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**Dispersion Measurement as a Method of Quantifying Geologic
Characterization and Defining Reservoir Heterogeneity**

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TABLE OF CONTENTS

LIST OF TABLES	v
LIST OF FIGURES	vi
ABSTRACT	x
I. INTRODUCTION	1
II. LITERATURE REVIEW	3
2.1 Definition of Dispersion	3
2.2 Dispersion Model	4
2.3 Correlation of Dispersion Coefficient	5
2.4 Gas-Gas Dispersion	7
III. EXPERIMENTAL METHOD AND APPARATUS	9
3.1 Experimental Apparatus	9
3.2 Experimental Steps	10
3.2.1 Installation of the Core Holder	10
3.2.2 Cleaning and Drying of the Cores	11
3.2.3 Measurement of Porosity and Air Permeability	11
3.2.4 Calibration of Gas Chromatograph	11
3.2.5 Experimental Steps of Gas-Gas Dispersion	12
IV. EXPERIMENTAL RESULTS AND ANALYSIS	13
4.1 Properties of the Tested Cores and Gases Used in This Study	13
4.2 Experimental Results	14
4.3 Effect of Flowrate and Pressure on Gas-Gas Dispersion	14
4.4 Dispersion Coefficient and Dispersivity	16
4.5 Dispersion Factor	22
V. ROCK CHARACTERIZATION	25
5.1 Determination of the Pore Volume of Resident Fluid Displaced	25

5.2 Correlations of Dispersivity and Dispersion Factor	29
IV. CONCLUSIONS AND RECOMMENDATIONS	31
5.1 Conclusions	31
5.2 Recommendations	31
NOMENCLATURE	33
REFERENCES	34

LIST OF TABLES

<u>Table</u>	<u>Page</u>
3.1 Pore Volume and Porosity of the Tested Cores.....	11
4.1 Physical Properties of the Tested Cores.....	13
4.2 Physical Properties of the Gases Used in This Study.....	13
4.3 Experimental Parameters Used in This Study.....	17
4.4 Dispersion Coefficients Calculated by CXTFIT and Analytical Solution Method.....	20
4.5 Effective Molecular Diffusion Coefficients Obtained in This Study	21
4.6 Dispersivities and Dispersion Factors Obtained in This Study.....	24
5.1 Correlation Coefficients and Exponents of Dispersivity and Dispersion Factor.....	29

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
2.1 Relationship Between Molecular Diffusion and Convection Dispersion (from Pfannkuch,1962).....	38
3.1 Experimental Apparatus for Gas-Gas Dispersion	38
3.2 Schematic Diagram of Core Holder Assembly.....	39
3.3 Calibration Curve of Gas Chromatograph.....	39
3.4 Flow Chart of Experimental Procedures for Gas-Gas Dispersion	40
3.5 Recording of Effluent Concentration by Chart Recorder	41
4.1 Air Permeability Versus Porosity for the Tested Cores	41
4.2 Experimental Breakthrough Curves Under Different Pore Velocities for Core YF1 ($P_i=15$ psig)	42
4.3 Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YF1 ($P_i=15$ psig)..	42
4.4 Experimental Breakthrough Curves Under Different Pore Velocities for Core YD6 ($P_i=15$ psig)	43
4.5 Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YD6 ($P_i=15$ psig)..	43
4.6 Experimental Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=15$ psig)	44
4.7 Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=15$ psig)..	44
4.8 Experimental Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=30$ psig)	45

4.9	Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=30$ psig) ..	45
4.10	Experimental Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=40$ psig)	46
4.11	Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=40$ psig) ..	46
4.12	Experimental Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=40$ psig)	47
4.13	Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=40$ psig) ..	47
4.14	Effect of Pressure on Gas-Gas Dispersion for Core YA8.....	48
4.15	Comparison of Breakthrough Curves of Gas-Gas Dispersion with Liquid-Liquid Dispersion for Core YF1	48
4.16	Comparison of Breakthrough Curves of Gas-Gas Dispersion with Liquid-Liquid Dispersion for Core YD6	49
4.17	Comparison of Breakthrough Curves of Gas-Gas Dispersion with Liquid-Liquid Dispersion for Core YA8	49
4.18	Comparison of Experimental and Fitted Breakthrough Curves for Core YF1 ($P_i=15$ psig)	50
4.19	Comparison of Experimental and Fitted Breakthrough Curves for Core YD6 ($P_i=15$ psig)	50
4.20	Comparison of Experimental and Fitted Breakthrough Curves for Core YA8 ($P_i=15$ psig)	51
4.21	Dispersion Coefficient Versus Pore Velocity for Core YF1 ($P_i=15$ psig).....	51
4.22	Dispersion Coefficient Versus Pore Velocity for Core YD6 ($P_i=15$ psig).....	52

4.23	Dispersion Coefficient Versus Pore Velocity for Core YA8 (Pi=15 psig).....	52
4.24	Dispersion Coefficient Versus Pore Velocity for Core YA8 (Pi=30 psig).....	53
4.25	Dispersion Coefficient Versus Pore Velocity for Core YA8 (Pi=40 psig).....	53
4.26	Obtaining the Effective Diffusion Coefficient by the Dispersion Coefficients Under Low Velocities for Core YF1 (Pi=15 psig)	54
4.27	Obtaining the Effective Diffusion Coefficient by the Dispersion Coefficients Under Low Velocities for Core YD6 (Pi=15 psig)	54
4.28	Obtaining the Effective Diffusion Coefficient by the Dispersion Coefficients Under Low Velocities for Core YA8 (Pi=15 psig)	55
4.29	Obtaining the Effective Diffusion Coefficient by the Dispersion Coefficients Under Low Velocities for Core YA8 (Pi=30 psig)	55
4.30	Obtaining the Effective Diffusion Coefficient by the Dispersion Coefficients Under Low Velocities for Core YA8 (Pi=40 psig)	56
4.31	Effect of pressure on Effective Diffusion Coefficient Measured on Core YA8	56
4.32	Effective Diffusion Coefficient Versus Inverse Injection Pressure Measured on Core YA8.....	57
4.33	Dispersivity as a Function of Pore Velocity for Core YF1 (Pi=15 psig)	57
4.34	Dispersivity as a Function of Pore Velocity for Core YD6 (Pi=15 psig)	58
4.35	Dispersivity as a Function of Pore Velocity for Core YA8	58
4.36	Dispersivity as a Function of Pore Velocity for Core YF1 on Log-Log Plot Pi=15 psig)	59

4.37	Dispersivity as a Function of Pore Velocity for Core YD6 on Log-Log Plot ($P_i=15$ psig)	59
4.38	Dispersivity as a Function of Pore Velocity for Core YA8 on Log-Log Plot ($P_i=15, 30$ and 40 psig)	60
4.39	Dispersion Factor as a Function of Pore Velocity for Core YF1 ($P_i=15$ psig)	60
4.40	Dispersion Factor as a Function of Pore Velocity for Core YD6 ($P_i=15$ psig)	61
4.41	Dispersion Factor as a Function of Pore Velocity for Core YA8	61
4.42	Relationship of Dispersivity and Dispersion Factor for Core YF1 ($P_i=15$ psig)	62
4.43	Relationship of Dispersivity and Dispersion Factor for Core YD6 ($P_i=15$ psig)	62
4.44	Relationship of Dispersivity and Dispersion Factor for Core YA8 ($P_i=15, 30$ and 40 psig)	63
5.1	Pore Volume of Resident Fluid Displaced versus the Effluent Relative Concentration for the Three Cores.....	63
5.2	Correlation Coefficients of Dispersivity and Dispersion Factor versus Effective Diffusion Coefficient.....	64
5.3	Correlation Exponents of Dispersivity and Dispersion Factor versus Effective Diffusion Coefficient.....	64

ABSTRACT

Dispersion of fluids flowing through porous media is an important phenomenon in miscible displacement. Much of the research involving dispersion and dispersivity as a property of reservoir rock has focused on miscible liquid-liquid displacement processes. This study addresses the measurement of dispersion in a gas-gas displacement system. It will enlarge the understanding of the characteristics of dispersivity and flow systems of reservoir rocks.

New experimental methods and apparatus for gas-gas dispersion were developed in this study. Twenty eight gas-gas miscible displacement measurements under different flowrates and pressures were conducted on three Berea sandstone cores of varying lengths and physical properties. A gas chromatograph was utilized and modified to measure the concentration of gas at the outlet of the cores. Nitrogen was used as the displacing gas, while helium was used as the displaced gas.

The experimental results were illustrated using S-shaped effluent breakthrough curves. The effect of flowrate and pressure on gas-gas dispersion, dispersion coefficient, dispersivity, and dispersion factor were determined from these curves. Gas effective diffusion coefficients were obtained by graphical methods using the dispersion coefficients under low velocities. A new method to determine the total flowing pore volume by dispersion measurement was proposed in this study. The heterogeneity of reservoir rock can be studied by this method.

