

EXPERIMENTAL DETERMINATION OF STEAM WATER RELATIVE  
PERMEABILITY RELATIONS

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Willis J. Ambusso

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## Abstract

A set of relative permeability relations for simultaneous flow of steam and water in porous media have been derived from experiments conducted under conditions that eliminate most errors associated with saturation and pressure measurements. These relations show that the relative permeability for steam phase in porous media varies linearly with saturation. The liquid phase, however shows a variation close to that observed by Corey (1954) in water/gas experiments. This departure from the nitrogen/water behavior indicates that there are fundamental differences between steam/water and nitrogen/water flows.

The saturations in these experiments were measured by using a high resolution X-ray computer tomography (CT) scanner. In addition the pressure gradients were obtained from accurate measurements of liquid phase pressure over portions with flat saturation profiles. These two aspects constitute a major improvement in the experimental method compared to those used in the past.

Comparison of the saturation profiles measured by the X-ray CT scanner during the experiments shows good agreement with those predicted by numerical simulations. To obtain results that are applicable to general flow of steam and water in porous media similar experiments should be done at higher temperature and with porous rocks with different wetting characteristics and porosity distribution.

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# Chapter 1

## Introduction

Application of Darcy's law to the description of simultaneous flow of two or more phases of fluids in a porous medium requires the use of relative permeability relations (Hassler et al., 1936; Osoba et al., 1951; Corey, 1954; Brooks and Corey, 1964). In most applications in petroleum engineering such as those involving the flow of oil and water as in water flooding and oil and gas as in gas injection, these relations are well known and can be determined from routine laboratory experiments (Osoba et al., 1951). However, for the flow of steam and water or for the general case of single component two-phase flows these relations are not well known. To our knowledge, no single set of relations among the many that have been reported in the last few decades are known to be error free (Verma, 1986; Sanchez et al., 1980; Clossman and Vinegar, 1988). The main difficulties in these experiments, as we show later, have been due to inaccurate measurements of fluid saturations and inappropriate assignment of pressure gradients. Other techniques involving analysis of enthalpy transients from producing geothermal fields have been used to

infer relative permeability relations (Grant, 1977; Sorey et al., 1978; Horne and Ramey, 1978). However these techniques do not eliminate all the variables and quite often the in-situ fluid saturations and the overall permeability structure (i.e matrix, fracture) are unknown. These curves are therefore at best good approximations.

As shown by experiments by Osoba et al. (1951) and Hassler et al. (1936), laboratory measurements of relative permeability can still have error if capillary end-effects are not taken into account. The end-effects are known to cause pressure gradients and by extension saturation gradients resulting in nonuniform distribution of fluids in the core particularly at low flow rates. Ignoring this effect may result in underestimating the relative permeability of the wetting phase and attributing a permeability value for the non-wetting phase to a wrong saturation (Verma, 1986). Though this type of error can be avoided for two-phase two-component flows under isothermal conditions, all of the experiments meant to determine steam and water relative permeability relations reported in the past have not been able to eliminate these errors for two main reasons; 1) measurements of fluid saturations are not easy since the phase change with pressure drop along the core implies that the material balance methods used in isothermal cases are inapplicable, and 2) the changing pressure gradients along the core due to the combined effect of the end-effects and changing flowing fractions with phase change generally imply that any average pressure gradient measurement across the core would be different from the actual gradients at points along the core.

In the experiments reported here the errors discussed above have been reduced significantly by using X-ray computer tomography (CT) to measure fluid saturations and by using pressure gradients from zones with constant fluid saturations to compute the relative permeability relations. The CT scanner is an adaptation of the X-ray equipment used conventionally in hospitals for examining internal parts of human body. Through manipulation of images taken by this equipment it is possible to determine the fluid saturations to an accuracy of a few percent and this has been done successfully in experiments involving other fluids in porous media (Johns et al., 1993; Satik et al., 1995). Another advantage of using the CT scanner is that it enables the internal structure of the porous material to be examined for variations in porosity and also the examination of the fluid distribution within the core. It is therefore possible to investigate samples of porous material for homogeneity and evaluate flow experiments for fluid segregation, channeling e.t.c. By measuring the pressure of one phase at various points along the core it is possible to eliminate the errors involved in assigning wrong pressure gradients to the flowing components by using only the intervals over which the saturations are constant for calculating relative permeability. In this work it was not possible to conduct the experiments under adiabatic conditions as the CT scanner imposes limits on the kind of materials that can be used thus effectively eliminating the use of guard heaters. However, heat losses were minimized by using a thick layer of high performance ceramic insulation material. In addition heat losses from the core were measured at several points using heat flux sensors.

