obtained the optimized constant values for  $\alpha$  and  $\beta$  in the Hayduk and Cheng [1971] correlation, for propane and butane to measure the diffusion coefficients. The empirical correlation for butane was:

$$D_s = 4.13 \times 10^{-10} \mu^{-0.46} \quad (2.7)$$

However, a different value of  $\alpha$  was obtained for propane and the correlation was:

$$D_s = 1.306 \times 10^{-9} \mu^{-0.46} \quad (2.8)$$

Their results shows that diffusivity is a function of mixture viscosity, which is again the function of gas concentration and temperature.

Upreti and Mehrotra [2000, 2002] estimated the diffusivity of  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{C}_2\text{H}_6$ , and  $\text{N}_2$  in Athabasca bitumen, in the range of 25–90°C at 4 and 8 MPa. They used indirect non-intrusive pressure decay experimental method to find the diffusivity of these gases as a function of gas concentration in bitumen. Based on the experimental results, they developed the following correlation for average gas diffusivities:

$$\ln D = d_0 + d_1(T + 273.15) \quad (2.9)$$

## 2.1 Factors that affect VAPEX

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They observed that diffusivity is a function of gas concentration in bitumen, and at a given gas concentration and pressure, diffusivity increases with temperature. Their results indicate that gas diffusivity generally increases with pressure at a given temperature and gas concentration.

Boustani and Maini [2001] compared the estimated propane intrinsic diffusion coefficient in Penny bitumen as a function of solvent concentration based on three different correlations. It was found that the diffusivity estimated by Das and Butler [1996] was an order of magnitude higher than those estimated by the correlations of Hayduk et al. [1973] and Hayduk and Minhas [1982] correlations. They claimed the optimized  $\alpha$  and  $\beta$  coefficients used by Das and Butler [1996] as the primary reason, which provided better history match to their experiments in the Hele-Shaw cell.

The oil recovery rate for experiment in Hele-Shaw cell agrees fairly with the drainage rate predicted by molecular diffusion-based model [Das, 1995]. However, the recovery rate in sand-packed porous media is quite higher than the predicted rate [Dunn et al., 1989, Das, 1995, Das and Butler, 1998]. As the heavy oil and bitumen viscosity reduces due to gas diffusion, the reduced viscosity oil drains under the action of gravity. At this point, other factors also promote the production rate of VAPEX process in combination with diffusion. Das [1995] and Das and Butler [1998, 1996] suggested those factors would be increased interfacial area in the porous media (compared to diffusion on a planar surface), physical dispersion, increased solubility (due to solvent vapor condensation in fine capillaries), surface renewal (as a result of reduced viscosity oil draining), enhancement during the rising of the solvent chamber, and capillary phenomena at the solvent-oil interface.

### 2.1.3 Dispersion of Solvent Gases in Heavy Oil and Bitumen

Diffusion is a special case of dispersion where the fluid is stationary (convective flow rate is zero). Hence, basically dispersion is a combined effect of diffusion and convective motion.

## 2.1 Factors that affect VAPEX

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Mixing at a pore scale can be called a microscopic dispersion, and can be called a macroscopic dispersion at a reservoir scale. At a macroscopic scale, this convective transport in a porous media is described by Darcy's law. The variation in the reservoir properties results in a macroscopic dispersion. When the fluids are moving through a porous medium, the dispersion coefficient increase due to convective mixing and the dispersion may be higher than that due to diffusion alone [Perkins and Johnston, 1963]. Dispersion in porous media comprises concentration gradient in both, longitudinal and transverse to the direction of solute-solvent flow. These two component of dispersion are thus referred to as longitudinal and transverse dispersion. To date, not much work has been reported on dispersion between high and low viscosity fluids, which results in significant change in solute viscosity [Oballa and Butler, 1989].

Butler and Mokrys [1989] performed the experiments in a Hele-Shaw cell with Athabasca and Suncor bitumen, using toluene as a solvent. Their predicted production rate by using the diffusion value for the developed analytical model was well within the range.

However, Dunn et al. [1989], Das [1995], Lim et al. [1996] and Das and Butler [1998] realized that production rate in porous media is quite higher than Hele-Shaw cell. In their analytical model, they used diffusion value higher than available in literature to match the production rate. They suggested that different values of dispersion would play a major role in production rate of VAPEX.

Boustani and Maini [2001] examined VAPEX in a Hele-Shaw cell. Using Taylor dispersion coefficient instead of diffusion coefficient, they showed that this discrepancy can be reduced by accounting for the enhanced mass transfer due to solvent convection during VAPEX. However, Taylor dispersion can not apply to porous media. It is limited to Hele-Shaw cell only.

Cuthiell et al. [2003] used a computed tomography scanner to examine the solvent action of liquid toluene in Lloydminster oil dispersed in sand and silica packs at 25°C. They also

## 2.1 Factors that affect VAPEX

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simulated important solvent displacement characteristics with assumed solvent dispersion coefficient. To simulate the viscous instability of solvent displacement, they used a two dimensional spatial grid with alternating porosity. They considered dispersion along vertical direction ten times of that along horizontal direction. Using different values of solvent dispersion coefficients, they also extricated physical dispersion from its numerical counterpart.

### 2.1.4 Deasphalting of heavy oil and bitumen

Heavy oil and bitumen are considered to be made up of four representative classes of Saturates, Aromatics, Resins and Asphaltenes (SARA fractions) [Strausz, 1989], which affect the recovery and transportation. Among these fractions, industries are mostly concerned about asphaltenes, as they can precipitate with change in pressure, temperature or composition [Akbarzadeh et al., 2002]. Asphaltenes are defined as the complex high-molecular-weight molecules containing nickel, iron and vanadium, that are soluble in  $\text{CS}_2$ , pyridine,  $\text{CCl}_4$  and benzene but insoluble in low-molecular-weight  $n$ -alkanes [Speight], and can be derived from petroleum oil or shale oil [Long]. Due to the significant amount of asphaltene content, heavy oil and bitumen have higher viscosity, which creates a serious and complex problem in transportation, and requires dilution with light components, or conversion to make it transportable [Mokrys and Butler, 1993b]. Bray and Bahlke [1938] studied the effectiveness of various  $n$ -alkanes in deasphalting, and found that among all these solvents, ethane gives maximum asphaltene precipitation, and the precipitation decreases in the order of propane, butane, pentane and hexane. Das and Butler [1994a] performed the experiment in Hele-Shaw cell and found that deasphalting takes place if the injected solvent pressure is close to or higher than the vapor pressure of solvent at the reservoir temperature, which results in additional viscosity reduction. In their experiment they observed that a specific minimum solvent concentration (threshold value) was required before the onset of deasphalting, and it was inferred that this value varies from solvent to solvent. They used propane above its vapor pressure at  $20^\circ\text{C}$  on Cold Lake bitumen and Lloydminster heavy oil, and in this case,

## 2.1 Factors that affect VAPEX

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the minimum concentration required to precipitate the asphaltene was 20% and 30% by weight, respectively. The work concluded that the propane deasphalted crude could lower the viscosity of Lloydminster heavy oil and Cold Lake bitumen by a factor of 50 and 300, respectively. This partially in-situ deasphalted oil is lighter and better quality upgraded oil.

The asphaltene precipitation from the deasphalted crude oil occupied less than 20% of the void space whereas in the VAPEX process, only partial deasphalting could be obtained [Das and Butler, 1998]. Hence, according to Das and Butler [1998], asphaltene precipitation might not clog the production wells. Das [2002] confirmed in their investigation that deasphalting does not stop oil flowing out from reservoir; but due to the additional viscosity reduction, the production rate increased with deasphalting by 10-20% compared to without deasphalting. It was observed that at a specific temperature, if the vapor pressure was lowered by only about 5 psi, the asphaltene precipitation did not exist [Das, 2002]. Oduntan et al. and Jin [1999] also observed that asphaltene precipitation during VAPEX did not cause significant hindrance to oil production in porous media and mostly deposited towards the end of the production well. Some asphaltene also deposited at the oil-solvent interface. The precipitation starts near the oil-solvent interface due to highest solvent concentration at the oil-solvent interface [Butler and Jiang, 2000]. In a recent study, Ramakrishnan [2003] also found similar results in his experiments, and he postulated that asphaltenes might be carried out to the surface by diluted oil and deposited on the oil-solvent interface.

In VAPEX process, in situ asphaltene may deposit near or inside the well bore, which may clog production wells. Hence, to prevent/control deasphalting, it is essential to predict the asphaltene precipitation and asphaltene precipitation envelop should be developed for troubleshooting.

## 2.1 Factors that affect VAPEX

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### 2.1.5 Solvent injection condition and solvent selection

The low-molecular-weight vaporized solvent can be injected at its dew point as a recovery agent in the VAPEX process. The use of vaporized solvent at its dew point has several advantages, which are:

- (i) As the vaporized solvent offers maximum solubility near its dew point, the ingress of vaporized solvent is advantageous near its vapor pressure at reservoir temperature [Das, 1995].
- (ii) The injection of solvent near its vapor pressure at the reservoir temperature results in deasphalting, and offers additional viscosity reduction rather than only by dilution, which promotes the production rate [Das and Butler, 1998].
- (iii) In addition to this, the use of vaporized solvents offers higher density difference with bitumen, and produces higher driving force for gravity drainage [Das and Butler, 1998].
- (iv) The vaporized solvent is recommended to reduce the residual amount of solvent in extracted reservoir rather than the use of liquid solvent for economical point of view [Das and Butler, 1998].

In general, solvent selection criteria are based on several factors: mainly equilibrium pressure, molecular weight, density difference, solubility, diffusivity, and reservoir temperature and pressure [Ramakrishnan, 2003]. Das and Butler [1996, 1994a] suggested that propane and butane are very effective solvents for VAPEX process, and proved that propane diffuses faster than butane.

Using the liquid solvent (pure propane, pure butane, or mixtures) with a 20–30 mesh Ottawa sand (220 Darcies and 33–35% porosity), and the crude oil from the Atlee Buffalo field, Butler and Jiang [2000] investigated the effect of temperature, pressure, injection rates, types of solvent, mixed solvents, well spacing and configuration to develop the process conditions to give high production rates with economic solvent requirements. As the mixture of light



## 2.1 Factors that affect VAPEX

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hydrocarbons are less expensive than pure solvents, it can help remarkably to reduce the cost related to VAPEX operation. Thus, it was necessary to study the effect of mixed solvent on VAPEX.

For the case of effect of mixed solvents, Butler and Jiang [2000] found that propane gives higher production rate than butane; but the mixture of propane and butane (50:50 liquid volume ratio) was more effective than butane alone, and the performance was almost equivalent to propane.

For investigation of mixed solvent (mixture of propane and butane) injection rate they injected the mixed solvent at constant rate of 30 ml/hr and of 20 ml/hr. The results showed that the increment of injection rate by 50% resulted in only 11% of increased production rate, which suggested that oil production rate will not increase significantly with increase in mixed solvent injection rate. In another set of experiment they studied the effect of high initial solvent injection rate, and concluded that high start up rates followed by reduced rates allowed high oil production with less cumulative solvent; the performance was better than constant injection rate.

The use of non-condensable gas in VAPEX process is also feasible as a carrier gas for solvent, and this non-condensable gas injection rate should be low enough to replace the volume vacated by produced oil plus a low by-pass [Das and Butler, 1994b]. During the investigation of pure solvent Butler and Jiang [2000] studied effect of butane (with almost constant methane gas injection rate) injection rate on oil production at the injection rate of 10 ml/hr and 20 ml/hr. The results showed that as the injection rate was doubled, the oil production rate increased by about 70% due to increased amount of solvent dissolved in oil, and suggested that more experimental data are needed for determination of optimal solvent injection rate.

## 2.1 Factors that affect VAPEX

### 2.1.6 Geological Factors

The economic viability of any process depend on the production rate. Several authors have studied the effect of geological factors (pay zone length, permeability, heterogeneity, dip angle and residual oil saturation) on the production rate.

*i) Effect of Pay Zone Length on Production rate:* The pay zone length is the height of the reservoir where the heavy oil and bitumen are situated. Oduntan et al. used rectangular channel of variable length (21–247 cm); but same cavity dimensions to study the effect of pay zone length on production rate. They observed that the production rate was constant until 80–90% of cumulative oil production had taken place, for a given length. The overall recovery was found to be about 85–92% of the initial oil in place. They found that the volumetric production rate was proportional to the square root of the pay zone length, and the correlation for a composition of 136 darcy permeability and 38% porosity at 45° dip angle was:

$$Q = 0.0014L_{pz}^{0.55} \quad (2.10)$$

where  $Q$  (m<sup>3</sup>/h.m) is the volumetric production flow rate per unit width of model and  $L_{pz}$  is thickness of the payzone in meter.

*ii) Effect of Dip Angle:* Ramakrishnan [2003], and Oduntan et al. studied the effect of dip angle on the production rate. Ramakrishnan [2003] used homogeneous system of 156 darcy permeability to conduct the experiment with the dip angles of 45°, 75°, 80° and 90°. The results showed that production rate increased with increased dip angle from 45° to 90°, and maximum production rate was obtained at 90° dip angle, due to the fact that steep angle possesses more gravity. The conclusion stated that dip angle has a major effect on the production rate.