An increase in displacing velocity was found to decrease the mixing or dispersion of gases in porous media under low pressure (15, 30 and 40 psig). The presumption was made that a critical velocity exists for a given displacement, below which the increase of velocity results in a decrease in dispersion, and above which an increase in dispersion occurs. An increase in pressure will decrease the mixing of gases when the displacement velocity remains constant.

In liquid-liquid dispersion, higher dispersion coefficients are indicative of higher dispersion. In gas-gas dispersion under low displacing pressure, however, higher dispersion coefficients correspond to less dispersion in reservoir rocks.

Heterogeneity of reservoir rocks can be investigated by dispersion measurements using the method proposed in this study. Total flowing pore volumes determined for the three tested cores are only 27% to 53% of the total pore volume in gas-gas displacement.

CHAPTER I

INTRODUCTION

Miscible displacement has been used successfully in enhanced oil recovery (EOR) processes. The processes promise high recovery from homogeneous reservoirs, but only a small fraction of reservoir volume may be displaced at the time displacing fluid breaks through to the producing well because of the heterogeneity of reservoir. To improve the process of miscible displacement, it is very important to understand well the heterogeneity of the reservoir.

Dispersion in miscible displacement is a characteristic of porous media. It is influenced mainly by the heterogeneity of reservoir and fluid flowing conditions. S-shaped breakthrough curves are typically used to describe the dispersion phenomenon in porous media.

Almost all research in the area of dispersion has focused on the flow of liquids through porous media. Menzie, *et al*, (1989) have been conducting the study of dispersivity as a reservoir rock property for several years. A significant amount of experimental work has been conducted in this area. The effects of scale, velocity and rock properties on liquid-liquid dispersion have been studied. The objective in previous research was to characterize and define reservoir heterogeneities by measuring liquid-liquid dispersion in porous media. The measurement of dispersion with gases will significantly contribute to the overall understanding of flow systems in reservoir rocks.

The objectives of this study are:

- (1) To develop a method and set up an experimental apparatus to measure gas-gas dispersion in consolidated rocks.
- (2) To study the effect of displacement velocity and pressure on gas-gas dispersion and dispersivity.
- (3) To study the heterogeneity of reservoir rocks and investigate the relationship between dispersivity and rock properties to characterize the flow system using gas-gas dispersion measurements.

In this study, twenty eight gas-gas dispersion measurements with different velocities and pressures were conducted on three Berea sandstone cores. The effects

of velocity and pressure on gas-gas dispersion were thoroughly investigated. The characterization of the rocks through dispersion measurement was studied.

Chapter II contains a brief literature review of past research on dispersion. Chapter III presents the setting up of the experimental apparatus used in this study and procedures for gas-gas dispersion measurement. Chapter IV reports all of the experimental results obtained in this study. The effects of flowrate and pressure on gas-gas dispersion and dispersivity were analyzed. Chapter V includes the investigation of rock heterogeneity by dispersion measurements and the relationship between effective diffusion coefficient and correlation of dispersivity and dispersion factor. Chapter VI contains the conclusions from this study and recommendations for future research.

CHAPTER II

LITERATURE REVIEW

Study of dispersion in porous media has attracted considerable attention in recent years due to its potential application in soil physics, chemical engineering processes, biological system analysis and petroleum engineering. Various branches of science and engineering have contributed to the literature, ranging from analytical/numerical models to experimental data, to develop the theory of dispersion and its application. Much of the research on dispersion focused on the phenomena of liquid-liquid dispersion in porous media. Less attention has been placed on gas-gas dispersion. Therefore, theory on gas-gas dispersion in porous media needs to be developed.

2.1 Definition of Dispersion

As one miscible fluid displaces another, the displacing solution continuously mixes with the resident fluid, so that the arrival of the displacing solution at a given point in the porous medium is characterized by a gradual change in the solution concentration from that of the original fluid to that of the invading fluid. This mixing or interfusing of the two fluids, due to both molecular diffusion and convection, is termed dispersion (Sandrea, 1974).

The two important phenomena used to describe dispersion are molecular diffusion and convection. The flow and heterogeneity of the pore system are responsible for the convection process. The variation of concentration within a mixture of liquids or gases gives rise to molecular diffusion, which is significant in gas-gas dispersion. In liquid-liquid dispersion, molecular diffusion is only significant at low flowing velocity.

Darcy's Law is used to describe the macroscopic fluid flow behavior in porous media. However, since it does not consider the effects of dispersion, its application in miscible displacement is fallible.

Fick's Law, which states that the rate of transfer of the diffusing substance through a unit area of cross section is proportional to the concentration gradient normal to the cross section and is expressed as:

$$\frac{dn}{dt} = -D_o A \frac{\partial C}{\partial x} \quad (2.1)$$

where:

n = mass of material diffusing across a plane (mg),
t = time (second),
D_o = molecular diffusion coefficient (cm²/sec),
A = cross sectional area of diffusion (cm²),
C = concentration (mg/liter),
X = distance (cm).

is generally recognized as an adequate characterization for mixing of miscible fluids flowing through porous media.

Even though D_o is treated as a constant, it depends on many factors, such as absolute temperature, fluid concentration, and the presence of other types of molecules. For compressible fluids such as gases, pressure is an additional factor to be considered. Although the mechanisms of dispersion and diffusion are different, the dispersion coefficient D is used as a substitution for the molecular diffusion coefficient D_o in Fick's Law.

2.2 Dispersion Model

Dispersion in porous media is a very complex phenomenon. Several mechanisms of transport, including molecular diffusion, viscous and slip flow, may contribute to the flux of fluids through porous media. In addition, it is impossible to describe the complicated geometry of pore structure of solid in any mathematical form. Hence, the relationship between structure and flux is not easily described mathematically.

Much research has been done to describe the dispersion phenomena in porous media. Several approaches have been commonly employed. The first approach was to use a simplified model, in which the mixing can be analyzed by exact mathematical methods to replace the actual medium, such as a single capillary tube, a bundle of capillaries, or an array of cells. A second approach was to construct a statistical model of the microscopic motion of the marked fluid particles and to average these motions to obtain a macroscopic description of the movement of the marked particles.

The third approach was to describe porous media as a continuous system and assume that the continuity equation applies at every point. Continuity equation and Fick's Law were combined to produce a description of the macroscopic flow geometry called the Convection-Dispersion Equation (C-D Equation):
where:

$$-\nabla(u \cdot C) + \nabla \cdot (\phi D \cdot \nabla C) = \frac{\partial(\phi C)}{\partial t} \quad (2.2)$$

u = Darcy velocity (cm/sec),
 C = concentration (mg/liter),
 D = tensor formulation of dispersion coefficient (cm²/sec),
 t = time (sec),
 ϕ = porosity (fraction),
 ∇ = vector partial differential operator.

This equation was derived from mass balance considerations. One of the most important assumptions in this equation is that dispersion obeys Fick's Law of molecular diffusion.

2.3 Correlation of Dispersion Coefficient

Dispersion coefficient is used as a term to describe the extent of dispersion taking place in porous media. It has been analyzed by many investigators. Correlations have been made between dispersion coefficients and other parameters.

Pfannkuch (1962) plotted the experimental data for D_l/D_o versus the Peclet number vd_p/D_o (Figure 2.1). In the relationship, d_p is a characteristic dimension perpendicular to the flowing direction usually referred to as the effective particle diameter, D_o is the molecular diffusion coefficient of the displacing fluid, and D_l is the longitudinal dispersion coefficient.

Figure (2.1) shows that three distinct regions exist in the relationship. For the region where P_e is between 0 to 0.01, D_l/D_o remains constant. In this region, mixing is dominated by molecular diffusion and velocity has no effect on dispersion. The ratio D_l/D_o is less than one because of the effect of tortuosity which increases the path length for diffusion. The effective molecular diffusion coefficient in porous media is:

$$D_e = \frac{D_o}{\tau} \quad (2.3)$$

where:

τ = tortuosity (dimensionless),

D_e = effective molecular diffusion coefficient (cm²/sec).

For the region where Pe is between 0.01 to 4, the mixing gradually overrides the diffusion in the direction of flow as velocity increases. Both diffusion and velocity affect dispersion. For Pe value greater than 4, D_l/D_o is proportional to velocity exponentially. In this region, the effect of flowing velocity overrides diffusion and dominates the dispersion of one fluid into another.

Klinkenberg (1951) discussed the analogy between diffusion and electrical conductivity in porous media and asserted that D_l/D_o is related to the formation factor F and porosity ϕ at low velocity by the following correlation:

$$\frac{D_l}{D_o} = \frac{1}{F\phi} \quad (2.4)$$

At high velocity, an empirical equation was developed as follows:

$$\frac{D_l}{D_o} = a \left(\frac{v d_p}{D_o} \right)^m \quad (2.5)$$

where:

a = mixing coefficient,

m = mixing exponent.

By combining equation (2.4) for low flow velocity and equation (2.5) for high flow velocity, a mathematical description of longitudinal mixing properties in porous media is given:

$$\frac{D_l}{D_o} = \frac{1}{F\phi} + a \left(\frac{v d_p}{D_o} \right)^m \quad (2.6)$$

Research has been conducted to study the coefficients a and m . Experimental results have shown that the mixing exponent, m , varies between 1 and 2. The mixing coefficient, a , varies widely depending on the geometry of the porous medium and viscosity ratio of the flowing fluids.