However a number of issues had to be resolved before the experiments could be performed. Among many other issues, constructing a core holder that could be used in the X-ray CT scanner was a challenging task. Using high density materials in the scanning area is unacceptable since such materials form artifacts in the images and which lead to errors in saturation measurements. Numerical simulations were carried out to determine the optimum experimental conditions. This included determining the appropriate core length, the effect of heat losses and the time required for steady state conditions to be reached.

This report therefore begins by looking at the origins and the concept of relative permeability. Following this our experimental approach is described together with the conditions that have to be met in order to overcome some of the errors associated with laboratory measurements. Next the results of the numerical investigations are presented followed by a chronology of the design and construction of the core holder. The last two sections then present the experimental investigations and a discussion of the results.



# Chapter 2

## The Concept and Previous Work

### 2.1 The Concept of Relative Permeability

The concept of relative permeability is an attempt to extend Darcy's law for single phase flow of fluid through porous media to account for simultaneous flow of several phases. In this regime the flow of each phase is governed by the microscopic pressure gradient of each phase and the fraction of the overall permeability that is associated with it. This fraction, normally expressed as a fraction of the medium's permeability to single phase fluid normally the wetting phase, is called the relative permeability. Since being introduced by Buckingham in 1907 and used extensively by investigators in the 1930's relative permeability has been expressed as a function of saturation principally because it was believed that it depended on the pore volume occupied by the fluids (Hassler et al., 1936). Whereas a great many experiments

have shown this to be true, a number of other experiments have shown that relative permeability depends on several other parameters among them interfacial tension, wetting characteristics and viscosity ratios of the flowing fluids (Fulcher et al., 1983; Osoba et al., 1951). Since these parameters are expected to change with the type of fluid, porous media and even with temperature, it should be expected that relative permeability would change for a given set of materials and experimental conditions.

Relative permeability is a manifestation of microscopic forces and physical factors governing pore level movement and distribution of fluids. Whenever two or more phases are present within the pore space, their distribution is governed by the balance of capillary forces between fluid components and the rock, and by the wetting characteristics of the rocks. These two forces coupled with inertial forces due to pressure gradients combine to determine how easily each phase moves within the porous material, hence the concept of relative permeability. Though the physics of pore level processes is well understood, understanding the problem of multiphase flow based on this is difficult since it requires a complete description of the pore structure. For two-phase single component systems as in steam water flows the problem is more difficult because of phase change. This implies that the thermodynamic state of the fluids, in the form of chemical potential, must be taken into account for a complete description of the flow regime. This is impractical for most applications.

Relative permeability relations are usually reported as functions showing

the variation of the relative permeability as a function of the saturation of the fluid. In addition it is necessary to define residual saturations which normally indicate the smallest saturation for a given phase to become mobile. The curves and the residual saturations together define the relative permeability relations. For most cases these relations can be expressed as simple mathematical functions (Corey, 1954; Brooks and Corey, 1964)

Generally, relative permeability curves are used for calculating the rates of flow of fluids in porous media. In geothermal applications, the effective viscosity and the enthalpy of flowing fluids can be shown to depend on the relative permeability as given by the following equations,

$$\frac{1}{\nu_t} = \frac{k_{rl}}{\nu_l} + \frac{k_{rv}}{\nu_v} \quad (2.1)$$

$$h_f = \nu_t \left( h_l \frac{k_{rl}}{\nu_l} + h_v \frac{k_{rv}}{\nu_v} \right) \quad (2.2)$$

where  $\nu$  is kinematic viscosity  $k_{rl}$  and  $k_{rv}$  are the the relative permeability coefficients for the liquid and steam phase, respectively.

Numerical studies by Bodvarsson et al. (1980) on the dependence of viscosity and enthalpy on the relative permeability relations used have shown that the two parameters have a strong dependence on the relations used and show a large variation in value between the Corey and the linear relative permeability curves. Similar studies on the sensitivity of the same parameters

on the value of residual saturations by Reda and Eaton (1980) have shown that there is an equally strong dependence of effective viscosity and enthalpy on the relative permeability. Thus, the use of correct relative permeability functions and residual limits is important in the evaluation of parameters involving the two-phase flow of water and steam.