*iii) Effect of Reservoir Permeability and Reservoir Heterogeneity:* The permeability and reservoir heterogeneity plays a significant role on the performance of the VAPEX process. Vapor is confined to the pore spaces as well as its ingress into fine pores can be limited by capil-

## 2.1 Factors that affect VAPEX

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lary, and vapor does not wet the solid [Jiang and Butler, 1995]. Several authors [Butler and Mokrys, 1989, 1998, Jiang and Butler, 1995, Oduntan et al.] have contributed to study the reservoir heterogeneity due to the presence of low and high permeability layers and shales in heavy oil and bitumen recovery. Butler and Mokrys [1989] performed the experiment in a vertical Hele-Shaw cell with Athabasca and Suncor Coker Feed bitumens using toluene as a solvent, and concluded that at low permeability of the Hele-Shaw cell, the drainage rate was a function of the square root of the permeability. The use of high permeability was not well understood because the relationship to calculate the permeability in Hele-Shaw cell was limited for low permeabilities only (small plate spacing). Following this work, Das [1997], and Butler and Mokrys [1998] performed the different set of experiments with various permeabilities in porous media, and found that production rate in VAPEX varies as the square root of the permeability. Their results showed linear relationship between oil production rate and square root of model permeability. In most recent study, Oduntan et al. used the permeability of 25, 85, 136 and 192 darcy in their experiment and found the similar result as Das [1997], and Butler and Mokrys [1998]. Oduntan et al. also found that volumetric flow rate is proportional to the square root of permeability, and the correlation was:








$$Q = 0.0348K^{0.47} \quad (2.11)$$

where  $Q$  is in  $\text{cm}^3/\text{min}$  and  $K$  is in darcy.

Jiang and Butler [1995] performed series of experiments to investigate the effects of continuous and discontinuous low-permeability layers using a two dimensional physical model (14 inches wide, 9 inches high and 1.25 inches thick) with horizontal layers of two different sized sands to get different permeability (20–30 mesh for 217 darcy and 30–50 mesh for 43.5 darcy), by using butane as solvent to recover Tangleflags, North field and Lloydminster oil. They found that low-permeability layers results in lower oil production rate than at with a homogeneous model of high-permeability packing. Capillarity due to interfacial tension between the oil and solvent vapor phases, plays a significant role on VAPEX process.

## 2.1 Factors that affect VAPEX

Figure 2.1 Model Configuration for Layered System, Oduntan et al.

		Q (cm <sup>3</sup> /min)	Dip Angle
I		0.30	90°
II		0.28	45°
III		0.26	45°
IV		0.25	45°
V		0.23	45°
VI		0.23	45°
VII		0.35	45°

## 2.1 Factors that affect VAPEX

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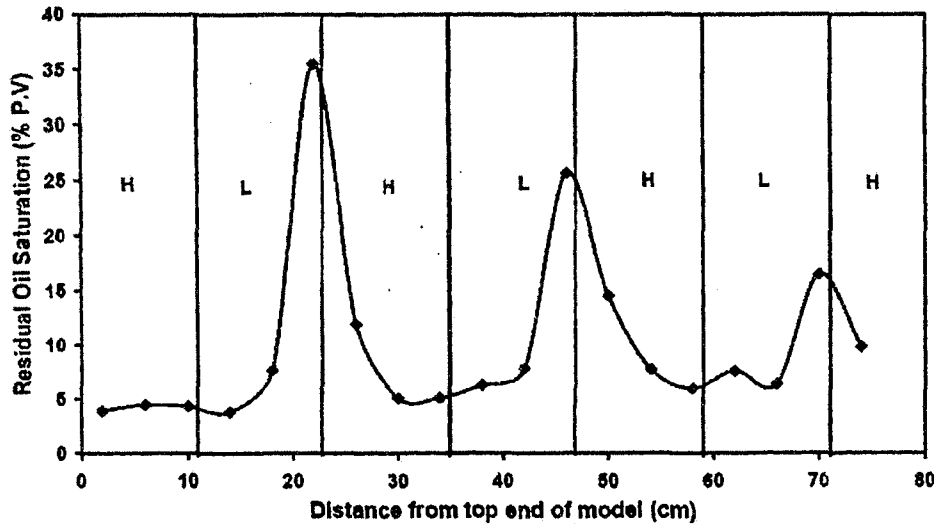
Oduntan et al. analyzed the effect of reservoir heterogeneity more deeply by using the 84 cm long physical model with layers of high (192 darcy) and low (85 darcy) permeability zone. They used seven different types of models with various high and low permeability configuration. The model configuration for layered systems are shown in figure 2.1. As shown in the figure 2.1, models I to IV were packed in such a way as to achieve the average permeability of 118 Darcy. Model VII on the other hand had an average permeability of 125 darcy. Their results showed that the overall production rate obtained for models I–VI did not differ significantly. Model VII with slightly higher average permeability gave a higher production rate compared to other layered systems, which can be attributed to the fact that smaller size of the low permeability zone was present. They observed a slight reduction in production rate with the increment in the number of layers. In addition to this, the production rate was found to be lower for heterogeneous system than that of a same size homogeneous reservoir of the same average permeability and high residual oil saturation was observed in low permeability layers situated above high permeability layers.

### 2.1.7 Residual Oil Saturation

Oduntan et al. performed the experiment by using butane as a solvent in a rectangular channel at a dip angle of  $45^\circ$  to study the residual oil saturation along the length of the physical model after vapor extraction. They selected two models to perform the experiment, first was homogeneous system, and second was heterogeneous layered system. In the homogeneous system, the residual oil saturation of the model varied between 3 to 5% pore volume, and was essentially constant throughout the swept region. As this result was obtained after blowdown, the residual oil saturation at in-situ conditions was postulated slightly higher and expected to vary between 5 to 8% pore volume because of the presence of dissolved gas. Ramakrishnan [2003] performed similar experiment at a dip angle of  $45^\circ$  with propane as a solvent and found the residual oil saturation between 10 to 13% pore volume for homogeneous system, and concluded that the higher percentage of residual oil saturation with

## 2.1 Factors that affect VAPEX

**Figure 2.2** Residual Oil Saturation Profile in a Layered System after Extraction, Oduntan et al.



propane gas than butane gas was due to higher asphaltene precipitation with propane.

Ramakrishnan [2003] developed the material balance equation to compute the residual oil saturation:

$$S_{RO} = \frac{M_{RO}}{V_B \phi \rho_0} \quad (2.12)$$

where  $M_{RO}$  is the mass of residual oil (g),  $V_B$  is the bulk volume of the packing ( $\text{cm}^3$ ),  $\phi$  is the porosity of packing and  $\rho_0$  is the density of dead oil ( $\text{g}/\text{cm}^3$ ).

For the layered system, Jiang and Butler [1995] and Oduntan et al. found high residual oil saturation in low permeability layers situated above high permeability layers. As shown in Figure 2.2, Oduntan et al. showed the residual oil saturation profile obtained for seven layers of high and low permeability 80 cm long physical model. They suggested the reduced pore size was the main reason behind the higher capillary pressure in low permeability layer.

Oduntan et al. conducted the experiments by varying the pay zone height. They observed

## 2.1 Factors that affect VAPEX

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that regardless of pay zone height oil recovery was not found from the bottom portion (6–7 cm) of the model, due to insufficient gravity force to overcome capillary pressure.

### 2.1.8 Pore Scale Events

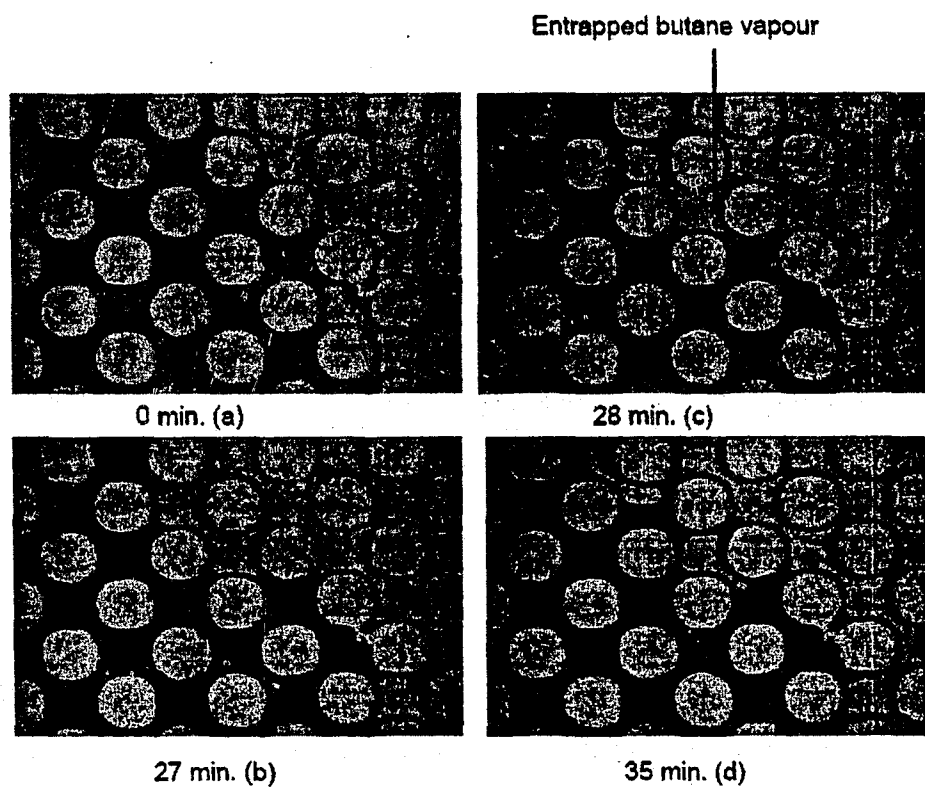
VAPEX is a process involving microscopic, pore scale phenomena that occur over a large, macroscopic area. Ramakrishnan [2003], Jin [1999], and Oduntan et al. studied the pore scale events occurred during vapor extraction to explain fluid phase interactions in porous media by using a two dimensional physical micro model. As solvent gas diffuses into the heavy oil and bitumen, it gets less viscous and drains out under the action of gravity. Their objective was to study mechanism of VAPEX at pore scale. Jin [1999], Oduntan et al., and Ramakrishnan [2003] used a micromodel that was etched on glass. The pore scale aspects of VAPEX observed in Oduntan et al.'s work [Oduntan et al.] is shown in the figure 2.3.

As shown in the Figure 2.3, the butane vapor gets absorbed into heavy oil and bitumen at surface pores, which trap the butane vapor, and viscous heavy oil and bitumen gets diluted so on. This low viscosity diluted oil drains consequently under the action of gravity. The new pores are exposed once the former drain as shown in figure fig.2.3a. As a result, there is a chain of drainage and replacement in the pores. At the top end of model where the packing begins, it replaces by solvent vapor since that end closes to oil flow when heavy oil in the pores gets diluted and drained. Rather than at the other sections of model, diluted oil empties faster from the pores at the top end of model. Such process results in the movement of the solvent vapor/oil interface down into the packing at the top end of model faster (see Fig. 2.4). After observing the butane vapor/heavy oil interface in Fig. 2.3b for another minute, trapping of butane vapor directly below the interface was noticed (see Fig. 2.3c). The entrapped butane vapor has been fragmented into two portions by snap off mechanism beneath the capillary interface for another 7 minutes (see Fig. 2.3d). Such a phenomenon enhances mixing of heavy oil with butane by exposing more surface of oil to butane and further enhancing the rate of diluted oil drainage. By this snap off mechanism,

## 2.1 Factors that affect VAPEX

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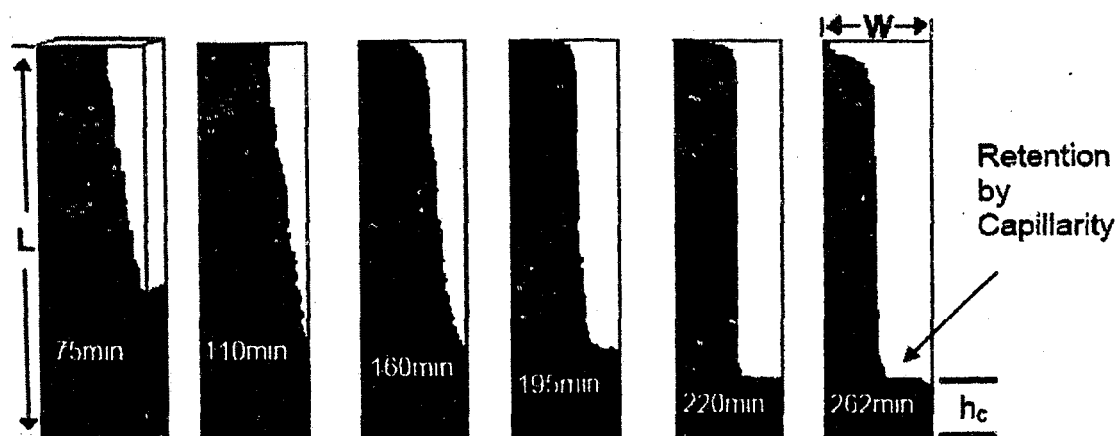
**Figure 2.3** Butane Vapor/Heavy oil interface at Pore Scale, Oduntan et al.





## 2.2 Scale-up of VAPEX Production Rates

**Figure 2.4** Different Stages of Solvent Chamber Growth in a Sintered Glass Bead Micro-model ( $L=31$  cm,  $W=2.4$  cm,  $h_c=5$  cm), Oduntan et al.



they explained enhanced mixing of butane vapor with heavy oil and bitumen due to surface renewal resulting in higher diffusion, and enhancement of production rate.