Brigham (1961) stated that the mixing coefficient, a , can be used successfully to characterize porous media. This is possible because a is a measure of the inhomogeneity of a porous medium under dynamic condition.

2.4 Gas-Gas Dispersion

Transport of gases in porous media is a very complex problem. Several mechanisms of transport including molecular diffusion, Knudsen diffusion, viscous and slip flow, as well as surface migration, may contribute to the dispersion of gases in porous media. Dullien (1992) pointed out that the flow of gases in porous media has certain characteristics that distinguish it from the flow of liquids. An important difference between flow of liquids and gases in porous media is that in the latter case the velocity at the solid walls can not generally be considered zero. A "slip" or "drift" velocity at the wall must be taken into account.

This effect becomes significant when the mean-free path of the gas molecules is of magnitude comparable to the pore size. When the mean-free path is much less than the pore size, the slip velocity becomes negligible. As in liquid flow, the mean-free path of no slip condition always applies. Another important factor is the compressibility of gases, which makes the study of gas-gas dispersion in porous media complex. In addition, a mathematical analysis may be slightly different for liquids than for gases, since a low liquid density corresponds to a low viscosity, while in gases this relationship does not apply.

Only a few references about gas-gas dispersion can be found in the literature. Schmidt (1940) carried out some experiments of gases mixing in man-made porous media under different storage pressures, using air and natural gas as the reservoir and displacing gases respectively. It was observed that at high pressure (500 psi), mixing increased as the linear velocity increased, while at lower pressure (14.7 and 200 psi), mixing increased as the linear velocity decreased.

Mertz (1941) conducted laboratory experiments and presented data to show that there are two factors governing the amount of mixing that takes place between reservoir and displacing gases. These factors are (1) the time of contact between the gases which governs the amount of mixing through ordinary diffusion effects and (2) the turbulent effects produced by the flow of the gases through the porous media. In the range of Reynolds number below 0.6, an increase in linear velocity or pressure tends to cancel out the effect of ordinary diffusion. At high pressure and linear velocity, where the Reynolds numbers is above 0.8, an increase in linear velocity increases the turbulent action, thereby increasing the amount of mixing.

Legatski (1967) performed an experiment to determine the gas-gas dispersion coefficients for gases flowing in consolidated porous media, assuming gas-gas dispersion characteristics of the type:

$$\frac{D_l}{D_o} = \frac{1}{F\phi} + 0.5\left(\frac{v d_p \sigma}{D_o}\right)^m \quad (2.7)$$

where:

d_p = particle diameter (cm),

σ = packing , or inhomogeneity, factor (dimensionless).

The stimulus-response technique, featuring on-line gas analysis by thermal conductivity and on-line data reduction by analog computation was used to determine the mixing parameters of eight natural sandstones and two dolomite samples. It was determined that the dispersion ratio, D_l/D_o , is a function of the Peclet number to a power between 1.0 and 1.5. Measurements of dispersion coefficients on cores containing deposited wax showed that the presence of an immobile phase, such as connate water, could increase the dispersion coefficients significantly.

CHAPTER III

EXPERIMENTAL METHOD AND APPARATUS

3.1 Experimental Apparatus

The following considerations were included in the development of the experimental apparatus in this study:

(1) Method to measure the effluent concentration of gas

A Carle Gas Chromatograph (GC) was selected to measure the effluent concentration of gas. Gas Chromatograph consists of two main parts: the thermal conductivity detector, or gas detector and the columns.

The principle of a gas detector is that the column effluent or gas to be measured flows through a cavity. The cavity is generally contained in a metal block which is heated to a constant temperature by a heat element contained in the cavity. When a constant gas current passes through the gas detector, the heat transfer is constant under equilibrium conditions. When the component of gas flowing through the column changes, the thermal conductivity of the gas changes the heat transfer mechanism within the cavity, which in turn affects the temperature of the heat element. The temperature change of the heat element is accompanied by a change in resistance, which causes an imbalance in a bridge circuit. This imbalance results in an analog signal being sent to a chart recorder. The extent of the imbalance is proportional to the gas component causing the change.

The performance of columns is to separate the components of the gas from each other when more than one component exists. The column is used to identify the amount of each component in the gas samples based on their adsorption time to the column.

(2) Displacing gas and displaced gas

Pure nitrogen and helium were used as the displacing and displaced gases, respectively. These fluids were used due to their nonflammability, availability, and compatibility with the gas chromatograph.

(3) Modification and bypassing of gas chromatograph

When a small amount of gas sample is injected into the gas chromatograph, different peaks on the chart recorder will indicate the kinds and the amounts of gases existing in the sample. In the calibration of the gas chromatograph, there was an indication that the gas chromatograph is very sensitive to the amount of gas sample injected. To use a needle as an injector to get an accurate result is almost impossible, especially after the concentration of the gas exceeded 90%. Therefore, an alternative was investigated.

Ali (1989) used a gas chromatograph to measure the gas concentration of diffusion in porous media. To get accurate and continuous smooth S-shaped breakthrough curves, he modified the gas chromatograph to let the tested gas bypass the column and flow into the gas detector directly. Using this method, very smooth S-shaped breakthrough curves were obtained. The gas chromatograph used in this study was modified based on Ali's method to allow the tested gas to bypass the column.

A schematic diagram of the equipment used for gas-gas dispersion is shown in Figure (3.1). The system included (1) two bottles of pure helium, one was used as the displaced gas, the another was used as the carrier gas in the gas chromatograph; (2) one bottle of nitrogen used as the displacing gas; (3) three precise pressure and flowrate regulators on the top of each gas cylinder; (4) a core holder; (5) a vacuum pump; (6) a pressure gauge; (7) a gas flow meter; (8) a bubble gas flow meter; (9) a gas chromatograph; and (10) some needle valves.

3.2 Experimental Steps

To compare the gas-gas dispersion with previous liquid-liquid dispersion studies, the core samples used in this study are these from Li's liquid-liquid dispersion experiments. They are 3.8 cm in diameter, drilled from Berea sandstone blocks obtained from the Cleveland Quarries located in Amhurst, Ohio. The cores were cleaned, dried, and coated with J-B Weld epoxy. The coating was pressure tested up to 70 psia. In Li's experiments, Isoxy was used as the displacing liquid and Naphtha as the displaced liquid.

3.2.1 Installation of the Core Holder

The core holder consisted of two end-plates and four bolts that spanned the length of the core holder. A schematic diagram of the core holder is given in Figure (3.2).

3.2.2 Cleaning and Drying of the Cores

Toluene extraction was used to clean the cores, due to its low vapor pressure. The cleaning continued until at least three pore volumes of toluene had been injected and the toluene produced at the outlet of the core was clean.

Air was used to dry the cores after the core was cleaned with toluene. To eliminate the moisture in the injected air, a moisture trap was connected between the air line and core samples.

3.2.3 Measurement of Porosity and Air Permeability

A volumetric method was used to measure the porosity of the cores. The three cores used in this study had comparable values of pore volume and porosity as those used by Li (Table 3.1).

Air permeability was determined by measuring the flowrate of air through the core under different injection pressures. Darcy's Law for laminar gas flow in porous media was used to calculate the air permeability of the cores.

Table 3.1 Pore Volume and Porosity of Tested Cores

Core	Pore Volume		Porosity	
	Obtained by Li (cm ³)	Obtained in This Study (cm ³)	Obtained By Li (%)	Obtained In This Study (%)
YF1	66.5	67	19.4	20.0
YD6	95.1	93.73	18.4	17.89
YA8	157.4	160.53	19.1	19.4

3.2.4 Calibration of Gas Chromatograph

The relation between the magnitude of the peak height recorded by the chart recorder and the analyzed concentration in the column effluent is linear, if all other apparatus parameters are constant. The calibration curve plotted on graph paper should be linear with an zero intercept at the origin.

The Calibration-Curve technique was used to calibrate the gas chromatograph. First, mixtures of gases with different concentrations were made in a vessel. Then the same amounts of gas samples with different concentrations were injected into the gas chromatograph by a needle injector. The peaks with different heights were recorded by the chart recorder. By plotting the concentration versus peak height on a cartesian plot as in Figure (3.3), an approximate straight line was obtained. Deviations from the straight line were attributed to sampling error, because peak heights were affected by the amount of samples.

Both the concentration and the amount of gas in the sample can affect the height of the peak generated by the GC. When equal volumes are used, the peak height should only be a function of the concentration of a given gas component. A correlation between the concentration and the peak height can be obtained with the point at 100% concentration.

To study the effect of velocity on gas-gas dispersion, different flow rates were used in the experiments. The peak height at 100% concentration was obtained when a flat top on the S-shaped breakthrough curve occurred. Then the correlation between concentration and the peak height under a certain flow rate was established. The S-shaped breakthrough curve, where the X axis represents the time and Y axis represents the peak height can be converted to a plot of the pore volume injected versus the effluent relative concentration. This method was used throughout this study.