## **2.2 Literature Review**

Relative permeability relations reported in the past have been from two main sources, 1) laboratory experiments performed by injecting either single or two phase fluids through small cores or models, and 2) theoretical methods using either field data from well tests or production histories of the wells in producing fields.

Relative permeability relations derived from field data have generally been obtained by matching enthalpy data (Grant, 1977; Sorey et al., 1978; Horne and Ramey, 1978). In deriving these relations the reservoir is normally treated as a porous medium. The enthalpy is then determined as a function of in-situ fluid saturations which have to be estimated from the flowing fractions. These models generally suffer from a number of short comings due to the assumptions used, the first of which is the porous medium assumption on which the equations for solving for enthalpy are based. Most reservoirs are known from independent data to be extensively fractured and therefore the enthalpy transient models on which the relations are derived are only

approximate. Secondly, these methods calculate the effective relative permeability relations from the effective viscosity as a function of the enthalpy and saturations are calculated only indirectly from the enthalpy. This can not be verified independently. Thirdly, saturation estimates are averaged over the entire reservoir which may have spatial variation. Finally, scatter in field data require that a large set of data be collected and curve-fitting techniques be used to obtain a reliable relation from the data. In general these relative permeability relations are prone to error.

As discussed by Heiba et al. (1983), experiments are the most reliable method to determine relative permeability. However, laboratory techniques suffer from limitations imposed by boundary effects caused by capillary forces. Capillarity introduces nonlinear effects on the pressure and saturation distribution of the wetting phase at the core exit. Thus experiments must be designed carefully to eliminate these effects. Osoba et al. (1951) have given a summary of the methods used to obtain relative permeability for two component systems that eliminate or minimize such effects and that have been used successfully in problems of oil and gas. These are reviewed below;

#### i) Penn State Method

In this method the sample being tested is held between two samples of similar material and the two-phase mixture of a given composition is injected through the set. The test sample and the other two pieces need to be in capillary contact. The assumption is that the capillary effects will be limited to the two pieces external to the test material and thereby eliminate

the end-effect. Measurements of pressure and saturation can then be made on the sample and the relative permeability can be determined. Though this method has been used successfully in oil-water systems, it requires more sophisticated equipment to be used for steam water flows where thermal equilibrium is important. In addition it is not always possible to ensure capillary continuity which would lead to errors if not recognized during experiments.

#### ii) Stationary Liquid Method

In this method the liquid phase is held stationary by the use of a very low pressure gradient across the core. Under very low pressure gradients capillary forces would dominate the flow of liquid phase and therefore the liquid phase would be retained within the core. The permeability of the gas phase is then determined for the given saturation of the liquid phase. By flooding the core with increasing liquid saturation, a curve can be generated. This method has never been applied to steam and water as the small gradients are not easy to generate in practical situations. Furthermore injecting steam into a two-phase system and expecting it to remain in the gas phase throughout the period of flow across the core is not feasible.

#### iii) Single Core Dynamic Method

This is the method most frequently used and involves injecting both phases simultaneously at a rate high enough to avoid the end-effects. The method is effectively the Penn State method with only one core. Unlike the former method the samples in this case have to be long enough and the flow rate high enough to avoid the end-effects. By changing the proportions of the flu-

ids being injected a complete relative permeability curve can be generated. However the two requirements are rarely met and this has lead to significant errors in results that have been reported in the past (Verma, 1986).

#### iv) Other Methods

Other methods include the gas drive and Hassler methods. In the first gas is injected into a core completely saturated by wetting phase and measurements of flowing fractions, pressure gradient and wetting phase saturations provide a relative permeability curve. This has to be done gradually to avoid viscous fingering while measurements are taken at each stage. Though applicable to oil-gas systems this method can not be used for steam and water as isothermal thermodynamic conditions are impossible to maintain and phase change will occur even with small changes in pressure. In the Hassler method, capillary end-effects are circumvented by ensuring similar end-effects on both ends of the core. As in the gas drive approach this method is not readily applicable to steam and water.

Given the difficulties with the other methods, it is not surprising that the method used by most investigators has been the single core dynamic method since it allows better experimental control. This was the method selected for the experiments reported here. However this method does not completely eliminate the end-effects. A review of the previous work shows that most of them did not completely address the issue of end-effects.

Capillary pressure effects can be overcome by use of sufficiently long cores or

by use of high injection rates (Osoba et al., 1951). Our experience shows that even conducting experiments at some rates referred to as high in published literature still leaves substantial end-effects. Thus taking pressure gradients across the core and averaging the saturation over the entire core still leads to errors in computing relative permeability.