## 2.2 Scale-up of VAPEX Production Rates

Scale-up of production rates is of greatest interest for oil industries to predict the production rates from lab-scale to field-scale. Extrapolation of experimental data to predict the field performance is usually accomplished by using factors, which can be derived through the dimensionless analysis of the fundamental equations governing the recovery process [Jiang, 1996].

Butler and coworkers [1991, 1993, 1998, 2000] reported the scaling of physical model to field conditions. They derived the scaling factors by assuming following factors [Jiang, 1996]:

- (a) A physical model and reservoir have similar geometry and well configuration,

### 2.3 Mathematical model development:

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- (b) The model and the field have the same porosity and oil saturation,
- (c) The oil used in the model has the same properties as those in the field,
- (d) The flow of oil without dissolved solvents is negligible, and the diluted oil drains by gravity.

By assuming the similar shape of the vapor chamber in model and field, the cumulative oil production in the model and field can be related as proportional to the reservoir volume (for same permeability):

$$\frac{Q_m}{Q_f} = \frac{L_m^2 \ell_m}{L_f^2 \ell_f} \quad (2.13)$$

where,  $\ell$  is length of well.

The determination of total production time can be calculated from:

$$t_f = t_m \frac{L_f^2}{L_m^2} \quad (2.14)$$

Oduntan et al. reported the relationship for the field oil production rate as (for different permeability):

$$\frac{Q_f}{Q_m} = \sqrt{\frac{K_f L_f}{K_m L_m}} \quad (2.15)$$

### 2.3 Mathematical model development:

Butler and Mokrys [1989] developed a mathematical model as a direct analog to SAGD process, for the bitumen extraction by using the liquid solvent in a vertical Hele-Shaw cell to predict the bitumen drainage rate from the diffusivity, viscosity and density data over a wide range of permeability. They assumed that mass transfer of solvent into the bitumen occurs at a steady state condition, and interface to be moving at constant velocity  $U$ . The developed analytical model to predict the production rate was as follows:

$$Q = \sqrt{2Kg\phi\Delta S_0 N_s h} \quad (2.16)$$

### 2.3 Mathematical model development:

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where,

$$N_S = \int_{C_{\min}}^{C_{\max}} \frac{\Delta \rho D_S (1 - C_S)}{\mu C_S} dC_S \quad (2.17)$$

Here,  $N_S$  is a dimensionless number, which is the function of concentration, density difference, diffusivity and viscosity. In analytical model, the values of  $\phi$  and  $\Delta S_0$  is unity. Butler and Mokrys [1989] performed series of experiments in a vertical Hele-Shaw cell for Athabasca and Suncor Coker Feed bitumens, using the toluene as a solvent, and the experimental results were in good agreement with the model.

Dunn et al. [1989] developed a mathematical model similar to that of Butler and Mokrys [1989] to predict the production rate in porous media using ethane and  $\text{CO}_2$  as a gaseous solvents to extract Athabasca bitumen. In order to match experimental rates, with their model they had to employ diffusion coefficients much higher than the known value from the literature, and to do so, they attempted to explain the enhanced recovery rate by incorporating convective dispersion in their analytical model [Boustani and Maini, 2001]. However, the order of discrepancy was considerably larger between the recovery rate obtained from experimental results and analytical model.

Das [1995] modified the mathematical model developed by Butler and Mokrys [1989] in order to make it applicable to porous media. He added a cementation factor  $\Omega$ . For the case of unconsolidated rocks he used 1.3 as a cementation factor  $\Omega$ , which was originally reported by Pirson [1958]. The modified model was as follows:

$$Q = \sqrt{2Kg\phi^\Omega \Delta S_0 N_S h} \quad (2.18)$$

In order to verify the modified model, Das and Butler [1998] carried out series of experiments in a sand pack with Peace River bitumen and Athabasca bitumen, using butane as a solvent, and they found that experimental production rate was significantly higher than the predicted value from the modified analytical model. They suggested the possible reason behind this enhance recovery rate in porous media due to extended interfacial area, capillary action and

### 2.3 Mathematical model development:

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surface renewal. They realized that effective diffusion coefficient, 3 to 10 times higher than molecular diffusion coefficient, is required to match their experimental results with analytical model.

In order to incorporate the effect of average permeability, Jiang [1996] further modified the model:

$$Q = \sqrt{2K_{av}g\phi^{\Omega}\Delta S_0N_S h} \quad (2.19)$$

where,

$$K_{av} = \frac{1}{H} \int_0^H K \, dy \quad (2.20)$$

Here,  $K_{av}$  is height-averaged permeability.

### 3 Experimental Setup

This chapter is divided into two sections. Section 3.1 gives detail of experimental setup designed to perform VAPEX experiment to determine gas dispersion in heavy oil and bitumen. In addition to this, the functionality and specifications of selected data acquisition system is discussed. However, due to time constrain, this experimental setup was not build up. Section 3.2 describes Oduntan [2001]'s experimental setup used at University of Waterloo to study the VAPEX production rate by using a rectangular channel or block. Based on his experimental setup, mathematical model was developed for VAPEX process.

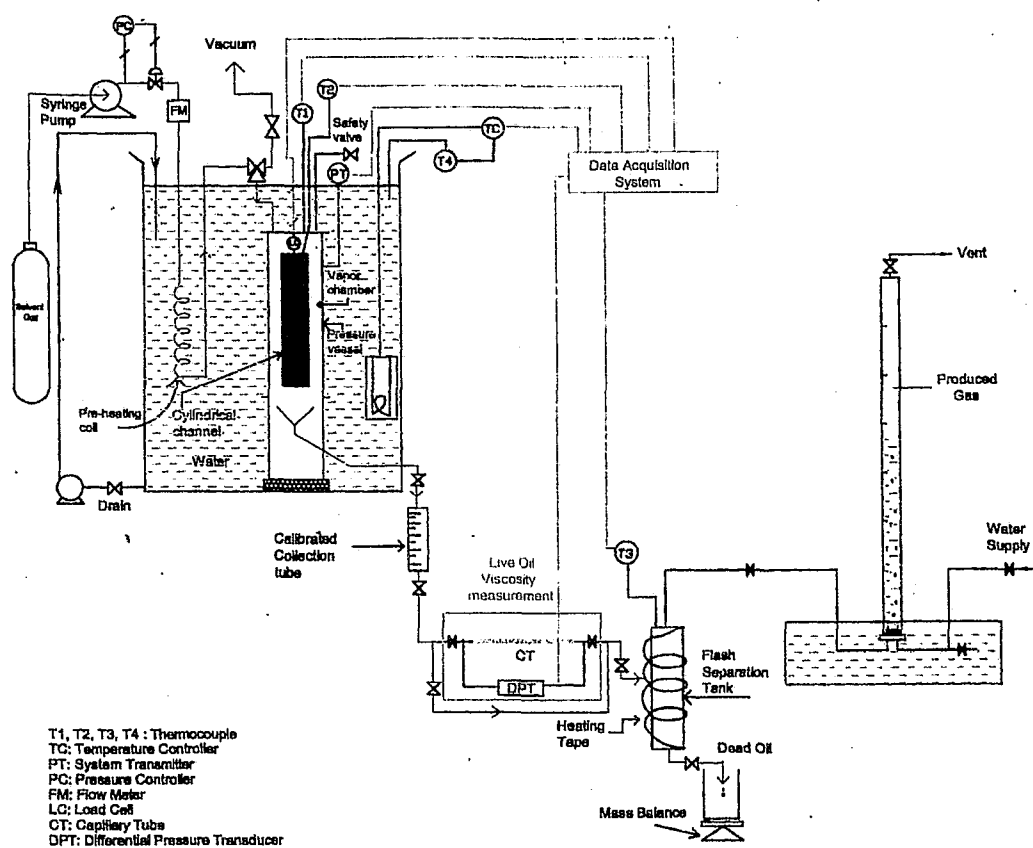
#### 3.1 Design of Experimental Setup

Figure 3.1 shows a schematic view of an experimental setup, which will be used to perform the VAPEX experiment to determine dispersion of gas in heavy oil and bitumen. In this experiment, a cylindrical wire mesh (80 cm x 4 cm) packed with oil saturated porous media would be used as a physical model. A pressure vessel will behave as a vapor chamber. The heavy oil and bitumen to be used in this experiment will have varying compositions of sand and glass beads of 38% porosity and other known characteristics (e.g. permeability and heterogeneity).

The apparatus consists of *clear PVC* pressure vessel of 15 cm inside diameter and 162 cm height, which holds the cylindrical channel hanging on the load cell. The concept behind the use of the load cell is that with the progress of diffusion the heavy oil viscosity reduces and a load cell will regularly record the decrease in the mass of the cylinder due to oil drainage. As shown in figure 3.2, the pressure vessel would be divided into two sections. The upper section would have 114 cm height and lower section would have 44 cm height. Both section would be connected by means of 1.25 cm thick and 7.53 cm wide *gray PVC* flange, and teflon gasket would be used to prevent gas or water leakage. A pressure vessel would rest on the

### 3.1 Design of Experimental Setup

Figure 3.1 Schematic diagram of experimental Setup



**Figure 3.2** Details of the Pressure Vessel



### 3.1 Design of Experimental Setup

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shock absorber to avoid the system vibration.

The temperature of the system will be maintained by using the temperature controller submerged in the cylindrical water bath. The water bath would be made of *clear PVC*, with 100 cm outside diameter, 188 cm height and 0.94 cm thickness. The water will be recycled continuously in the water bath to ensure proper temperature distribution, and the pressure of the vapor chamber will be maintained by means of an *Isco* syringe pump throughout the experiment. A syringe pump supplies the gas at the predetermined pressure into the vessel via preheating coil (4 m length, 6 mm outside diameter and 1.5 mm thickness) immersed inside a controlled temperature water bath, so that the inlet gas along with the system pressure and temperature remains constant. A vacuum pump will be used for the purging purpose.

A small funnel will be placed below the cylindrical channel at the bottom of the pressure vessel equipped with a valve, which permits the produced live oil from the cylindrical channel to calibrated collection tube (30 cm<sup>3</sup>). After the collection tube is filled with produced live oil, the live oil will be allowed to flow through a viscosity measuring unit via stainless steel tube of 12 mm outside diameter, and a thickness of 2 mm. To flow the live oil from the calibrated collection tube, the valve situated between the funnel and calibrated collection tube is necessary to keep open, in order to maintain the constant pressure. A viscosity measuring unit comprises of stainless steel capillary tube of internal diameter 0.55 mm and length 50 cm. A differential pressure transducer will be used to measure the pressure drop across the capillary tube for a given flow rate. The flow rate would be determined by measuring amount of time required to pass a known volume of diluted oil from the collection tube. Now the viscosity of live oil can be determined by using the Hagen-Poiseuille equation with known flow rate ( $Q$ ), pressure drop ( $\Delta P$ ), capillary tube diameter ( $D$ ) and length ( $L$ ) as:

$$Q = \frac{\pi D^4 \Delta P}{128 \mu L} \quad (3.1)$$

Furthermore, the collected live oil will be periodically flashed by using a stainless steel flash



### 3.1 Design of Experimental Setup

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separation tank (250 cm<sup>3</sup> capacity) wrapped with a flexible electrical heating tape; with controlled temperature at around 60°C or higher, to determine the amount of (i) absorbed gas by transferring the liberated gas to gas measuring column, and (ii) residual gas free oil (dead oil). The flashed liberated butane gas would be allowed to collect into transparent gas-measuring column (3000 cm<sup>3</sup>) for volume measurement of dissolved gas.

Butane will be used as a solvent gas for the temperature range of 20–40°C and pressure range of 0.21MPa–0.38MPa. However, after performing these experiments; Carbon dioxide, methane, ethane, propane and butane will be used separately as solvent gases for the temperature range of 25–90°C and pressure range of 0.21MPa - 7MPa, by using the stainless steel pressure vessel and waterbath.

The experimental conditions will be recorded automatically by using the Ethernet Data Acquisition System–EDAS (16 bit resolution), supplied from A-Tech Instruments Ltd., which will be connected with the computer. Labview - 7 software would be used for graphical user interface and online monitoring of following inputs: (i) the temperatures of the pressure vessel, suspended cylinder, and flash separation tank, (ii) the pressure of a gas, (iii) inlet flow of a gas, and (iv) the mass of a cylinder at a regular time intervals.