3.2.5 Experimental Steps of Gas-Gas Dispersion

Figure (3.4) shows the flow chart of the experimental procedures used in the measurement of gas-gas dispersion in this study.

CHAPTER IV

EXPERIMENTAL RESULTS AND ANALYSIS

Twenty eight experimental measurements of gas-gas dispersion were conducted on three Berea sandstone cores. The three cores have the same cross section diameters but different lengths. The three cores were labeled as YF1, YD6 and YA8, which are identical to the labeling used in the liquid-liquid displacement experiment (Li, 1992).

4.1 Properties of the Tested Cores and Gases Used in This Study

The geometries and properties of the cores are summarized in Table (4.1). The properties of helium and nitrogen are listed in Table (4.2). It should be noted that the two gases have similar viscosities but very different densities. Figure (4.1) shows the relationship between porosity and permeability for each core. Note that high permeability corresponds to high porosity for the three cores.

Table 4.1 Physical Properties of the Tested Cores

Core	Type	d (cm)	L (cm)	PV (cm ³)	Φ (%)	K (md)
YF1	Berea	3.8	29.1	67	20.0	300
YD6	Berea	3.8	45.6	93	17.89	97
YA8	Berea	3.8	72.6	160.5	19.39	185

Table 4.2 Physical Properties of Gases Used in This Study
(At T = 230°C and P = 1 atm)

Gas	ρ (g/cm ³)	μ (cp)	Molecular Weight
Nitrogen	0.001154	0.0177	28.02
Helium	0.000163	0.0186	4.0

4.2 Experimental Results

To study the effect of velocity and pressure on gas-gas dispersion, twenty eight runs were conducted on three cores under different flowrates and pressures. All of the experimental results obtained in this study are presented in Figure (4.2) through (4.13).

The measurements under different pressures were conducted only on core YA8, because its largest length served to reduce the effect of scale. The derivative curves depicted the rate of concentration change of the displacing gas at effluent with respect to pore volume of displacing gas injected for various pore flow velocities. These curves were developed analytically by calculating slopes of the breakthrough curves. Although the data were obtained by a continuous monitoring technique, they were depicted as discrete points in these figures for comparison.

4.3 Effect of Flowrate and Pressure on Gas-Gas Dispersion

The effect of flowrate on gas-gas dispersion was observed by plotting the effluent breakthrough curves under the same displacing pressure but different flowrates on the same cartesian plot as in Figure (4.2) through (4.13). The runs performed on all three cores produced data that infer that lower flowrates led to earlier breakthrough and higher dispersion and higher flowrates led to later breakthrough and less dispersion. This is in contradiction with the classic concept of miscible displacement.

In liquid-liquid dispersion, molecular diffusion is assumed to be negligible as compared to the effect of convection on dispersion. However, molecular diffusion plays a significant role in gas-gas dispersion. When the pressure in a gas system is uniform ($P_1 = P_0$), the mass flux is considered diffusive in nature. Several mechanisms, including Knudsen diffusion, molecular diffusion and surface migration contribute to the gas diffusion (Youngquist, 1970). Surface migration only occurs when the diffusing gases are adsorbed in a mobile layer. In a consolidated porous medium, surface migration effect are considered negligible. Molecular diffusion is caused by the collision between molecules, and between the molecules and walls of porous media. In the free atmosphere, molecular diffusion depends only on the concentration gradient of the gas mixture. The molecular flux of a given component of the gas mixture increases as its concentration increases.

In porous media where the pore radii are such that the mean free paths of molecules are large compared to the diameter of the pores, the transport of molecules

will be governed by the collision of molecules with the wall of the porous medium (Youngquist, 1970). This type of transport is referred to as Knudsen diffusion. When the displacing velocity is lower than the velocity caused by diffusion flux, the increase of displacing velocity will tend to decrease the diffusion of the gases. This concept explains why less dispersion was encountered at higher velocities.

It is presumed that in a porous media for a specific displacement, there is a critical velocity at which the effects of velocity and diffusion to gas-gas dispersion will cancel each other and least dispersion will take place. Below the critical velocity, an increase of velocity will lead to less dispersion. However, above the critical velocity, the increase of velocity will lead to more dispersion.

To determine the critical velocity, experiments were conducted at high velocities under displacing pressures of 15 psig and 40 psig with core YA8 as shown in Figure (4.6) and (4.12). Because of the pressure restriction of the coating, the pressures used in the experiments were too low to obtain the critical velocity, even though the velocities used were high enough.

Schmidt (1940) conducted experiments using synthetic porous media. It was observed that the mixing of gases increased as the displacement velocity increased at a displacement pressure above 500 psig. It is presumed that a higher displacement pressure will lead to a lower critical velocity, or vice versa.

In liquid-liquid dispersion, the effect of pressure is negligible due to the incompressibility of liquids. However, the effect of pressure in gas-gas dispersion is significant due to the compressibility of gases. Figure (4.14) shows the effect of pressure on gas-gas dispersion. Three experimental runs were conducted on the same core at similar velocities but different displacement pressures (15, 30 and 40 psig). It is observed that the increase of displacement pressure led to less dispersion in gas-gas displacement. It is easy to understand from the above analysis that the effect of diffusion decreased at higher pressure due to the restriction to the movement of the gas molecules. Even though the velocities were similar, less dispersion took place. The velocities used in the three runs were not exactly the same. The effect of pressure will be seen more clearly if the exact velocity is used on each run because of the effect of velocity on gas-gas dispersion as discussed previously.

If the displacement pressure is increased continually and the gas is liquefiable, the extreme situation will be liquefaction and gas-gas dispersion will transform into liquid-liquid dispersion. As expected, less dispersion should take place, because the effect of diffusion reduces to zero in liquid-liquid dispersion..

The comparisons of gas-gas dispersion with liquid-liquid dispersion in Figure (4.15) through (4.17) illustrate these expected results. Much less dispersion took place in the liquid-liquid dispersions. Another reason for the reduction in dispersion is because gases diffuse only, or more easily, through the larger pores of porous media. This makes more dispersion take place in gases.

Table (4.3) shows the pressures and flowrates used in the experiments of this study. The pressures used in the experiments are 15, 30 and 40 psig. The pressure drops are between 0.2 to 3.8 psig and the displacement velocities used are between 0.002152 to 0.2125 cm/sec.

Gravity forces may also influence dispersion. In this study, the gases used have a big difference in density, which can be noticed from Table(4.2). Nitrogen is almost seven times higher in density than helium. This may be another reason that caused the dispersion in the nitrogen-helium system. It will not be considered further in this study, but future work should include this consideration.

4.4 Dispersion Coefficient and Dispersivity

Because of the compressibility of gases, the C-D Equation can not be used to fully describe gas-gas dispersion in porous media. In this study, the pressure difference between the inlet and outlet ranged from 0.2 to 3.8 psia, allowing the compressibility of gases to be assumed negligible. Therefore, two methods for liquid-liquid dispersion were used in this study to calculate the gas-gas dispersion coefficients.

The first method used in this study is the curve matching method, which utilizes the convection-dispersion transport model to match the experimental data to obtain the dispersion coefficients. The computer program used in this study is called CXTFIT (Parker & Van Genuchten, 1984). It combines the one-dimensional analytical solution of C-D Equation along with the non-linear least square numerical method to match the experimental data. The typical experimental breakthrough curve and the fitted breakthrough curve generated by CXTFIT for each core are shown in Figure (4.18) through Figure (4.20).

Table 4.3 Experimental Parameters Used in This Study

Core	Q_i (cm³/sec)	v (cm/sec)	P_i (psig)	P_o (psig)	ΔP (psig)
YF1	0.02368	0.005056	15.7	15.5	0.2
	0.03253	0.006955	15.7	15.3	0.4
	0.07214	0.015420	15.7	15.2	0.5
	0.12670	0.027000	15.9	15.2	0.7
YD6	0.01248	0.003028	15.2	14.8	0.4
	0.02569	0.006271	15.2	14.45	0.75
	0.06467	0.015610	15.2	14.1	1.1
	0.12780	0.030300	16.7	14.7	2
	0.18100	0.044360	15.2	14.0	1.2
	0.26320	0.065300	15.2	13.5	1.7
YA8	0.03201	0.007156	15.2	14.9	0.3
	0.05802	0.013010	15.2	14.7	0.5
	0.12780	0.028810	15.2	14.4	0.8
	0.45380	0.104400	15.5	13.2	2.1
	0.89930	0.212500	15.5	11.7	3.8
	0.03171	0.004729	30.4	30	0.4
	0.04241	0.006335	30.2	29.6	0.6
	0.08754	0.013180	30.2	29.2	1
	0.17540	0.026470	30.2	29.0	1.2
	0.37700	0.057350	30.2	28.3	1.9
	0.01759	0.002152	40.2	39.7	0.5
	0.04652	0.005737	40	39	1
	0.05550	0.006820	40.2	39.2	1
	0.06636	0.008154	40.2	39.2	1
	0.08294	0.010200	40.4	39.2	1.2
	0.15210	0.018820	40	38.7	1.3
	0.72250	0.090620	40	37.2	2.8
	1.06850	0.135300	40	36.2	3.8

The second method used to calculate the dispersion coefficients is the Analytical Solution Method (ASM) proposed by Greenkorn (1983), which is expressed by following equation:

$$D_l = \frac{vL}{4\pi \left[\frac{d(C/C_0)^2}{d(V/V_p)} \right]_{\frac{V}{V_p}=1}} \quad (4.1)$$

where:

- D_l = longitudinal dispersion coefficient (cm²/sec),
- v = interstitial velocity (cm/sec),
- L = core length (cm),
- C = concentration (mg/liter),
- C_i = initial concentration (fraction),
- C_0 = injected concentration (fraction),
- V = pore volume injected (cm³),
- V_p = one pore volume of the core (cm³).