The second most common source of error has been the determination of saturation. A number of techniques have been reported, yet each can be shown to have difficulties of some kind when applied to steam-water flow.

One of the earliest attempts to measure relative permeability relations for single component two-phase flow was reported by Miller (1952). The experiments used propane injected as liquid at the core inlet. Propane was allowed to flash as it moved across the core thus creating a two-phase flow with increasing gas fraction as the fluid moved further downstream. From the pressure and temperature measurements along the core and application of material and energy balance it was possible to determine the flowing fractions at each point and therefore to estimate the relative permeability relations. Though the results were too general to be applicable to the flow of steam and water, it is not clear whether capillary end-effects were adequately eliminated. Furthermore, the calculated saturation could not be checked by other independent means.

Among the first attempts to measure saturations directly were those reported by Chen (1978) and Council (1979) using a capacitance probe. In this tech-



nique determined the saturation from a calibration based on the relation between the capacitance and the saturation within the core (Council, 1980). However the margin over which readings were obtained was small and thus these studies did not obtain reliable relative permeability relations. Chen et al. (1979) recommended the use of gamma-ray densitometer for measuring saturations. Verma(1985) used a gamma-ray densitometer for experiments using an artificial sand pack. Though this was an improvement over the capacitance probe, the portion of the sample accessed by the densitometer was small (5%). Problems with overheating of the equipment during the experiments resulted in only a small part of the relative permeability curve being investigated and created the impression of high residual saturations. In addition, fluid bypass between the core holder and the sand pack was suspected to contribute to the larger steam relative permeability obtained in the experiments.

Sanchez et al. (1988) reported the use of average recovery time of a tracer injected with the fluid to determine the saturation of water in the core. In the experiments, pressure was measured at only two points a short way from either end, effectively ignoring capillary end-effects. The mean residence time ( $t_r$ ) of the tracer was given by,

$$t_r = \frac{\int_0^{\infty} c(t)tdt}{\int_0^{\infty} c(t)dt} \quad (2.3)$$

where  $c(t)$  is the measured tracer concentration as a function of time. Then the average saturation for the liquid phase is given by,

$$S_w = \frac{q_l t_r}{V_p} \quad (2.4)$$

where  $q_l$  and  $V_p$  are the liquid phase flow rate and porous media pore volume, respectively. Equation (2.4) gives the average water saturation over the whole core and ignores the variations in saturation expected from the capillary end-effects at low flow rates. In addition, the pressure drops reported by Sanchez et al. (1988) over the interval of 50 cm are about 0.3 bars and phase change due to the pressure drop alone even in the absence of capillary end-effects would lead to a saturation gradient along the core. It is therefore possible to question the accuracy of these results.

Clossman and Vinegar (1988) are probably the first investigators to report the use of computer tomography scanner to measure water and steam saturations in porous materials. They investigated steam-water relative permeability in cores from oil fields at residual oil saturations. The cores used for the experiments were rather small i.e., 6.06 inches in maximum length and 0.973 inches in diameter. The flow rates were also moderate, 3.31 cc/min to 20 cc/min. Steam quality was determined from two temperature measurements at the inlet and exit. The same readings were used to estimate heat losses from the core. Relative permeability relations were calculated from pressure measurement at the same points. Temperatures were not measured along the core but the distribution within the core was assumed to vary in three possible ways, linear, quadratic and constant. The core was enclosed in an aluminum sleeve kept under vacuum conditions. The relative permeability

values for the steam phase were close to those reported by Brooks and Corey (1964) but those for the liquid phase were somewhat smaller.

Though it is not clear how much each of the assumptions contributed to the final curves, Clossman and Vinegar (1988) did not investigate the influence of capillary end-effects which were bound to be significant because of the core lengths and flow rates used. Secondly, it is probably inaccurate to assume that the temperature within the core would vary in the manner assumed in their calculations. In two-phase systems, temperature and pressure are coupled by the Clausius-Clapeyron equation and depend on the capillary end-effects, giving rise to temperature variations that are highly nonlinear and not quadratic. Thus the agreement between results obtained by the authors with those obtained by Corey (1954) is might be mere coincidence.