The details of selected instruments for experimental setup are as follows:

1. **Ethernet Data Acquisition System (EDAS)**  $\Rightarrow$  Resolution: 16 bit, Analog inputs (Channels): 16 single-ended / 8 differential
2. **High Accuracy S-Type Load cell (LC)**  $\Rightarrow$  Range:  $\pm 25$  lbs, Accuracy: 0.1 % FSO, Output: 0–3 mV/V, Excitation: 10 VDC, 15 VDC max
3. **Pressure Transducer (PT)**  $\Rightarrow$  Range: 0–200 psig, 0.1% FSO static accuracy, Output: 4–20 mA
4. **Differential Pressure Transducer (DPT)**  $\Rightarrow$  Range: 0–30 psid, Accuracy: 0.5% FSO, Output: 4–20 mA

### 3.1 Design of Experimental Setup

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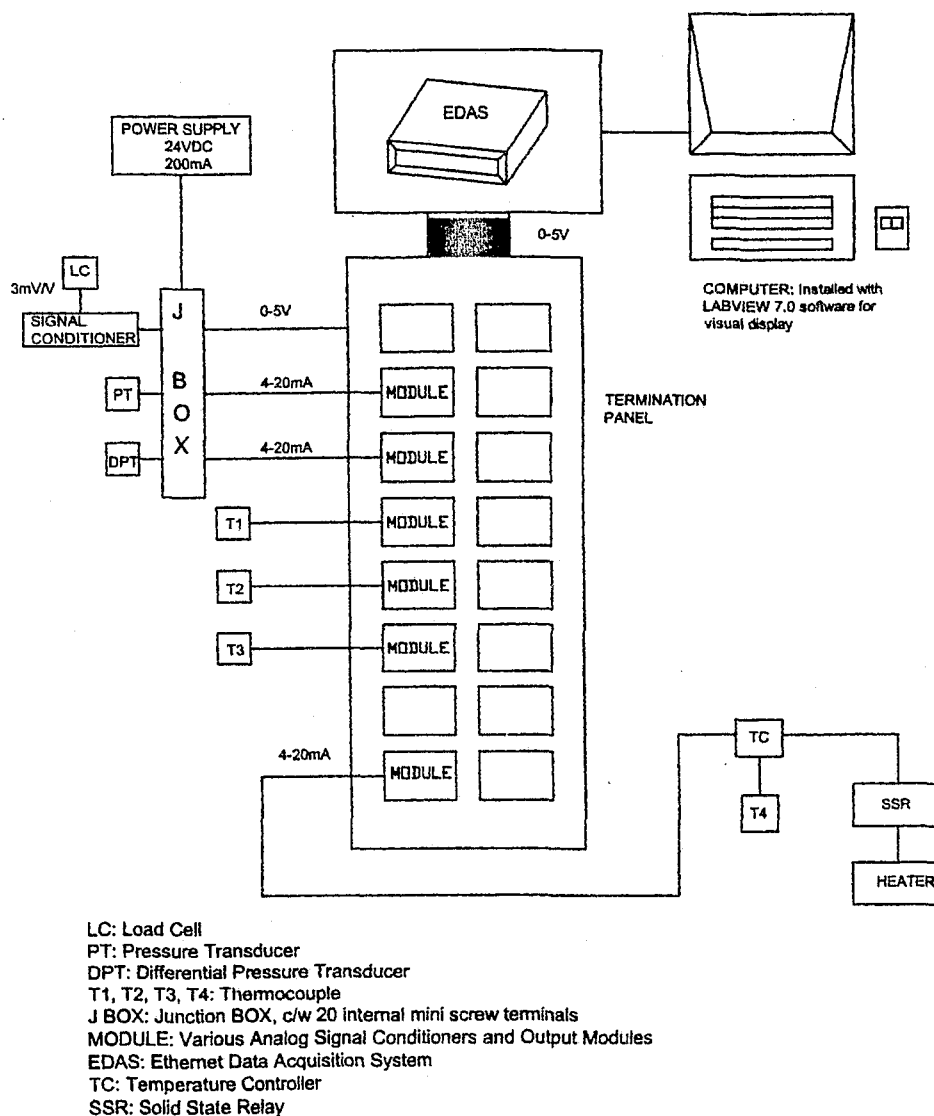
5. **Temperature sensor**  $\Rightarrow$  (T1) High Accuracy RTD plug sensor: Pressure rating: 2500 psi, Max. temperature rating: 230°C, 1/4"NPT, 3"Nose;  
(T2) T Type autoclave probe: Max. temperature range 0–200°C, 15 mm needle and  
(T3) High Accuracy RTD plug sensor: High Pressure RTD plug sensor: Pressure rating: 2500 psi, Max. temperature rating: 230°C, 1/4"NPT, 1"Nose
6. **Temperature Controller (TC)**  $\Rightarrow$  Omega CNi 32-5-4, Accuracy:  $\pm 0.5^\circ\text{C}$ ,  
Output 1: 4–20mA or voltage output (would be used retransmit a value to EDAS),  
Output 2: 10 VDC at 0–20mA pulse output for use with external SSR (would be used to drive an external DC SSR in order to control a heater)
7. **Soldi State Relay (SSR)**  $\Rightarrow$  DC Control Signal (24–280 VAC line), 50 A Nominal rating

**Temperature Controller Loop:** The temperature controller would be used to maintain the waterbath temperature at desired temperature. The temperature of waterbath would be sensed by thermocouple. The output of thermocouple would be input for temperature controller (Omega - CNi3254). The waterbath temperature can be controlled in  $\pm 0.5^\circ\text{C}$  with this controller. The output of temperature controller would be input to solid state relay (SSR - Omega, SSRL240DC50), and SSR would be connected with water immersion heater.

**Data Acquisition System Loop** The selected data acquisition system is for monitoring purpose only. It monitors load, pressure and temperatures. As shown in figure 3.3, load cell (LC), pressure transducer (PT) and differential pressure transducer (DPT) would be connected to corresponding module through junction box (J Box). Temperature probes (T1, T2, T3) would be connected directly to the corresponding module. These instruments consists their own characteristic output, which will be converted into 0 - 5V common output by individual module. Termination panel consists 16 channels, where in this work, 6 channels

### 3.1 Design of Experimental Setup

Figure 3.3 Data Acquisition System Loop



### **3.2 Details of Experimental Setup used to develop the Mathematical Model**

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would be used for 6 modules, and rest of 10 channels are purchased for future expansion. Following this, converted 0 - 5V output would be input to data acquisition system (EDAS), which will be interfaced with computer, installed with Labview 7.0 software.

Due to limitation of time, this experimental setup was not build up. However, mathematical model was developed based on experimental setup used by Oduntan [2001]. This experimental details has been described in the following section.

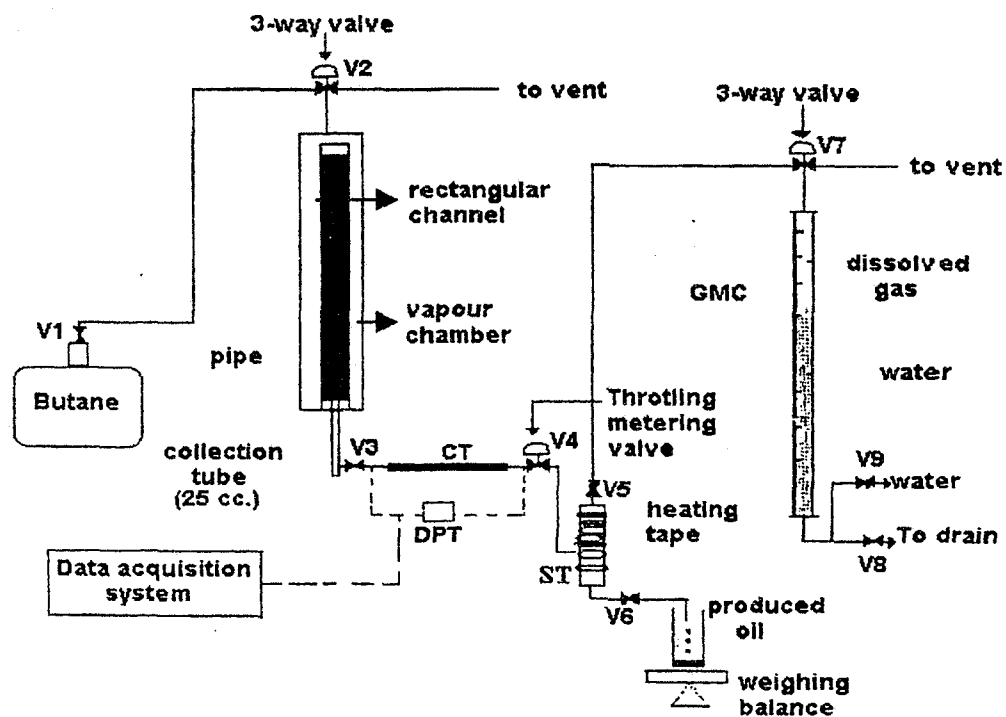
### **3.2 Details of Experimental Setup used to develop the Mathematical Model**

The developed model in Chapter 4 is based on the following experiment performed by Oduntan [2001]. Oduntan [2001] used a rectangular channel as a physical model. Figure 3.4 shows the schematic diagram of the experimental setup, and Figure 3.5 shows the details of the rectangular channel.

The used rectangular channel was of fixed cavity of 1.9 cm width and 1.6 cm depth. Several homogeneous physical models were used by varying the lengths of 21 cm, 47 cm, 84 cm, 160 cm and 247 cm. All models were packed with glass beads (average particle diameter of 400  $\mu\text{m}$ ) to create a system with porosity of about 38% and permeability of 136 darcy. Once the rectangular channel is packed with glass beads and bitumen, the model was placed inside a pipe of larger diameter, which behave as a vapor chamber. A wire mesh screen was used to cover the open face of the rectangular channel. The original heavy oil had a viscosity of 40,550 mPa-s and a density of 970.3 kg/m<sup>3</sup> at room temperature. The experiments were carried out between 19°C and 22°C by using the butane as a solvent. Before starting the experiment, the vapor chamber was fixed at the desired dip angle. After that, butane vapor was injected at pressure equal to its vapor pressure at room temperature. The butane starts diffusing into the oil, and consequently reduced viscosity diluted oil starts draining. The produced oil was collected in a graduated collection tube. Once the collection tube is filled

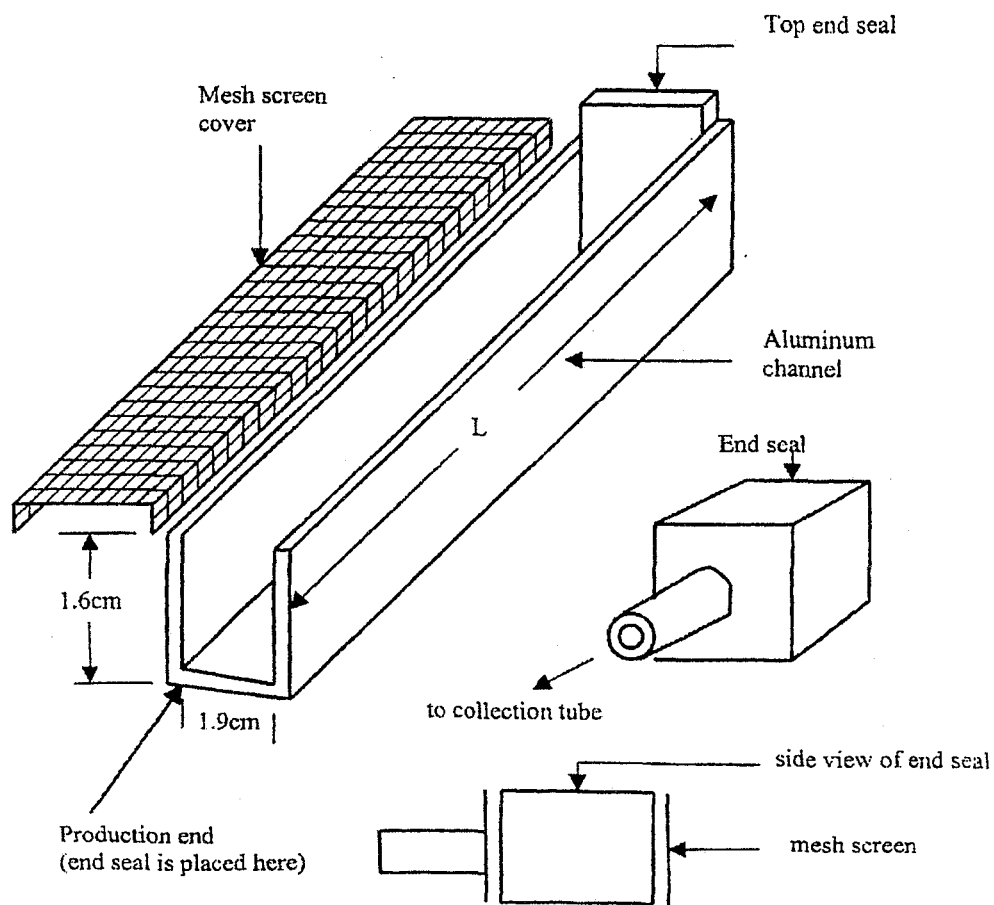
### 3.2 Details of Experimental Setup used to develop the Mathematical Model

Figure 3.4 Schematic diagram of experimental Setup, Oduntan et al.



### 3.2 Details of Experimental Setup used to develop the Mathematical Model

Figure 3.5 The details of rectangular channel, Oduntan et al.



### **3.2 Details of Experimental Setup used to develop the Mathematical Model**

with diluted oil, the oil was allowed to flow through a capillary tube (CT), where the pressure drop was measured by the means of differential pressure transducer in order to measure the live oil viscosity by using the Hagen-Poiseuille equation. Following to that, the live oil was collected into a cylindrical stainless steel separator. The separation tank was maintained at 60°C or higher for flashing of dissolved butane gas from the live oil. In order to measure the amount of absorbed butane into the oil, the liberated butane was allowed to collect in a graduated gas measuring column. At the end, the dead oil was collected in a jar placed on a weighing balance.

Based on this experimental setup, the mathematical model has been developed by considering rectangular block, which is described in Chapter 4.