In this method, the slope of the effluent breakthrough curve at one pore volume injected should be used in equation (4.1). Under ideal displacing conditions, the slope at one pore volume injected should be the maximum slope on the effluent breakthrough curve. Only material balance was considered when the C-D Equation was derived. In reality, many other factors could affect the dispersion of fluids in porous media. Hence, the S-shaped effluent breakthrough curves obtained from experiments always shifted up or down. Therefore, to be reasonable, the maximum slope on the effluent breakthrough curve was used in equation (4.1) to calculate the dispersion coefficients.

The results of the calculation with the two methods are provided in Table (4.4). To analyze the relationship between dispersion coefficient and displacement velocity, dispersion coefficients versus velocity were plotted on a cartesian plot as in Figure (4.21) through (4.25). It is observed from these plots that dispersion coefficients obtained from the curve matching method do not correlate well with velocities. One reason is probably because the consideration of the flow and boundary conditions for porous media in deriving the C-D Equation and its solution was based on an infinite boundary system but applied to a finite system.

Another reason is probably because of the mathematical problem in the program, because big differences were observed between the experimental curves and the fitted curves in some matching results. The analytical solution method expressed by equation (4.1) worked better than the curve matching method, as the dispersion coefficients obtained by this method had better correlations with velocities.

In liquid-liquid dispersion, higher dispersion coefficient corresponds to higher dispersion, while in gas-gas dispersion, higher dispersion coefficient corresponds to less dispersion. By observing equation (4.1), it is realized that the dispersion coefficient is a function of velocity and the square of maximum slope of S-shaped breakthrough curve. For liquid-liquid dispersion, the slope of S-shaped curve decreases with velocity, hence the dispersion coefficient increases with velocity. For gas-gas dispersion, the slope of the S-shaped breakthrough curve increases with velocity. The increase of velocity overrides the increase of slope, hence dispersion coefficient increases with velocity.

Dispersivity is considered to be a property of porous media. The following is a relationship between dispersivity, diffusion, and dispersion:

$$D_l = D_e + \alpha v \quad (4.2)$$

where:

D_l = longitudinal dispersion coefficient (cm^2/sec),
 D_e = effective molecular diffusion coefficient (cm^2/sec),
 α = dispersivity (cm).

For liquid-liquid dispersion, the molecular diffusion is assumed to be negligible or D_e is set equal to zero. Hence, dispersivity value for liquids is proportional to dispersion coefficient and inversely proportional to velocity.

In gas-gas dispersion, the effect of molecular diffusion is significant and assumed to be constant. In reality, it is a function of pressure and rock properties. The increase in pressure will decrease the diffusion of gases and the effective molecular diffusion coefficients. Rock heterogeneity will increase the diffusion of gases in porous media.

**Table (4.4) Dispersion Coefficients Calculated by CXTFIT
and Analytical Solution Method**

Core	P _i (psi)	ν (cm/sec)	D _i (CXTFIT) (cm ² /sec)	D _i (ASM) (cm ² /sec)
YF1	15.7	0.005056	0.03045	0.01598
	15.7	0.006955	0.04161	0.02149
	15.7	0.01542	0.05571	0.04260
	15.9	0.02700	0.07046	0.05375
YD6	15.2	0.003028	0.02948	0.01177
	15.2	0.006271	0.04439	0.02521
	15.2	0.01560	0.05166	0.04253
	16.7	0.03030	0.05896	0.04027
	15.2	0.04436	0.05696	0.05799
	15.2	0.06530	0.06522	0.06530
	15.2	0.007156	0.06332	0.03600
	15.2	0.01301	0.07000	0.05014
YA8	15.2	0.02881	0.07906	0.06883
	15.5	0.1044	0.07000	0.06543
	15.5	0.2125	0.06417	0.07216
	30.4	0.004729	0.05697	0.02704
	30.2	0.006335	0.05784	0.02574
	30.2	0.013180	0.06356	0.03841
	30.2	0.026470	0.05771	0.03996
	30.2	0.05735	0.06254	0.04079
	40.2	0.002152	0.08201	0.008686
	40.0	0.005737	0.03555	0.020810
	40.2	0.006820	0.05201	0.02419
	40.2	0.008154	0.07479	0.02602
	40.4	0.0102	0.06223	0.02937
	40	0.01882	0.03997	0.02747
	40	0.0906	0.0836	0.03029
	40	0.1353	0.04452	0.04074

The effective molecular diffusion coefficients can be obtained experimentally. However, an experimental apparatus different from the gas-gas dispersion experimental apparatus used in this study has to be developed. Hence, graphical method was proposed in this study. By plotting the first three dispersion coefficients under low velocities for each core as in Figure (4.26) through (4.30), it is observed that gas-gas dispersion coefficient is proportional to velocity at low velocities. The effective molecular diffusion coefficients were obtained by linear regression and extrapolation of the velocity to zero. The effective molecular diffusion coefficients are listed in Table (4.5).

Ali (1989) conducted gas-gas diffusion experiments on four types of sandstone outcrop and calculated the effective diffusion coefficients. The effective diffusion coefficient obtained from Ali's experiments on Berea sandstone was 0.0225 cm²/sec. It is close to the value of core YA8 at 15 psig, which is 0.02804 cm²/sec.

**Table 4.5 Effective Molecular Diffusion Coefficients
Obtained in This Study**

Core	Φ (%)	K (md)	P (psig)	D_e (cm ² /sec)
YF1	20.00	300	15	0.003409
YD6	17.89	97	15	0.007296
YA8	19.39	185	15	0.02804
			30	0.01831
			40	0.001535

As discussed above, high pressure reduces both molecular diffusion and effective molecular diffusion coefficients. By plotting the effective diffusion coefficients versus pressure for core YA8 as in Figure (4.31), it is observed that the effective molecular diffusion coefficient decreases with pressure.

For liquid-liquid dispersion, diffusion is considered negligible, so the effective molecular diffusion coefficient should be approximately zero. If the effective molecular diffusion coefficients are plotted versus the inverse pressure,

the effective molecular diffusion coefficient at $1/p$ equal to zero ($P_i = \text{infinite}$) should be approximately zero. This intersection point corresponds to the effective molecular diffusion coefficient of liquid. Figure (4.32) shows the result obtained in this study for core YA8. Only three points were obtained in this part of the study. The straight line shown in Figure (4.32) was obtained by linear regression analysis.

Using the effective molecular diffusion coefficients obtained above, and dispersion coefficients obtained by the analytical solution method, dispersivities were calculated. The results are listed in Table (4.6).

By plotting the dispersivities versus velocity as in Figure (4.33) through (4.35), it was concluded that dispersivity decreases with velocity for gas-gas dispersion under the experimental conditions of this study. It decreases more rapidly at low velocity than at high velocity. All of the points for three different pressures (15, 30 and 40 psig) almost follow the same curve in Figure (4.35) for core YA8 due to the small difference in pressures. By plotting the dispersivity versus velocity on log-log plot as in Figure (4.36) through (4.38), three approximate straight lines were obtained. The correlations between dispersivity and displacing velocity were obtained by using regression analysis.

Observing the equations (4.1) and (4.2), dispersivity is a function of the maximum slope on the S-shaped effluent breakthrough curve. The slope on the S-shaped breakthrough curve is a function of velocity, therefore dispersivity is also a function of velocity.

It is presumed that for gas-gas dispersion under a certain pressure, there will be a critical velocity, above which dispersivity increases with velocity, under which dispersivity decreases with velocity. When pressure is high enough, gas-gas dispersion will transform into liquid-liquid dispersion where diffusion is negligible, dispersivity will increase with velocity only.

4.5 Dispersion Factor

Li (1992) proposed a method to calculate dispersion factors in the study of the effect of scale on liquid-liquid dispersion. The dispersion factor was defined as Equation (4.3).

$$DF_{ML} = \frac{\left(\frac{V}{V_p}\right)_{50\%} - \left(\frac{V}{V_p}\right)_{15.9\%}}{\left(\frac{V}{V_p}\right)_{50\%}} \quad (4.3)$$

DF_{ML} = dispersion factor (dimensionless),

V = volume injected (cm^3),

V_p = one pore volume (cm^3),

$(V/V_p)_{50\%}$ = pore volume injected at 50% concentration (dimensionless),

$(V/V_p)_{15.9\%}$ = pore volume injected at 15.9% concentration (dimensionless).