More recently Piquemal (1994) has reported relative permeability relations for steam and water using methods similar to those used by Verma (1986). The porous medium was an unconsolidated material packed in a tube 250 mm long and with an internal radius of 50 mm. Pressure and temperature were measured at four points 50 mm apart along the core holder. The injection rates were from  $10^{-4}$  to  $10^{-3}$  kg/s (6.0 to 60.0 gm/min). The experiments were done at 180°C. Though Piquemal (1994) does not report any errors in his measurements, it is unlikely that the experiments were able to successfully overcome the problems reported by Verma(1986) who used a similar apparatus. The problems include limitations on saturation measurement by the gamma-ray densitometer and steam by-pass between the porous medium

and the core holder. It is important to notice that the results reported by Piquemal (1994) are different from those obtained by Verma(1986) who observed enhanced permeability of the steam phase. Piquemal(1994) obtained results showing that steam-water flows are similar to nitrogen-water.

The foregoing review shows that there is a wide range of results that have been reported, some of them using similar experimental apparatus. The main reason for this has been difficulties in saturation measurement and use of incorrect pressure gradients to compute relative permeability. The investigations reported here overcame these difficulties by using the X-ray CT scanner for measuring saturation and by evaluating pressure gradients from the pressures from zones with constant saturation only. In the remaining sections of this report we discuss the design and the outcome of the experiments.

## Chapter 3

# Numerical Simulation

This section discusses the theoretical and experimental aspects of this investigation. Numerical simulations were carried out to determine the optimum dimensions of the core required to overcome capillary end-effects and to evaluate the effect of injection rates and gas fractions on the results. The effects of heat losses on the temperature, pressure and saturation measurements were also evaluated. In addition the numerical simulations were used to estimate the time required for the experiments to reach state conditions.

The STARS software was used for the numerical investigation. This program is a multicomponent thermal simulator specifically designed to handle heavy oil operations such as surfactant flooding, steam injection and in-situ combustion in single and dual porosity media, and fractured reservoirs. The simulator has capabilities that enable it to handle individual hydrocarbon and hydrophilic components in flows that involve exchange of components between phases. Three main aspects were investigated; the effect of the type

of relative permeability curves, the effect of flow rates and flowing fractions on pressure, temperature and saturation and the effect of heat losses on fluid distribution along the core and fluid segregation due to the combined effects of gravity and condensation.

Several methods of investigation were used. In all cases the overall dimensions of the models were similar to those used for the experiments i.e, a 2.0 inch diameter and 17.0 inch long core. A permeability of 600 millidarcy was used and a value of 20% was used for the porosity. The injection and production points were fixed at the centers of the end plates. In each case the parameters of interest were saturation, pressure and temperature.

### **3.1 Relative Permeability Curves**

The relative permeability curves used for the simulations were the widely used Corey (1954) and Linear curves together with those derived by Verma (1986). The curves reported by Verma(1986) were of particular interest since these curves represent a more recent measurement and the methods used in obtaining them were similar to those used here.

Figure 3.1 shows a plot of the three sets of curves. The Verma curves were originally derived for a smaller range (Verma, 1986). In order to reduce the number of variables between the curves the irreducible saturations for the liquid phase from the curves obtained by Verma (1986) were used for all