## 4 Mathematical Model

### 4.1 Introduction

Crucial to the economic viability of VAPEX is the mixing of solvent with crude oil, which is governed by the phenomenon of dispersion. The porosity of reservoir media augments this phenomenon, which otherwise would include molecular diffusion only. In a reservoir, a solvent gas mixes with heavy oil and bitumen phase through the combined phenomena of molecular diffusion, viscosity reduction, gravitational flow, capillary action, and surface renewal [Das and Butler, 1998]. The net effect is dispersion, which can not be accurately described by molecular diffusion alone. As a matter of fact, the recovery rates of heavy oil and bitumen with VAPEX correspond to effective diffusivities, which are two to five orders of magnitudes higher than the molecular diffusivities.

A considerable amount of experimental and theoretical research exists on the determination of dispersion in different solvent-medium systems [Perkins and Johnston, 1963]. However, the phenomenon of dispersion is poorly understood in systems like solvent-crude oil in porous media, which undergo significant viscosity changes [Oballa and Butler, 1989]. Laboratory experiments show that the oil production rates in physical model tests using reservoir sand and falling film geometry can be several folds higher than the rates predicted through molecular diffusion. Possible reasons for this enhancement could be the increase in molecular diffusivity with solvent concentration leading to decreased oil viscosity, an increase in gas/oil interfacial area, and interfacial instabilities. To match VAPEX oil production rates, researchers [Dunn et al., 1989, Das and Butler, 1998, Lim et al., 1996, Oduntan et al.] had to use different values of dispersion, all of which are quite higher than molecular diffusion. These values indicate a strong concentration dependence of dispersion [Boustani and Maini, 2001] as observed in the case of molecular diffusion [Upreti and Mehrotra, 2002].

For the accurate prediction of heavy oil and bitumen recovery with VAPEX leading to



## 4.2 Model Development

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effective designs and optimal operations of commercial VAPEX applications, it is essential to experimentally determine the dispersion of various solvents used in VAPEX. Literature survey indicates a paucity of the much-needed dispersion data. In this work, we develop and simulate a detailed mathematical model to determine solvent dispersion in VAPEX. A laboratory scale physical model of heavy oil and bitumen saturated porous medium is utilized for this purpose. The physical model was invented, and has been used by the researchers at University of Waterloo in various studies on VAPEX [Oduntan et al., Oduntan, 2001, Ramakrishnan, 2003]. The experimental data of live oil production from VAPEX reported by Oduntan et al. are used in the simulation of the developed model to determine the dispersion of butane in Cold Lake bitumen.

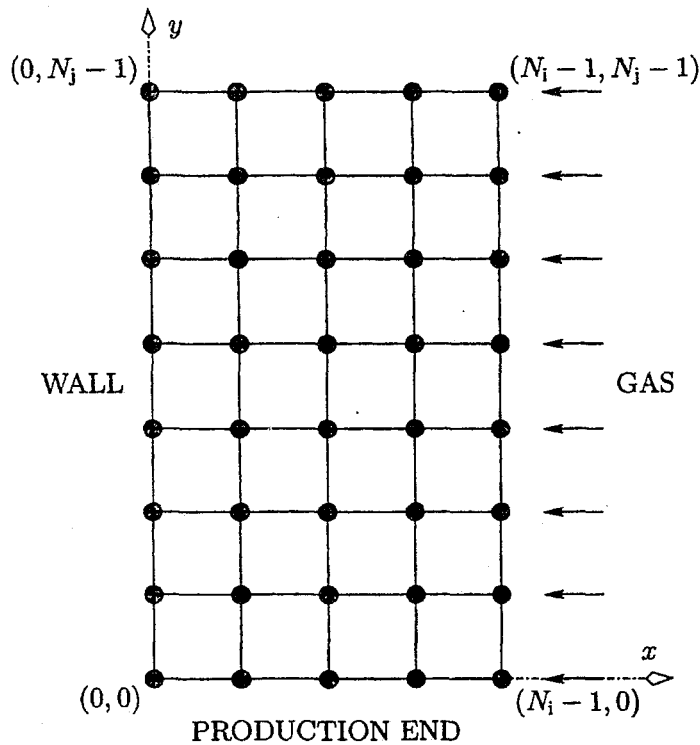
## 4.2 Model Development

Figure 4.1 shows a lateral cross section of the physical model [Oduntan et al., Oduntan, 2001], which is a rectangular block of porous medium saturated with heavy oil and bitumen throughout at the onset of VAPEX. Under specified temperature and pressure conditions, the block is initially exposed to a solvent gas on the vertical face on right hand side. The gas diffuses into the block, and gets absorbed in heavy oil and bitumen. The absorption of gas reduces the viscosity of heavy oil and bitumen causing it to flow under gravity through porous medium. The low-viscosity oil or "live oil" is produced at the bottom of the block. The flow of live oil at the exposed surface renews it continuously, thereby enhancing the transfer of gas into heavy oil and bitumen. The production of live oil with time causes the block to shrink in size. The height of block reduces with time, and varies along  $x$ -axis, i.e. along the width of the block. The reduction of height exposes the block to the gas from top, thereby augmenting the exposed surface area. This effect further enhances the transfer of gas.

In the mathematical model developed below, the main assumptions are as follows:

## 4.2 Model Development

**Figure 4.1** Lateral cross section of the physical model with the arrangement of grid points at the onset of VAPEX



1. VAPEX is carried out at constant temperature and pressure.
2. The porous medium has uniform porosity and permeability.
3. The mass fraction of gas at the exposed surface of porous medium is the saturation mass fraction under equilibrium.
4. The dispersion of gas takes place along  $x$ -direction. The transfer of gas along  $y$ -direction is governed by the  $y$ -component of Darcy velocity in porous medium, and the solution has constant mass density.
5. The dispersion of gas incorporates molecular diffusion, the effects of surface renewal

## 4.2 Model Development

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and augmentation, and any convective component along  $x$ -direction.

6. There is no mass transfer across the vertical face of the block on left hand side, which is a wall.
7. There is no variation of state variables along the thickness of the block.

The unsteady state mass balance for solvent gas in the block results:

$$\phi \frac{\partial \omega}{\partial t} + \frac{\partial n_y}{\partial y} + \frac{\partial n_x}{\partial x} = 0 \quad (4.1)$$

As per our assumption, the dispersion of gas takes place along  $x$ -direction, and dispersion incorporates convective component along  $x$ -direction:

$$n_x = -\mathcal{D} \frac{\partial \omega}{\partial x} \quad (4.2)$$

The transfer of gas along  $y$ -direction governed by darcy velocity, and diffusion is negligible while bulk is moving along  $y$ -direction:

$$n_y = \omega v \quad (4.3)$$

By substituting equation (4.2) and (4.3) into equation (4.1), results in the following partial differential equation:

$$\phi \frac{\partial \omega}{\partial t} = \frac{\partial}{\partial x} \left( \mathcal{D} \frac{\partial \omega}{\partial x} \right) - v \frac{\partial \omega}{\partial y} \quad (4.4)$$

In Equation (4.4),  $\phi$  is the porosity of medium,  $\omega$  is the mass fraction of gas in the block,  $\mathcal{D}$  is the dispersion of gas along  $x$ -direction, and  $v$  is the Darcy velocity along  $y$ -direction given by

$$v = \frac{K_r K \rho g \cos \theta}{\mu} \quad (4.5)$$

## 4.2 Model Development

In Equation (4.5),  $K_r$  is relative permeability, and  $K$  is permeability of porous medium.  $\rho$  is the density of live oil,  $g$  is gravity, and  $\theta$  is the angle between the base of physical model and the horizontal.  $\mu$  is the concentration-dependent viscosity of live oil given by the following correlation [Oduntan, 2001]:

$$\mu = \mu_o \omega^{-2} \quad (4.6)$$

For the dispersion of gas in heavy oil and bitumen, we use the following dependence

$$D \propto \mu^{-0.5} \quad (4.7)$$

based on an empirical model correlated by Das and Butler [1996]. Combining Equations (4.6) and Equation (4.7), we get the following linear, concentration-dependent model for dispersion

$$D = D_o \omega \quad (4.8)$$

where  $D_o$  is dispersion coefficient, or gas dispersion for  $\omega = 1$ .

The change in the height of block ( $Y$ ) with time at any location on  $x$ -axis is the negative of Darcy velocity at the bottom of block, i.e.

$$\frac{\partial Y}{\partial t} = -v \quad (4.9)$$

Initially, there is no gas in the block except at its exposed vertical face on right hand side, where gas concentration is its equilibrium saturation value under prevailing temperature and pressure. Furthermore, there is no production of live oil at the beginning so that the initial height of block is its specified height,  $Y_o$ . Thus, the initial conditions at  $t = 0$  are

$$\omega = \begin{cases} 0, & \text{for } 0 \leq y \leq Y_o, \quad 0 \leq x < X, \\ \omega_{\text{sat}}, & \text{for } 0 \leq y \leq Y_o, \quad x = X \end{cases} \quad (4.10)$$

$$Y = Y_o \quad (4.11)$$

At all times, any exposed surface of block is saturated with gas. This condition applies to the top face of block when it gets exposed to gas. Furthermore, the concentration gradient is

### 4.3 Solution

zero at the wall on the vertical face on left hand side across which there is no mass transfer.

Thus, the boundary conditions for  $t \geq 0$  are

$$\omega = \omega_{\text{sat}} \begin{cases} \text{for } 0 \leq y \leq Y, & x = X \\ \text{for } 0 \leq x < X, & y = Y; \text{ if } Y < Y_0 \end{cases} \quad (4.12)$$

$$\frac{\partial \omega}{\partial x} = 0; \quad \text{for } 0 \leq y \leq Y \text{ and } x = 0 \quad (4.13)$$

At any time, the cumulative volume freed up within the initial boundaries of porous block due to oil production is given by

$$V_{\text{cal}} = \phi^{\frac{2}{3}} Z \int_0^X (Y_0 - Y) dx \quad (4.14)$$

and is the cumulative volume of oil produced. However, this volume corresponds to the volume of dead oil initially present in the porous block. Hence, the cumulative volume of live oil produced at any time is given by

$$V_{\text{cal}} = \delta \phi^{\frac{2}{3}} Z \int_0^X (Y_0 - Y) dx \quad (4.15)$$

where,  $\delta$  is the coefficient for volume correlation.

### 4.3 Solution

The above mathematical model can not be solved analytically. In this work, it was numerically solved using finite differences. The application of second order finite differences along  $x$  and  $y$  directions results in the set of simultaneous ordinary differential equations with time as an independent variable. With  $N_i$  and  $N_j$  grid points respectively along  $x$  and  $y$  direction as shown in Figure 4.1, the finite-differenced ordinary differential equations are as follows:

### 4.3 Solution

For intermediate grid points in the block:

$$\begin{aligned} \frac{d\omega_{i,j}}{dt} = & \frac{D_o}{\phi} \left[ \omega_{i,j} \left( \frac{\omega_{i+1,j} - 2\omega_{i,j} + \omega_{i-1,j}}{(\Delta x)^2} \right) + \left( \frac{\omega_{i+1,j} - \omega_{i-1,j}}{2\Delta x} \right)^2 \right] - \\ & \frac{K_r K \rho g \cos \theta}{\mu_o \phi} \omega_{i,j}^2 \left( \frac{\omega_{i,j+1} - \omega_{i,j-1}}{2\Delta y_i} \right); \end{aligned} \quad (4.16)$$

$0 < i < N_i - 1, \quad \text{and} \quad 0 < j < N_j - 1$

For all grid points (except corners) on left hand side:

$$\frac{d\omega_{0,j}}{dt} = - \frac{K_r K \rho g \cos \theta}{\mu_o \phi} \omega_{0,j}^2 \left( \frac{\omega_{0,j+1} - \omega_{0,j-1}}{2\Delta y_0} \right); \quad 0 < j < N_j - 1 \quad (4.17)$$

For the corner grid point on left hand side at and bottom:

$$\frac{d\omega_{0,0}}{dt} = - \frac{K_r K \rho g \cos \theta}{\mu_o \phi} \omega_{0,0}^2 \left( \frac{-\omega_{0,2} + 4\omega_{0,1} - 3\omega_{0,0}}{2\Delta y_0} \right) \quad (4.18)$$

For the corner grid point at left hand side and top:

$$\frac{d\omega_{0,N_j-1}}{dt} = - \frac{K_r K \rho g \cos \theta}{\mu_o \phi} \omega_{0,N_j-1}^2 \left( \frac{3\omega_{0,N_j-1} - 4\omega_{0,N_j-2} + \omega_{0,N_j-3}}{2\Delta y_0} \right) \quad (4.19)$$

For grid points on right hand side exposed to gas:

$$\frac{d\omega_{N_i-1,j}}{dt} = 0; \quad 0 \leq j < N_j \quad (4.20)$$

For grid points (excluding corners) at the bottom:

$$\begin{aligned} \frac{d\omega_{i,0}}{dt} = & \frac{D_o}{\phi} \left[ \omega_{i,0} \left( \frac{\omega_{i+1,0} - 2\omega_{i,0} + \omega_{i-1,0}}{(\Delta x)^2} \right) + \left( \frac{\omega_{i+1,0} - \omega_{i-1,0}}{2\Delta x} \right)^2 \right] \\ & - \frac{K_r K \rho g \cos \theta}{\mu_o \phi} \omega_{i,0}^2 \left( \frac{-\omega_{i,2} + 4\omega_{i,1} - 3\omega_{i,0}}{2\Delta y_i} \right); \end{aligned} \quad (4.21)$$