The dispersion Factor above is a non-dimensional value from 0 to 1, which is directly proportional to the degree of dispersion. A value of zero is indicative of piston displacement without dispersion, while a value of one is indicative of infinitely high dispersion. The dispersion factor represents the spread of the mixing fluid in terms of the variation.

In order to apply equation (4.3) above to the data of this study, the S-shaped effluent breakthrough curves were plotted on lognormal probability papers. Equation (4.3) is applicable to the data set only if a straight line is obtained. Very good lognormal distribution curves were obtained in these plots.

The calculation results of dispersion factor are shown in Table (4.6). By plotting the dispersion factors versus the velocity on cartesian plots as in Figure (4.39) through (4.41), it was observed that the dispersion factor decreases with velocity just as dispersivity does. The correlations of dispersion factor and velocity in these figures were obtained by using regression analysis.

Combining the correlations of dispersivity and dispersion factor with velocity, the correlations of dispersivity and dispersion factor were obtained and shown in Figure (4.42) through Figure (4.44).

Table 4.6 Dispersivities and Dispersion Factors Obtained in This Study

Core	P_i (psi)	ν (cm/sec)	α (cm)	DF_{ML}
YF1	15.7	0.005056	2.4853	0.4984
	15.7	0.006955	2.5998	0.4831
	15.7	0.01542	2.5414	0.3911
	15.9	0.02700	1.8644	0.3096
YD6	15.2	0.003028	1.4783	0.5062
	15.2	0.006271	2.8565	0.4200
	15.2	0.01560	2.2570	0.3487
	16.7	0.03030	1.0882	0.2654
	15.2	0.04436	1.1428	0.2190
	15.2	0.06530	0.8883	0.2196
YA8	15.2	0.007156	1.1117	0.4886
	15.2	0.01301	1.6991	0.3081
	15.2	0.02881	1.4160	0.2228
	15.5	0.1044	0.3581	0.1134
	15.5	0.2125	0.2076	0.1619
	30.4	0.004729	1.8458	0.4000
	30.2	0.006335	1.1723	0.4709
	30.2	0.013180	1.5254	0.2659
	30.2	0.026470	0.8178	0.2045
	30.2	0.05735	0.3920	0.1436
	40.2	0.002152	3.3229	0.5065
	40.0	0.005737	3.3605	0.3412
	40.2	0.006820	3.3221	0.3235
	40.2	0.008154	3.0030	0.3193
	40.4	0.0102	2.7284	0.2895
	40	0.01882	1.3779	0.2189
	40	0.0906	0.3174	0.0922
	40	0.1353	0.2898	0.0816

CHAPTER V

ROCK CHARACTERIZATION

Reservoir heterogeneity is usually described by the permeability distribution in the reservoir. However, permeability is an averaged value obtained from core analysis or well testing. In addition, the existence of fractures and channels in reservoirs is another important cause of heterogeneity in reservoir rock. It is important to understand the heterogeneity of the reservoir in EOR processes.

5.1 Determination of the Pore Volume of Resident Fluid Displaced

Capillary pressure-saturation curves have been employed to represent what is termed the pore size distribution of porous media. The porous medium is imagined to be composed of a collection of "pores" having some distribution of radii. This simple definition contributed to our understanding of the part played by pore size in determining the characteristics of flow systems in porous media.

S-shaped breakthrough curves obtained from dispersion measurements can provide another approach to investigate the heterogeneity of reservoir rock. In an absolutely homogeneous reservoir, the effluent concentration curve should appear as a sharp-step change. However, smearing occurs at the breakthrough point due to mixing caused by non-uniform flow velocities within individual pores, which occurs during displacement. The concentration profile is strongly dependent upon the heterogeneity of reservoir rock. The earlier portion of the S-shaped curve represents the flow in pores with high conductivity, or the larger pores. The later portion of the curve represents the flow in pores with low conductivity, or the smaller pores. The slope in the middle portion of the curve is indicative of the theoretical considerations related to the heterogeneity of reservoir rock, or the pore size distribution.

Li (1992) proposed a capillary tube model to determine the pore size distribution using S-shaped breakthrough curves. The pore size distribution was modeled as a bundle of straight cylinder tubes with different radii. The flow in each tube was quantitatively evaluated using Poiseuille's equation:

$$Q_i = \frac{\pi r_i^4 \Delta p}{8 \mu L} \quad (5.1)$$

where,

Q_i = flowrate in a single tube (cm³/sec),
 r_i = radius of a flow tube (cm),
 Δp = pressure drop between the inlet and outlet of core (atm),
 μ = viscosity of fluid (cp),
 L = length of flow tube (cm).

The total flowrate of a bundle of tubes is:

$$Q_T = \sum_{i=1}^N \frac{\pi r_i^4 \Delta p}{8 \mu L} \quad (5.2)$$

where,

Q_T = total flowrate of the core (cm³/sec),
 N = total number of tubes in the porous media

It was assumed that the injection fluid breakthrough occurs first from the flow channel that has the largest flow radius. After the initial breakthrough, the tubes will produce injection fluid only.

Poiseuille's equation was applied to the miscible displacement of the injection fluid as:

$$Q_T C_n = \frac{\pi \Delta p}{8 \mu L} \sum_{i=1}^n r_i^4 \quad (5.3)$$

and for the displaced fluid:

$$Q_T (1 - C_n) = \frac{\pi \Delta p}{8 \mu L} \sum_{i=n+1}^N r_i^4 \quad (5.4)$$

where,

C_n = concentration of the injection fluid measured at outlet (%),
 n = number of tubes which are full of injection fluid,
 N = total number of flow tubes in porous media.

In dispersion measurement, the flowrate, Q_T , and pressure drop, Δp , are considered constant. If the viscosity of fluid and the length of core are known, the following calculation can be made:

$$\sum_{i=1}^n r_i^4 = \frac{8\mu L Q_T C_n}{\pi \Delta p} \quad (5.5)$$

The left side of equation (5.5) represents the sum of r_i^4 of the tubes that are full of injection fluid. It was assumed that for every increment of concentration, there is only one more tube, R_i , that contributes to the increment of flow of injection fluid through the porous media. In actuality, the tube R_i consists of many small tubes, but the number and the size of the tubes are not readily identifiable. The R_i , in fact, is the equivalent radius of a single tube, whose sectional area is equal to the sum of the sectional areas of many small tubes. The R_i can be

$$R_i^4 = \sum_{i=1}^n r_i^4 - \sum_{i=1}^{n-1} r_i^4 = \frac{8\mu L Q_T (C_n - C_{n-1})}{\pi \Delta p} \quad (5.6)$$

calculated using the following equation:

Therefore, the pore volume of resident fluid displaced by injection fluid between every concentration increment can be calculated as:

$$(PV)_i = \pi R_i^2 * L \quad (5.7)$$

The cumulative pore volume of resident fluid displaced by injection fluid at concentration C_n is:

$$\sum_{i=1}^n (PV)_i = \sum_{i=1}^n \pi R_i^2 * L \quad (5.8)$$

The concentration C_n can be read from the S-shaped breakthrough curves for each pore volume injected. If the cumulative pore volume displaced by injection fluid is plotted on a cartesian plot versus the concentration of displaced fluid at the outlet of the core, the slope of the curve can indicate the degree of

heterogeneity of the core. A core associated with a large slope is considered more homogeneous than a core with small slope. The difference in slope refers to more pore volumes of resident fluid being displaced between the same concentration increment. Therefore, the heterogeneity of the rock can be evaluated qualitatively with this method.

By plotting the pore volume of resident fluid displaced versus the effluent relative concentration for the three cores as in Figure (5.1), it was observed that only part of the pore volume contributes to the flow. For core YA8, the contribution was calculated to be 53%. For core YF1, the contribution was 41%. For core YD6, the contribution was only 27%. The difference in contribution explains why the three core have similar porosities, but very different air permeabilities.

The heterogeneity of the cores were analyzed using Figure (5.1). The higher slope at the earlier part of the curve indicates that the core has a higher percentage of large pores. A higher percentage of small pores is indicated if the later part of the curve has a higher slope.

In Figure (5.1), core YD6 has a low slope at both the earlier and later portion of the curve. The total flowing pore volume is also the smallest. This indicates that core YD6 has a poor flowing system, both high heterogeneous and low conductivity. Both highest slope and total flowing pore volume are observed for core YA8, which means that the core was more homogeneous than the other two cores and has a higher conductivity.

For core YF1, a lower slope at the earlier portion of the curve was observed, but a higher slope occurred at the later portion of the curve. This indicates that the core has a small percentage of big pores and a high percentage of small pores in the total pore volume. It is observed that core YF1 has the highest permeability, which was attributed to the heterogeneity of porous media.

Another reason for the high permeability observed may be due to the higher pressures used during the permeability measurements. Core YF1 has a fine flowing system or system composed of many small pores. Under higher pressure, gas has less freedom of movement and is compelled to flow through the small pores resulting in a large total flowing pore volume and a high permeability as observed.