$0 < i < N_i - 1$

For grid points (excluding corners) at the top:

$$\frac{d\omega_{i,N_j-1}}{dt} = \begin{cases} \frac{D_o}{\phi} \left[ \omega_{i,N_j-1} \left( \frac{\omega_{i+1,N_j-1} - 2\omega_{i,N_j-1} + \omega_{i-1,N_j-1}}{(\Delta x)^2} \right) + \left( \frac{\omega_{i+1,N_j-1} - \omega_{i-1,N_j-1}}{2\Delta x} \right)^2 \right] - \\ \quad \frac{K_r K \rho g \cos \theta}{\mu_o \phi} \omega_{i,N_j-1}^2 \left( \frac{3\omega_{i,N_j-1} - 4\omega_{i,N_j-2} + \omega_{i,N_j-3}}{2\Delta y_i} \right); \\ \quad \text{if } Y_i = Y_o \\ 0; \quad \text{if } Y_i < Y_o \end{cases} \quad (4.22)$$

$0 < i < N_i - 1$

### 4.3 Solution

In the above equations,  $\omega_{i,j}$  is the mass fraction of gas at the node,  $(i, j)$  corresponding to the coordinate,  $(x, y)$ .  $\Delta x$  and  $\Delta y$  are the distances between equispaced grid points respectively along  $x$  and  $y$  directions. Note that  $Y$ , which is the height of block, changes with time and  $x$ , and is calculable through the simultaneous integration of the following equation:

$$\frac{dY_i}{dt} = -v_{i,0} = -\frac{K_r K \rho g \cos \theta}{\mu_o} (\omega_{i,0})^2; \quad 0 \leq i \leq N_i - 1 \quad (4.23)$$

While  $\Delta x$  is constant, and is given by

$$\Delta x = \frac{X}{N_i} \quad (4.24)$$

$\Delta y_i$  varies along  $x$ -direction with time, and is given by

$$\Delta y_i = \frac{Y_i}{N_j}; \quad 0 \leq j \leq N_j \quad (4.25)$$

Equations (4.16)–(4.23) are coupled, highly nonlinear and stiff to solve. In this work, they were numerically integrated using semi-implicit Bader-Deuffhard algorithm, and adaptive step-size control [Press et al., 2002]. Analytical jacobians of Equations (4.16)–(4.23) were employed for integration. To fix the number of grid points,  $N_i$  and  $N_j$ , the equations were integrated with the increasing number of grid points until the changes in solution became negligible.

Table 4.1 lists the various parameters used in the simulation of the mathematical model.

The cumulative volume of live oil produced at any time is given by the following equation:

$$V_{cal} = \delta \phi^{\frac{2}{3}} \Delta x Z \sum_{i=0}^{N_i-2} \left( Y_o - \frac{Y_i + Y_{i+1}}{2} \right) \quad (4.26)$$

The algorithm was programmed to generate  $V_{cal}$  at the experimental time instants for its direct comparison with its experimental counterpart,  $V_{exp}$ . The root mean square fractional error between these volumes was calculated as

$$e = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} \left( 1 - \frac{V_{cal,n}}{V_{exp,n}} \right)^2} \quad (4.27)$$

### 4.3 Solution

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In Equation (4.27),  $N$  is the number of experimental data points, and  $n$  denotes the  $n$ th experimental time instant.

In this work, the experimental data published earlier by Oduntan [2001] were used for the operation time of about 4 h. These data are for the vapor extraction of Cold Lake bitumen from a laboratory scale physical model using butane at temperature in the range, 19–22°C with pressure close to dew point, i. e. in the range, 0.21–0.23 MPa.



### 4.3 Solution

**Table 4.1** Various parameters used in this study

Parameter	Value	Source
$g, \text{ cm/s}^2$	981	This study
$N_i$	6	
$N_j$	34	
$\mathcal{D}_o, \text{ cm}^2/\text{s}$	0.194–1.39	
$\omega_{\text{sat}}$	0.7–1.0	
$K, \text{ cm}^2$	$1.34 \times 10^{-6}$	Oduntan [2001]
$K_r$	1	
$t_f, \text{ h}$	4	
$X_o, \text{ cm}$	1.9	
$Y_o, \text{ cm}$	21	
$Z_o, \text{ cm}$	1.6	
$\theta, \text{ rad}$	$\pi/4$	
$\mu_o, \text{ g/cm}\cdot\text{s}$	$5.4709 \times 10^{-3}$	
$\rho, \text{ g/cm}^3$	0.85	
$\phi$	0.28	
$\delta$	2	

## 5 Result and Discussion

Root mean square errors were obtained by solving Equations (4.16)–(4.27) with various values of  $\omega_{\text{sat}}$  and  $\mathcal{D}_o$  in the range 0.7–1.0 and 0.194–1.39 cm<sup>2</sup>/s, respectively. Table 5.1 shows the errors that are less than 8%, and surround the minimum error. The Figure 5.1 shows the variation of RMS% error with respect to various saturation mass fraction and various dispersion coefficient used in this study. It can be analyzed from Table 5.1 and Figure 5.1 that optimum RMS% error found was 2.2198%, with corresponding optimal values of  $\omega_{\text{sat}} = 0.87$ , and  $\mathcal{D}_o = 0.556$  cm<sup>2</sup>/s. This optimal value of  $\mathcal{D}_o$  is four orders of magnitude higher than the corresponding coefficient reported for the molecular diffusion of butane in Peace River bitumen. The high value of  $\mathcal{D}_o$  underlines the role of convection and surface renewal encapsulated through dispersion in VAPEX. Figure 5.1 shows the variation of RMS% error with respect to various dispersion values for 0.87 saturation mass fraction.

Further calculations with  $\omega_{\text{sat}} > 0.88$ , and  $\mathcal{D}_o > 1.39$  cm<sup>2</sup>/s did not result in the root mean square error lower than its optimal value of 2.2198%. At very high values of  $\mathcal{D}_o$ , the integration of the set of differential equations, i.e. Equations (4.16)–(4.23) became very time consuming as the step size of integration became prohibitively small. The reason is that  $\mathcal{D}_o$  appears only in Equations (4.16), (4.21) and (4.22) of the set of ordinary differential equations. A higher value of  $\mathcal{D}_o$  as such increases the stiffness of the whole set of equations requiring smaller step sizes for integration.

Predicted live oil production versus time for the optimal values of  $\omega_{\text{sat}}$  and  $\mathcal{D}_o$  is compared with the experimental data of Oduntan [2001] in Figure 5.2. It is observed that the predicted production follows experimental production very closely during the operation time of about 4 h. The rate of production during this time stays practically constant as has been experimentally reported earlier [Oduntan, 2001].

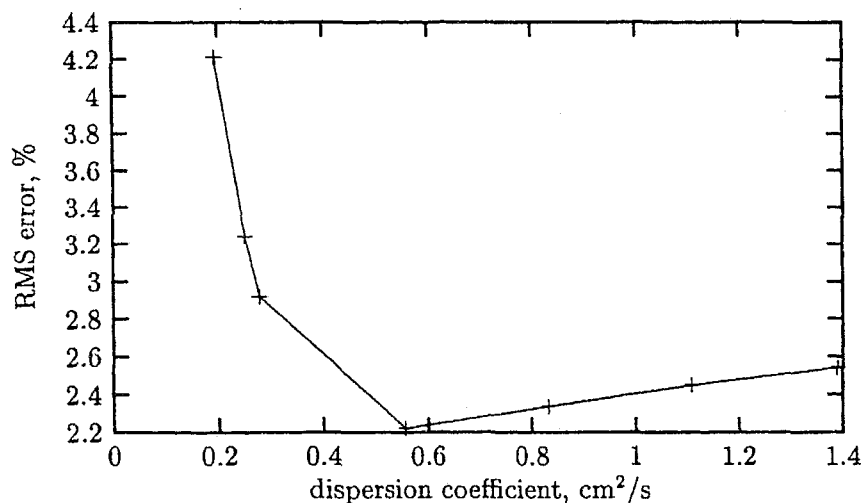
For the optimal values of  $\omega_{\text{sat}}$  and  $\mathcal{D}_o$ , Figure 5.3 shows the variation of height of the porous

**Table 5.1** Percentage root mean square error (in gray cells) between predicted and experimental live oil production

$D_o \times 10^1$ (cm <sup>2</sup> /s)	Saturation mass fraction of butane			
	0.85	0.86	*0.87	0.88
1.94	7.9925	5.9630	4.2130	3.1795
2.50	6.8543	4.8592	3.2361	2.7811
2.78	6.4580	4.4752	2.9202	2.7616
*5.56	4.7998	2.9416	*2.2198	3.4657
8.33	4.2823	2.5685	2.3366	3.8916
11.1	4.0360	2.4226	2.4497	4.1382
13.9	3.9009	2.3461	2.5417	4.2852

\*: optimal

**Figure 5.1** RMS% error versus Dispersion Coefficient for 0.87 saturation mass fraction



block at different times. The height is observed to reduce with width at any time. The gradient of height with respect to width decreases considerably with time as can be seen from the figure. The gradient is the most negative in the end. The reason for this behavior is the implementation of VAPEX under the constraint of initial and boundary conditions given by Equations (4.10)–(4.13). Initially, the concentration of gas and resulting live oil production are higher, closer to the exposed surface of block on right hand side where the consequent reduction of height begins. With the passage of time, this reduction increasingly exposes the block to gas from the top, beginning from the top right corner. This exposure, which progressively increases with time, results in the increasingly negative gradient of height of block with respect to its thickness. The rate of production with time, however, remains almost constant for most of the operation time as can be seen in Figure 5.2.

The changes in mass fractions with respect to height, width and time were obtained by solving equations (4.12)–(4.22) for optimum case (where saturation mass fraction was 0.87). The variation of mass fraction in the block at 1.2 hrs and 4 hrs is shown in Figure 5.4 and

**Figure 5.2** Experimental and model predicted production of live oil versus time

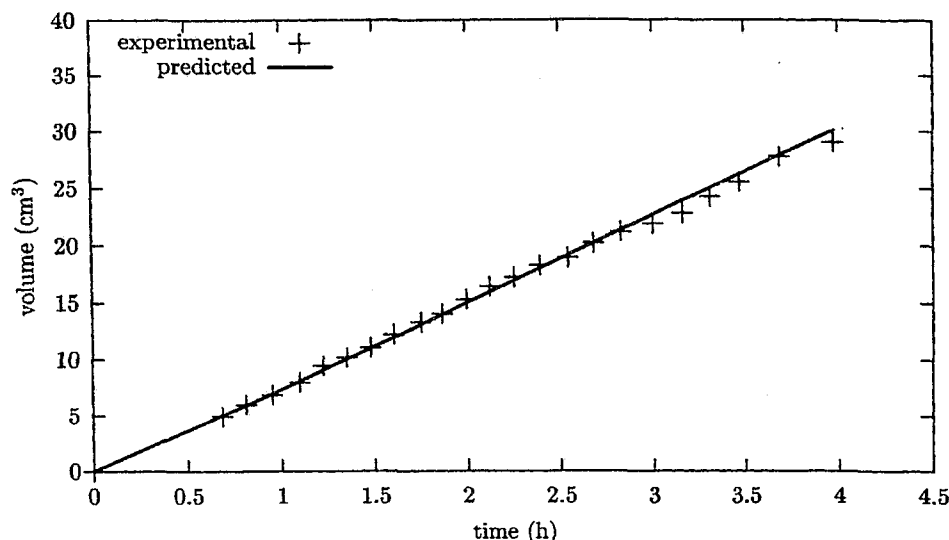
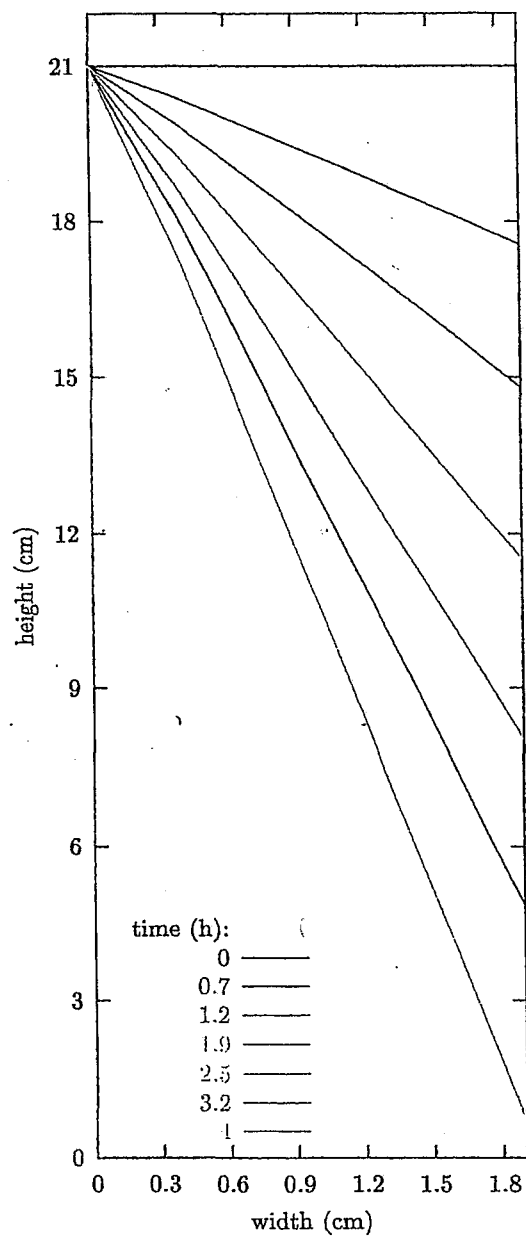


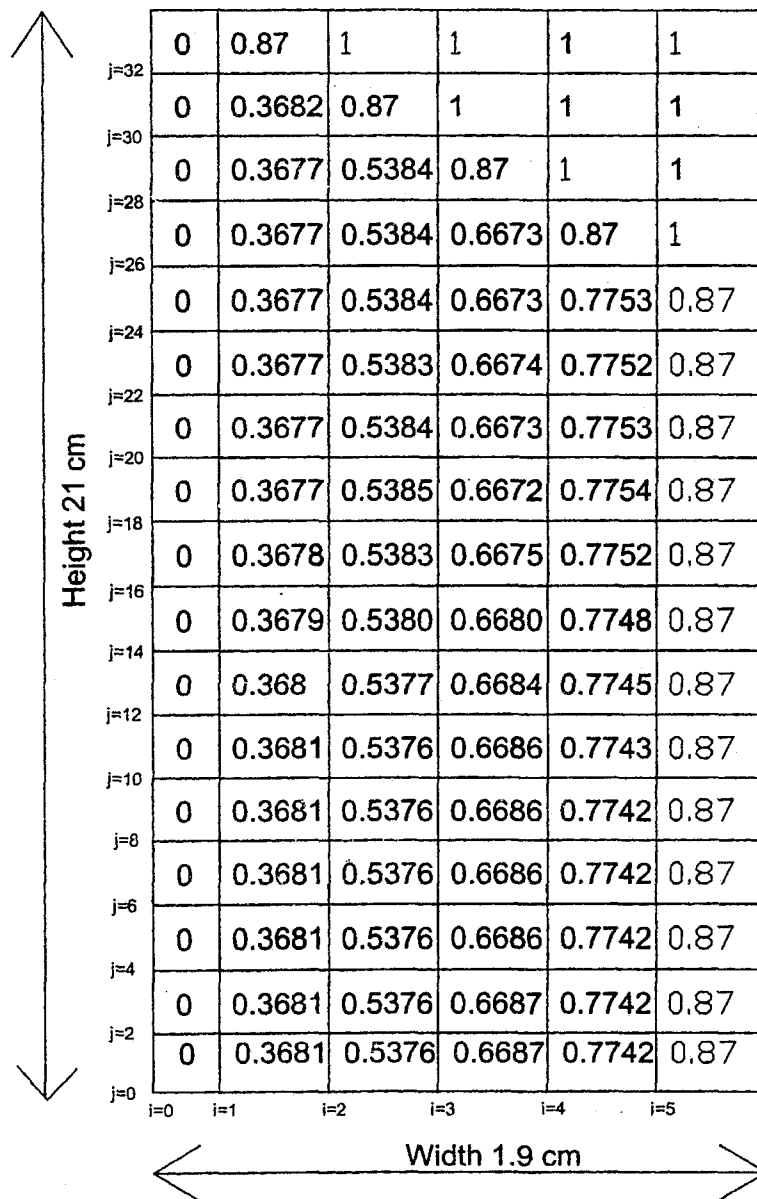
Figure 5.5, respectively. When time  $t = 0$ , the grid size of the block is original grid size. However, the grid size shrink with respect to shrinkage of the block at a given time but the number of grid points remain same. In order to explain the variation of mass fraction in the block at given time, the extrapolation of shrinked grid size to original grid size was done. As the block was exposed to gas at right hand side, the saturation mass fraction was obtained at the oil-solvent interface, which is shown in Figures 5.4 and 5.5. The layer of saturation mass fraction was moved from time  $t = 1.2$  hrs to  $t = 4$  hrs (Figures 5.4 and 5.5). The variation of mass fraction from exposed surface to wall side was decreased. It could be due to dispersion of gas along  $x$ -direction. At the wall side, there is no mass transfer. Hence, the mass fraction obtained at the left hand side of the block was zero.

As the production starts, the low viscosity oil drains under the action of gravity, the surface renewal occurred due to bulk motion, and block exposed to gas from top right hand side (Figure 5.3). Once the low viscosity live oil drains under the action of gravity, the solvent

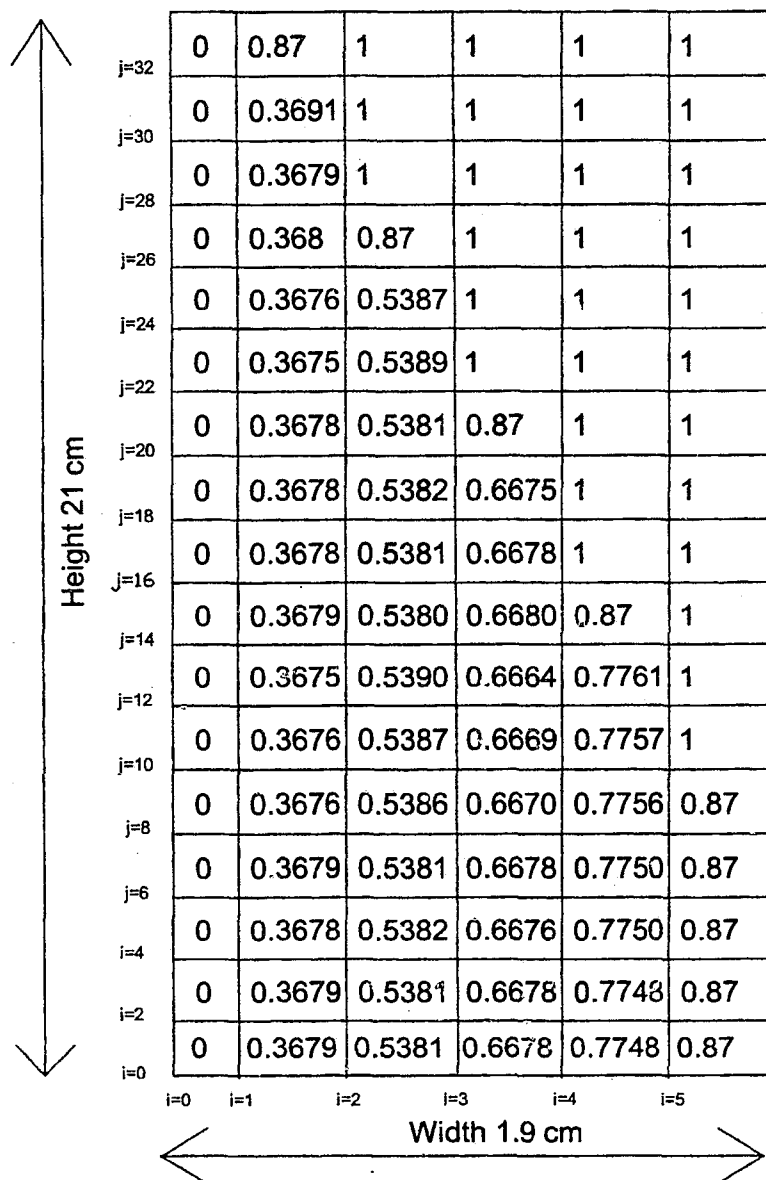
Figure 5.3 The height of block versus its width at different times



**Figure 5.4** The variation of mass fraction in the block at 1.2 hrs



**Figure 5.5** The variation of mass fraction in the block at 4.0 hrs





gas replaces the volume vacated by oil. Figures 5.4 and 5.5 shows that  $\omega = 1$ , which indicates that gas was replaced by the volume of vacated oil. The figure 5.4 shows volume of oil was produced at 1.2 hrs was less than that at 4 hrs. At 4 hrs, the block shrunk remarkably, and gas occupied higher volume than at 1.2 hrs of operation time. On right hand side, as the oil was always exposed to gas, the saturation mass fraction was observed in oil (Figures 5.4 and 5.5).

It can be analyzed from Figure 5.4 and Figure 5.5 that at  $t=1.2$  hrs, only 10 grid points have the pure gas i.e.  $\omega = 1$ . However, when time  $t = 4$  hrs the channel consists pure gas ( $\omega = 1$ ) in 30 grid points. This indicates that higher amount of oil was drained after 4 hrs of operation time, and the volume vacated by oil was replaced by gas. Figures 5.3, 5.4 and 5.5 clearly depicts the phenomena of solvent mass fraction, and surface renewal during the production at various time intervals.

The Cold Lake bitumen used in VAPEX experiments had 40.55 Pa.s viscosity, and 0.9703 g/cm<sup>3</sup> density at room temperature [Oduntan, 2001]. Experimental temperature varied in the range, 19–22°C with pressure close to dew point, i.e. in the range, 0.21–0.23 MPa. Under these conditions on the basis of the above calculations, the saturation mass fraction or solubility of butane is 0.87. The dispersion of butane in Cold Lake bitumen (held in a homogenous porous medium) during its vapor extraction is expressed by the following relation:

$$\mathcal{D} = 0.556\omega \quad [\text{cm}^2/\text{s}] \quad (5.1)$$

where  $\omega$  is the mass fraction of butane in Cold Lake bitumen.

## 6 Conclusion

This thesis is the ground work for the determination of dispersion of solvent gases in heavy oil and bitumen at VAPEX operating conditions. As a part of dispersion determination, the experimental setup was designed to perform the lab-scale VAPEX experiment. Further, a mathematical model was developed and simulated to describe VAPEX in a rectangular block of homogenous porous medium at specified temperature and pressure. This model was used to determine the solubility (saturation mass fraction) and dispersion of butane in Cold Lake bitumen. Both heavy oil and bitumen viscosity, and gas dispersion were considered to be dependent on composition. The shrinkage of block during VAPEX, i. e. its moving boundary with time and space was taken into account. The simulations of model were based on the previously reported experimental data of VAPEX implementation in a laboratory scale physical model. Different values for the solubility and dispersion of butane were used in the simulations. The optimum solubility and dispersion were determined for which the root mean square fractional error between the simulated and experimental values of live oil production is minimum. Corresponding dispersion of butane in Cold Lake bitumen was found to be four orders of magnitude higher than previously reported molecular diffusion of butane in heavy oil and bitumen.

## 7 Recommendations for Future Work

1. The dispersion coefficients of butane in heavy oil and bitumen can be measured for above ambient temperature.
2. The dispersion coefficients of other gases i.e. propane, ethane, methane and carbon dioxide can be measured for different temperature and pressure conditions.
3. Recent study has proved that the use of mixed solvents with proper proportion can give the production rate almost same as pure solvent. As a matter of fact that mixed solvents are more economic to pure solvents, so the dispersion coefficients for mixed solvents can be measured for economic viability.

## Bibliography

- Ayatollahi S. Akbarzadeh, K., K. Nasrifar, H. W. Yarranton, and M. Moshfeghian. Equation lead to asphaltene deposition prediction. *Oil & Gas Journal*, 100(44):51-55, Oct 28 2002.
- F. H. Allen. The Canadian Oil Sands: A Race Against the Clock. 1st UNITAR Conference, Edmonton, Alberta (June 4-12, 1979), reported in *The Future of Heavy Oils and Tar Sands*, 1981.
- J. C. Allen. Method for recovering viscous oils by solvent extraction. 1973. Canadian Patent No. 1008361, Texaco Development, April 12, 1977, US Application No. 391434, August 24.
- J. C. Allen. Gaseous solvent heavy oil recovery. 1974. Canadian Patent No. 1027851, Texaco Development, March 14, 1978, US Application No. 446874, February 28.
- J. C. Allen and A. D. Redford. Combination solvent-noncondensable gas injection method for recovering petroleum from viscous petroleum-containing formations including tar sand deposits. United States Patent No. 4109720, Texaco, New York, August 29, 1978, US Application No. 740281, November 9, 1976.
- C. E. Beecher and L. P. Parkhurst. Effect of dissolved gas upon the viscosity and surface tension of crude oils. *Petroleum Development and Technology in 1926, Petroleum Division AIME*, page 51, 1926.
- National Energy Board. Canada's oil sands: Opportunities and challenges to 2015. A Report Published by National Energy Board, May, 2004.
- A. Boustani and B. B. Maini. The role of diffusion and convective dispersion in vapour extraction process. *J. Can. Pet. Tech.*, 40(4):68-77, 2001.
- U. B. Bray and W. H. Bahlke. Refining with liquified propane. *The Science of Petroleum*, 3:1966-1979, 1938.

## BIBLIOGRAPHY

---

- A. Brown, C. H. Wu, and D. T. Konopnicki. Combined multiple solvent and thermal heavy oil recovery. 1977. United States Patent No. 4004636, Texaco, New York, January 25.
- R. M. Butler. Steam-Assisted Gravity Drainage: Concept, Development, Performance and Future. *J. Can. Pet. Tech.*, 33(2):44, 1982.
- R. M. Butler and Q. Jiang. Improved recovery of heavy oil by VAPEX with widely spaced horizontal injectors and producers. *J. Can. Pet. Tech.*, 39(1):48–56, 2000.
- R. M. Butler and I. J. Mokrys. Solvent analog model of steam-assisted gravity drainage. *AOSTRA Journal of Research*, 5(1):17–32, 1989.
- R. M. Butler and I. J. Mokrys. A new process (VAPEX) for recovering heavy oils using hot water and hydrocarbon vapour. *J. Can. Pet. Tech.*, 30(1):97–106, 1991.
- R. M. Butler and I. J. Mokrys. Recovery of heavy oils using vaporized hydrocarbon solvents: Further development of the VAPEX process. *J. Can. Pet. Tech.*, 32(6):56–62, June 1993.
- R. M. Butler and I. J. Mokrys. Closed-loop extraction method for the recovery of heavy oils and bitumens underlain by aquifers: The VAPEX process. *J. Can. Pet. Tech.*, 37(4): 41–50, 1998.
- R. M. Butler and C. T. Yee. Progress in the in situ recovery of heavy oils and bitumen. *J. Can. Pet. Tech.*, 41(1):31–40, 2002.
- D. Cuthiell, C. McCarthy, T. Frauenfeld, S. Cameron, and G. Kissel. Investigation of the VAPEX process using CT scanning and numerical simulation. *J. Can. Pet. Tech.*, 42(2): 41–49, 2003.
- S. Das. VAPEX — A unique Canadian technology. *J. Can. Pet. Tech.*, 41(8):32–34, 2002.
- S. K. Das. *In Situ Recovery of Heavy Oil and Bitumen Using Vaporized Hydrocarbon Solvents*. PhD thesis, University of Calgary, 1995.