5.2 Correlations of Dispersivity and Dispersion Factor

Chapter IV presented exponential correlations between dispersivity (α), dispersion factor (DF_{ML}) and velocity. [These correlations are of the form $Y=b.v^n$, see Figures (4.18) through (4.20) and (4.24) through (4.26)]. The values of the correlation coefficients and exponents are provided in Table (5.1). It appears that these coefficients and exponents are related to the effective diffusion coefficients, D_e .

Table (5.1) Correlation Coefficients and Exponents of α and DF_{ML}

Core	D_e	α		DF_{ML}	
	(cm ² /sec)	Coefficient	Exponent	Coefficient	Exponent
YF1	0.003409	1.1621	-0.1546	0.1141	-0.2854
YD6	0.007296	0.5234	-0.256	0.09627	-0.2905
YA8	0.02804	0.0777	-0.6658	0.03607	-0.4641

It is observed from Table (5.1) that the coefficients in the correlations for both dispersivity and dispersion factor are positive values; however, the correlation exponents are negative.

The effective diffusion coefficient for gas is a function of the core's geometry and physical properties. Heterogeneity are conducive to high molecular diffusion, hence, increasing the effective diffusion coefficients.

Figure (5.2) is a plot of the correlation coefficients versus the effective diffusion coefficients at 15 psig. Examination of this plot reveals that the correlation coefficients decrease at high effective diffusion coefficients. The correlation exponents also exhibit a decreasing trend with D_e as evidenced in Figure (5.3).

From the analysis of the presented data, one can conclude that cores with high effective diffusion coefficients will have low correlation coefficients and exponents. These parameters are, therefore, possible effective tools in characterization of reservoir rocks.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions were obtained from this study:

- (1) The experimental method and apparatus developed in this study for gas-gas dispersion measurement provides a simple and accurate way to study the dispersion phenomenon in porous media.
- (2) Under low pressures (15, 30, and 40 psig), increasing displacing velocity will decrease the dispersion of gases. Although not verified experimentally, a critical velocity exists below which the increase of velocity will decrease the dispersion and above which the dispersion of gas increases.
- (3) The increase in pressure will decrease the dispersion of gases.
- (4) Dispersivity is a function of displacing velocity, pressure and rock properties in gas-gas dispersion.
- (5) Dispersion Factor, DF_{ML} , is a reliable parameter for describing the dispersion of gas in porous media. It has a similar behavior to dispersivity.
- (6) The total flowing pore volume for a core can be determined by the method proposed in this study. In gas-gas displacement, only part of the total pore volume contributes to the fluid flowing in porous media.
- (7) The flow system and heterogeneity of a reservoir can be analyzed qualitatively by dispersion measurements.

5.2 Recommendations

Based on this study, future research work should be continued in the following respects:

- (1) Improved analytical model and theories of gas-gas dispersion need to be further developed.
- (2) Gas-gas dispersion experiments with consolidated porous media under high pressure and velocities should be conducted to demonstrate the existence of the critical velocity.
- (3) Experiments should be conducted on several cores to characterize reservoir rocks by gas-gas dispersion measurements. The tested cores should have the same lengths and diameters to eliminate the effect of scale.
- (4) The effect of gravity on gas-gas dispersion should be considered. Vertical displacement can be conducted to study this effect.
- (5) The experimental apparatus can be improved by using a better and more accurate method to measure the flow rates of gas. A computer program should be developed to process the experimental results.

NOMENCLATURE

a	mixing coefficient (dimensionless)
A	cross sectional area of the core or diffusion (cm^2)
C	concentration (mg/liter)
C_i	initial concentration (fraction)
C_o	injected concentration (fraction)
d_p	particle diameter (cm)
D	tensor formulation of dispersion coefficient (cm^2/sec)
D_e	effective molecular diffusion coefficient (cm^2/sec)
D_l	longitudinal dispersion coefficient (cm^2/sec)
D_o	molecular diffusion coefficient (cm^2/sec)
DF_{ML}	dispersion factor (dimensionless)
F	formation factor (dimensionless)
L	core length (cm)
m	mixing exponent (dimensionless)
n	mass of material diffusing across a plane (mg)
N	total number of the tubes in porous media
P_e	Peclet number (dimensionless)
P_i	inlet pressure (atm)
P_o	outlet pressure (atm)
Δp	pressure drop between the inlet and outlet of core (atm)
Q_i	flowrate in a single tube (cm^3/sec)
Q_T	total flowrate of the core (cm^3/sec)
r_i	radius of a flow tube (cm)
R_i	equivalent radius of tube for a concentration increment (cm)
t	time (sec)
T	time required to inject or produce one pore volume of fluid (sec)
u	Darcy velocity (cm/sec)
v	interstitial velocity (cm/sec)
V	pore volume injected (cm^3)
V_p	one pore volume of the core (cm^3)
X	distance (cm)
α	dispersivity (cm)
μ	viscosity of fluid (cp)
ρ	density of fluid (gm/cm^3)
σ	packing, or inhomogeneity, factor (dimensionless)
τ	tortuosity (dimensionless)
ϕ	porosity (fraction)

REFERENCES

- Ali, Liaqat, "Quantitative Evaluation of High Rate Flow in Porous Media", Master's Thesis, University of Oklahoma, Norman, 1989.
- Aronofsky, J.S., and Heller, J.P., "A Diffusion Model to Explain Mixing of Flowing Miscible Fluids in Porous Media", Petroleum Transactions, AIME, Vol. 210, 1957, pp. 345-349.
- Arya, A., Hewett, T.A., Larson, R.G., and Lake, L.W., "Dispersion and Reservoir Heterogeneity", SPE Reservoir Engineering, February 1988, pp. 139-147.
- Bailey, R.H., and Gogarty, W.B., "Diffusion Coefficients from Capillary Flow", Society of Petroleum Engineers Journal, September 1963, pp. 256-266.
- Baker, L.E., "Effects of Dispersion and Dead-End Pore Volume in Miscible Flooding", Society of Petroleum Engineers Journal, June 1977, pp. 219-227.
- Blackwell, R.J., Ramey, J.R., and Terry, W.M., "Factors Influencing the Efficiency of Miscible Displacement", Paper presented at the 33rd Annual Fall Meeting of Society of Petroleum Engineers in Houston, TX., Oct. 5-8, 1958, pp. 197-201.
- Bear, J., "Some Experiments in Dispersion", Journal of Geophysical Research, Vol. 66, No. 8, August 1961, pp. 2455-2467.
- Bear, J., "Dynamics of Fluids in Porous Media", Dover Publications, Inc., New York, 1972.
- Blatz, S.K.H., "Transient Flow Through Porous Media", Master's Thesis, University of Oklahoma, Norman, 1988.
- Brigham, W.E., Reed, P.W., and Dew, J.N., "Experiments on Mixing During Miscible Displacement in Porous Media", Society of Petroleum Engineers Journal, March 1961, pp. 1-8.

Brigham, W.E., "Mixing Equation in Short Laboratory Cores", Society of Petroleum Engineering Journal, Feb. 1974, pp. 91-99.

Carman, P.C., "Flow of Gases Through Porous Media", Academic Press Inc., New York, 1956.

Chandrasekhara, B.C., Rudraiah, N., and Nagaraj, S.T., "Velocity and Dispersion in Porous Media", Engineering Science, Vol. 18, 1980, pp. 921-929.

Chen, Shixin, "Investigation of Dispersivity as a Reservoir Rock Characteristic and Its Determination From Well Logs", PhD Dissertation, University of Oklahoma, Norman, 1991.

Coats, K.H. and Smith, B.D., "Dead-End Pore Volume and Dispersion in Porous Media", Society of Petroleum Engineers Journal, Vol. 4, March 1964, pp. 73-84.

Cunningham, R.E. and Williams, R.J.J., Diffusion in Gases and Porous Media, Plenum Press, New York, 1980.

David, D.J., Gas Chromatograph Detectors, John Wiley & Sons, New York, 1974.

Deans, H.A., "A mathematical Model for Dispersion in the Direction of Flow in Porous Media", Society of Petroleum Engineers Journal, March 1963, pp. 49-52.

Dullien, F.A.L., Porous Media: Fluid Transport and Pore Structure, 2nd ed. Academic Press, Inc., San Diego, California, 1992.

Dutta, S., "An Experimental Investigation of Dispersivity and its Role as an Oil Reservoir Rock Property", Master's Thesis, University of Oklahoma, 1984.

Greenkorn, R.A., Flow Phenomena in Porous Media, Marcel Dekker, Inc., New York, 1983.

Guiochon, G. and Guillemin, C.L., Quantitative Gas Chromatograph, Elsevier Science Publishing Company Inc., New York, 1988.

Harleman, D.R.F., Mehlhorn, P.F., and Rumer, R.R., "Dispersion-Permeability Correlation in Porous Media", *Journal of the Hydraulics Division*, March 1963, pp. 67-85.

Hetherington, Charlee Ray, "The Unsteady Flow of Natural Gas Through Porous Media", Master's Thesis, University of Oklahoma, Norman, 1941.

Hurst, William, Advances in Petroleum Engineering, Pennwell Publishing Co., Tulsa, Oklahoma, 1981.

Khan, Abdul Raoof, "Laboratory Investigation of Linear Unsteady-State Gas Flow Through Porous Media Including the Effect of Non-Darcy Flow", Master's Thesis, University of Oklahoma, 1967.

Legatski, Max W., and Katz, Donald L., "Dispersion Coefficients for Gases Flowing in Consolidated Porous Media", Society of Petroleum Engineers Journal, March 1967, pp. 43-53.

Li, Y., "An Experimental Study of Dispersion Characteristics in Consolidated Porous Media and The Determination of The Flow Characterization in Miscible Displacement Flooding", PhD Dissertation, University of Oklahoma, Norman, 1992.

Menzie, D. and Dutta, S., "Dispersivity as an Oil Reservoir Rock Characteristic", Final Report to the Department of Energy, DOE/BC/10851/15, University of Oklahoma, December 1989.

Menzie, D., "Study of Dispersion Characteristics in Consolidated Porous Media and Determination of the Flow Characterization", Annual Report to the Department of Energy, DOE/BC/14652.000, University of Oklahoma, October 1992.

Mertz, V., "Mixing of Gases in Porous Media", Master's Thesis, University of Oklahoma, Norman, 1941.

Millheim, K., "An Experimental Study of Linear Unsteady State Gas Flow Through Low Permeability Porous Media", Master's Thesis, University of Oklahoma, Norman, 1964.

Novak, J., Quantitative Analysis by Gas Chromatograph, 2nd. ed. revised, Marcel Dekker, Inc., New York, 1988.

Parker, J. C. and Genuchten, M. Th. van, Determination Transport Parameters from Laboratory and Field Tracer Experiments, Virginia Agricultural Experiment Station, Virginia Polytechnic Institute and State University, 1984.

Perkins, T.K., "A Review of Diffusion and Dispersion in Porous Media", Society of Petroleum Engineers Journal, March 1963, pp. 70-84.

Poulin, T. J., "The Determination of the Coefficient of Dispersion in Sandstones", Master's Thesis, University of Oklahoma, Norman, 1985.

Sandrea, R., Dynamics of Petroleum Reservoirs Under Gas Injection, Gulf Publishing Company, Houston, Texas, 1974.

Scheidegger, Adrian.E., The Physics of Flow Through Porous Media, University of Toronto Press, 1960.

Scheidegger, A.E., "General Theory of Dispersion in Porous Media", Journal of Geophysical Research, Vol.66, No. 10, October 1961, pp. 3273-3270.

Shadizadeh, S. R., "An Experimental Investigation of the Dependence of Dispersion on Flow Parameters and Porous Media Properties During Solute Transport Through Consolidated Porous Media Independent of Fickian Assumptions", PhD Dissertation, University of Oklahoma, Norman, 1991.

Schmidt, C.D., "Mixing of Gas in Porous Media", Master's Thesis, University of Oklahoma, Norman, 1940.

Warner, M. J., "Characterizing Reservoir Core Samples and Measuring The Dispersion Coefficient Through Miscible Displacement Experiments", Master's Thesis, University of Oklahoma, Norman, 1987.

Youngquist, G.S., "Diffusion and Flow of Gases in Porous Solids", Flow Through Porous Media, American Chemical Society Publications, Washington, D.C., 1970, pp. 57-69.

Figure 2.1 Relationship Between Molecular Diffusion and Convection Dispersion
(from Pfannkuch, 1962)

Figure 3.1 Experimental Apparatus for Gas-Gas Dispersion

Figure 3.2 Schematic Diagram of Core Holder Assembly

Figure 3.3 Calibration Curve of Gas Chromatograph

Figure 3.4 Flow Chart of Experimental Procedures for Gas-Gas Dispersion

Figure 3.5 Recording of Effluent Concentration by Chart Recorder

Figure 4.1 Relation of Air Permeability and Porosity of the Tested Cores

Figure 4.2 Experimental Breakthrough Curves Under Different Pore Velocities for Core YF1 ($P_i=15$ psig)

Figure 4.3 Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YF1 ($P_i=15$ psig)

Figure 4.4 Experimental Breakthrough Curves Under Different Pore Velocities for Core YD6 ($P_i=15$ psig)

Figure 4.5 Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YD6 ($P_i=15$ psig)

Figure 4.6 Experimental Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=15$ psig)

Figure 4.7 Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=15$ psi)

Figure 4.8 Experimental Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=30$ psig)

Figure 4.9 Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YA8($P_i=30$ psig)

Figure 4.10 Experimental Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=40$ psig)

Figure 4.11 Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=40$ psig)

Figure 4.12 Experimental Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=40$ psig)

Figure 4.13 Rate of Concentration Change of the Breakthrough Curves Under Different Pore Velocities for Core YA8 ($P_i=40$ psig)

Figure 4.14 Effect of Pressure on Gas-Gas Dispersion for Core YA8

Figure 4.15 Comparison of Breakthrough Curves of Gas-Gas Dispersion with Liquid-Liquid Dispersion for Core YF1

Figure 4.16 Comparison of Breakthrough Curves of Gas-Gas Dispersion with Liquid-Liquid Dispersion for Core YD6

Figure 4.17 Comparison of Breakthrough Curves of Gas-Gas Dispersion with Liquid-Liquid Dispersion for Core YA8

Figure 4.18 Comparison of Experimental and Fitted Breakthrough Curve for Core YF1 ($P_i=15$ psig)

Figure 4.19 Comparison of Experimental and Fitted Breakthrough Curve for Core YD6 ($P_i=15$ psig)

Figure 4.20 Comparison of Experimental and Fitted Breakthrough Curve for Core YA8 ($P_i=15$ psig)

Figure 4.21 Dispersion Coefficient Versus Pore Velocity For Core YF1 ($P_i=15$ psig)

Figure 4.22 Dispersion Coefficient Versus Pore Velocity
For Core YD6 ($P_i = 15$ psig)

Figure 4.23 Dispersion Coefficient Versus Pore Velocity
For Core YA8 ($P_i = 15$ psig)

Figure 4.24 Dispersion Coefficient Versus Pore Velocity
For Core YA8 (Pi=30 psig)

Figure 4.25 Dispersion Coefficient Versus Pore Velocity
For Core YA8 (Pi=40 psig)

Figure 4.26 Obtaining the Effective Diffusion Coefficient by the Dispersion Coefficients Under Low Velocities for Core YF1 ($P_i=15$ psig)

Figure 4.27 Obtaining the Effective Diffusion Coefficient by the Dispersion Coefficients Under Low Velocities for Core YD6 ($P_i=15$ psig)

Figure 4.28 Obtaining the Effective Diffusion Coefficient by the Dispersion Coefficients Under Low Velocities for Core YA8 (Pi=15 psig)

Figure 4.29 Obtaining the Effective Diffusion Coefficient by the Dispersion Coefficients Under Low Velocity for Core YA8 (Pi=30 psig)

Figure 4.30 Obtaining the Effective Diffusion Coefficient by the Dispersion Coefficients Under Low Velocity for Core YA8 ($P_i=40$ psig)

Figure 4.31 Effect of Pressure on Effective Diffusion Coefficient of Gas

Figure 4.32 Effective Diffusion Coefficient Versus Inverse Injection Pressure Measured on Core YA8

Figure 4.33 Dispersivity as a Function of Pore Velocity for Core YF1 ($P_i=15$ psig)

Figure 4.34 Dispersivity as a Function of Pore Velocity for Core YD6 (Pi=15 psi)

Figure 4.35 Dispersivity as a Function of Pore Velocity for Core YA8

Figure 4.36 Dispersivity as a Function of Pore Velocity for Core YF1 on Log-Log Plot (Pi=15 psig)

Figure 4.37 Dispersivity as a Function of Pore Velocity for Core YD6 on Log-Log Plot (Pi=15 psig)

Figure 4.38 Dispersivity as a Function of Pore Velocity for Core YA8 on Log-Log Plot (Pi=15, 30 , 40 psig)

Figure 4.39 Dispersion Factor as a Function of Pore Velocity for Core YF1 (Pi=15 psig)

Figure 4.40 Dispersion Factor as a Function of Pore Velocity
For Core YD6 ($P_i = 15$ psig)

Figure 4.41 Dispersion Factor as a Function of Pore Velocity
For Core YA8

Figure 4.42 Relationship of Dispersivity and Dispersion Factor for Core YF1 (Pi=15 psig)

Figure 4.43 Relationship of Dispersivity and Dispersion Factor for Core YD6 (Pi=15 psig)

Figure 4.44 Relationship of Dispersivity and Dispersion Factor for Core YA8

Figure 5.1 Pore Volume of Resident Fluid Displaced versus Effluent Relative Concentration

Figure 5.2 Correlation Coefficient of Dispersivity and Dispersion Factor versus Effective Diffusion Coefficient

Figure 5.3 Correlation Exponent of Dispersivity and Dispersion Factor versus Effective Diffusion Coefficient

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