## BIBLIOGRAPHY

---

- S. K. Das. Vapex: An efficient process for the recovery of heavy oil and bitumen. SPE 37826, SPE International Thermal Operations Symposium held in Backersfield, California, (February 10-12), reported in *The Future of Heavy Oils and Tar Sands*, 1997.
- S. K. Das and R. M. Butler. Effect of asphaltene deposition on the VAPEX process: A preliminary investigation using a hele-shaw cell. *J. Can. Pet. Tech.*, 33(6):39-45, 1994a.
- S. K. Das and R. M. Butler. Investigation of vapex process in a packed cell using butane as a solvent. In *Paper No. HWC 94-47*, 20-23 March 1994b.
- S. K. Das and R. M. Butler. Diffusion coefficients of propane and butane in peace river bitumen. *Can. J. Chem. Eng.*, 74:985-992, 1996.
- S. K. Das and R. M. Butler. Mechanism of the vapour extraction process for heavy oil and bitumen. *J. Pet. Sci. Eng.*, 21(1):43-59, 1998.
- L. Denoyelle and C. Bardon. Diffusivity of carbon dioxide in reservoir fluids. In *Paper CIM 115-15-30, 86th Annual Meeting, Canadian Institute of Mining and Metallurgy, April, Ottawa, ON, 1984*.
- S. G. Dunn, E. H. Neggiger, and V. S. Rajan. A study of bitumen recovery by gravity drainage using low temperature soluble gas injection. *Can. J. Chem. Eng.*, 67:978-991, 1989.
- B. C. H. Fu and C. R. Philips. New technique for determination of diffusivities of volatile hydrocarbons in semi-solid bitumen. *Fuel*, 58:557-560, 1979.
- A. T. Grogan, W. V. Pinczewski, G. J. Ruskauff, and F. M. Orr. Diffusion of CO<sub>2</sub> at reservoir conditions: Models and measurements. *SPE Journal*, 3:93-102, 1988.
- Hayduk and Cheng. Review of relation between diffusivity and solvent viscosity in dilute liquid solutions. *Chem. Eng. Sci.*, 26:635-646, 1971.

## BIBLIOGRAPHY

---

- M. Hayduk and B. S. Minhas. Correlations for prediction of molecular diffusivities in liquids. *Can. J. Chem. Eng.*, 60:295-299, April 1982.
- W. Hayduk, R. Castaneda, H. Bromfield, and R. R. Perras. Diffusivities of propane in normal paraffin, chlorobenzene, and butanol solvents. *AIChE Journal*, 19(4):859-861, 1973.
- L. A. James, I. Chatzis, and M. A. Ioannidis. Determination of diffusion coefficient of butane in heavy oil and mass transfer rate at the pore scale in VAPEX. In *Petroleum Society's Canadian International Petroleum Conference*, Calgary, June 10-12 2003.
- A. Janisch. Oil sands and heavy oils: Can they ease the energy shortage. 1st UNITAR Conference, Edmonton, Alberta (June 4-12, 1979), reported in *The Future of Heavy Oils and Tar Sands*, 1981.
- Q. Jiang. *Recovery of Heavy Oil and Bitumen Using VAPEX process in Homogeneous and Heterogeneous Reservoirs*. PhD thesis, Department of Chemical and Petroleum Engineering, University of Calgary, Calgary, 1996.
- Q. Jiang and R. M. Butler. Experimental studies on effects of reservoir heterogeneity on VAPEX process. PAPER 95-21, 46th Annual Technical Meeting of The Petroleum Society of CIM in Banff, May 14-17, Alberta, 1995.
- W. Jin. Heavy oil recovery using the VAPEX process. Master's thesis, University of Waterloo, Waterloo, 1999.
- M. Latil. *Enhanced Oil Recovery*. Editions Technip, Paris, 1980.
- E. L. Lederer. Proceedings of World Pet. Cong. 2:526-528, 1933.
- G. B. Lim, R. P. Kry, B. C. Harker, and K. N. Jha. Three-dimensional scaled physical modelling of solvent vapour extraction of cold lake bitumen. *J. Can. Pet. Tech.*, 35(4): 32-40, 1996.

## BIBLIOGRAPHY

---

- R. B. Long. In *Chemistry of Asphaltene*. Editor: Bunger, J. W. and Li, N. C., Chapter: The Concept of Asphaltene. Americal Chemical Society, Washington, DC, 1981.
- R. Luhning. Removing constraints on oil sands potential: Pipeline transportation of emerging partially upgraded bitumen. *J. Can. Pet. Tech.*, 42(8):7-8, 2003.
- R. W. Luhning, S. K. Das, L. J. Fisher, J. Bakker, J. Grabowski, J. R. Engleman, S. Wong, L. A. Sullivan, and H. A. Boyle. Full scale VAPEX process—climate change advantage and economic consequences. *J. Can. Pet. Tech.*, 42(2):29-33, 2003.
- A. K. Mehrotra and W. Y. Svrcek. Viscosity, density and gas solubility data for oil sand bitumens. part i: Athabasca bitumen saturated with CO and C<sub>2</sub>H<sub>6</sub>. *AOSTRA Journal of Research*, 1(4):263, 1985a.
- A. K. Mehrotra and W. Y. Svrcek. Viscosity, density and gas solubility data for oil sand bitumens. part ii: Peace river bitumen saturated with N<sub>2</sub>, CO, CH<sub>4</sub>, CO<sub>2</sub> and C<sub>2</sub>H<sub>6</sub>. *AOSTRA Journal of Research*, 1(4):269, 1985b.
- A. K. Mehrotra and W. Y. Svrcek. Viscosity, density and gas solubility data for oil sand bitumens. part iii: Wabasca bitumen saturated with N<sub>2</sub>, CO, CH<sub>4</sub>, CO<sub>2</sub> and C<sub>2</sub>H<sub>6</sub>. *AOSTRA Journal of Research*, 2(2):83, 1985c.
- A. K. Mehrotra and W. Y. Svrcek. Properties of Cold Lake bitumen saturated with pure gases and gas mixtures. *Can. J. Chem. Eng.*, 66:656-665, 1988.
- I. J. Mokrys and R. M. Butler. In-Situ Upgrading of heavy oils and bitumen by propane deasphalting: The VAPEX process. SPE 25452, Production Operations Symposium, March 21-23, Oklahoma, 1993a.
- I. J. Mokrys and R. M. Butler. The Rise of Interfering Solvent Chambers: Solvent Analog Model of Steam-Assisted Gravity Drainage. *J. Can. Pet. Tech.*, 32(3):26-36, 1993b.



## BIBLIOGRAPHY

---

- E. H. Nenniger. Hydrocarbon recovery. 1979. Canadian Patent No. 1059432, Hatch Associates, July 31.
- T. A. Nguyen and S. M. Farouq-Ali. Effect of nitrogen on the solubility and diffusivity of carbon dioxide into oil and oil recovery by the immiscible WAG process. *J. Can. Pet. Tech.*, 37(2):24-31, 1998.
- V. Oballa and R. M. Butler. An experimental study of diffusion in the bitumen-toluene system. *J. Can. Pet. Tech.*, 28:63-69, 1989.
- A. R. Oduntan. Heavy oil recovery using the VAPEX process: Scale-up and mass transfer issues. Master's thesis, University of Waterloo, 2001.
- A. R. Oduntan, I. Chatzis, J. Smith, and A. Lohi. Heavy oil recovery using the VAPEX process: Scale-up issues. Petroleum Society's Canadian International Petroleum Conference, June 12-14, Calgary. Paper 2001-127.
- T. K. Perkins and O. C. Johnston. A review of diffusion and dispersion in porous media. *SPE Journal*, 3:70-84, 1963.
- S. J. Pirson. *Oil Reservoir Engineering*. McGraw Hill Book Company, New York, second edition, 1958.
- W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery. *Numerical Recipes in C++*. The Art of Scientific Computing, pages 719-727. Cambridge University Press, New York, second edition, 2002.
- V. Ramakrishnan. In situ recovery of heavy oil by VAPEX using propane. Master's thesis, University of Waterloo, 2003.
- T. A. Renner. Measurement and correlation of diffusion coefficients for CO<sub>2</sub> and rich-gas applications. *SPE Reservoir Eng.*, pages 517-523, May 1988.

## BIBLIOGRAPHY

---

- M. R. Riazi. A new method for experimental measurement of diffusion coefficients in reservoir fluids. *J. Pet. Sci. Eng.*, 14:235-250, 1996.
- A. Rosman and E. Zana. Experimental studies of low IFT displacement by CO<sub>2</sub> injection. SPE 6723, SPE 52nd Annual Fall Meeting, October 9-12, Denver, 1977.
- T. Schmidt, E. Jossy, and V. R. Puttagunta. Mass transfer studies, final report of project 188. Technical report, Alberta Research Council, Edmonton, AB, 1986.
- T. Schmidt, T. H. Leshchyshyn, and V. R. Puttagunta. Diffusivity of CO<sub>2</sub> into reservoir fluids. In *33rd Annual Technical Meeting of the Petroleum Society of CIM*, Calgary, June 6-9 1982.
- F. A. Seyer and C. W. Gyte. In L. G. Hepler and C. Hsi, editors, *AOSTRA Technical Handbook on Oil Sands, Bitumens and Heavy Oils*, chapter Viscosity, pages 174-175. Alberta Oil Sands Technology and Research Authority, Edmonton, Canada, 1989.
- W. R. Shu. A viscosity correlations for mixtures of heavy oil, bitumen and petroleum fractions. *SPE Journal*, 24(3):277-282, 1984.
- R. Simon and D. J. Graue. Generalized correlations for predicting solubility, swelling, and viscosity behavior of CO<sub>2</sub>-crude oil systems. *Journal of Petroleum Technology*, 17:102-106, 1965.
- A. K. Singhal, S. K. Das, S. M. Leggitt, M. Kasraie, and Y. Ito. Steam assisted gravity-drainage and VAPEX process reservoir screening. *JPT*, pages 1122-1124, October 1997.
- J. G. Speight. *Chemistry and Technology of Petroleum*. 316-325, 1991.
- O. P. Strausz. In L. G. Hepler and C. Hsi, editors, *AOSTRA Technical Handbook on Oil Sands, Bitumens and Heavy Oils*, chapter Bitumen and Heavy Oil Chemistry, pages 35-73. Alberta Oil Sands Technology and Research Authority, Edmonton, Canada, 1989.

## BIBLIOGRAPHY

---

- W. Y. Svrcek and A. K. Mehrotra. Gas solubility, viscosity and density measurements for athabasca bitumen. *J. Can. Pet. Tech.*, 21(4):31–38, 1982.
- A. T. Turta and A. K. Singhal. Overview of short-distance oil displacement process. *J. Can. Pet. Tech.*, 43(2):29–37, 2004.
- S. R. Upreti. *Experimental Measurement of Gas Diffusivity in Bitumen: Results for CO<sub>2</sub>, CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, and N<sub>2</sub>*. PhD thesis, Department of Chemical and Petroleum Engineering, University of Calgary, Calgary, 2000.
- S. R. Upreti and A. K. Mehrotra. Experimental measurement of gas diffusivity in bitumen: Results for carbon dioxide. *Industrial and Engineering Chemistry Research*, 39(4):1080–1087, 2000.
- S. R. Upreti and A. K. Mehrotra. Diffusivity of CO<sub>2</sub>, CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub> and N<sub>2</sub> in athabasca bitumen. *Can. J. Chem. Eng.*, 80:116–125, 2002.
- J. R. Welker and D. D. Dunlop. Physical properties of carbonated oils. *Journal of Petroleum Technology*, 5:373, 1963.
- B. Williams. Heavy hydrocarbons playing key role in peak-oil debate, future energy supply. *oil & Gas Journal*, 101(29):20–27, July 28 2003.
- D. E. Woessner, B. S. Jr. Snowden, R. A. George, and J. C. Melrose. Dense gas diffusion coefficients for the methane-propane system. *Ind. Eng. Chem. Fundam.*, 8(4):779–786, 1969.
- C. S. L. Yu. The time-dependent diffusion of CO<sub>2</sub> in normal-hexadecane at elevated pressures. Master's thesis, University of Calgary, Calgary, 1984.
- Y. P. Zhang, Hyndman C. L., and B. B. Maini. Measurement of gas diffusivity in heavy oils. *J. Pet. Sci. Eng.*, 25:37–47, 2000.