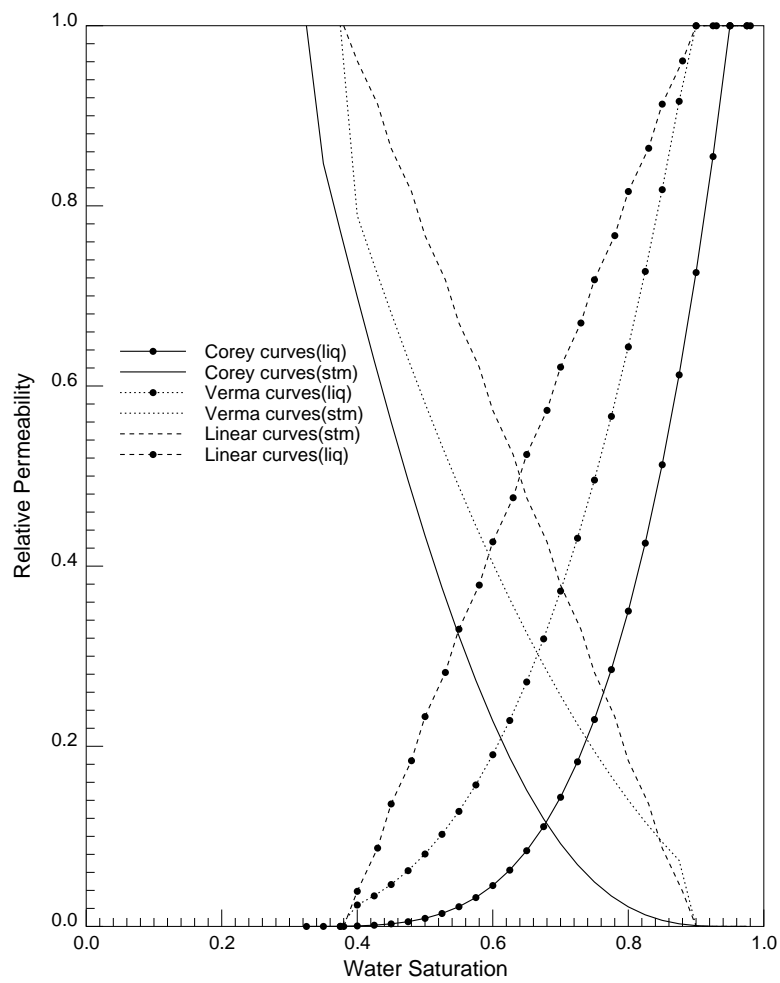


Figure 3.1: Relative permeability curves used for the numerical simulation.

the curves. The curves are given by the following equations,

$$k_{rl} = S_e^3 \quad (3.1)$$

$$k_{rv} = 1.2984 - 1.9832S_e + 0.7432S_e^2 \quad (3.2)$$

where

$$S_e = \frac{S_l - S_r}{S_m - S_r} \quad (3.3)$$

and  $S_m$  and  $S_r$  are the immobile saturation for the phases obtained by curve fitting to be 0.895 and 0.2, respectively. These values were used in computing the the Corey relative permeability curves which have the form,

$$k_{rl} = (S_l^*)^4 \quad (3.4)$$

$$k_{rv} = (1 - S_l^*)^2(1 - (S_l^*)^2) \quad (3.5)$$

where

$$S_l^* = \frac{(S_l - S_{lr})}{(1 - S_{lr} - S_{vr})} \quad (3.6)$$

while  $S_{lr}$  and  $S_{vr}$  are the residual saturations for the liquid and vapor phases respectively. The irreducible vapor saturation was set to 0.15 for the Verma curve while a value of 0.05 was used for the Corey and linear curves.

In order to reproduce the end-effects it was necessary to incorporate a capillary pressure in the simulator. These functions are well known for oil and water under static conditions. It is not known to us whether similar curves have been determined for steam and water. We therefore used the relations



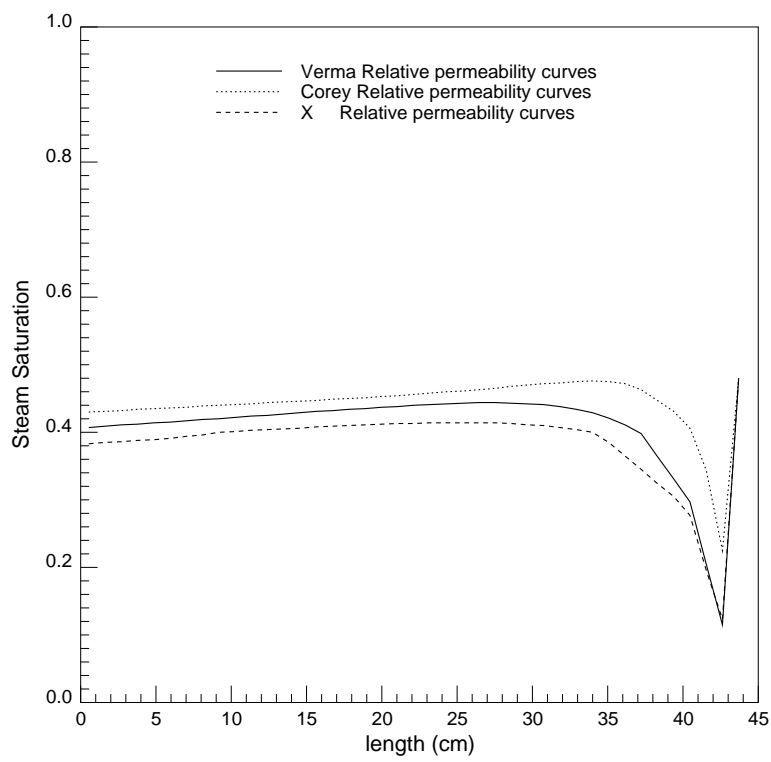


Figure 3.2: Saturation distribution for different relative permeability relations.

for water and nitrogen given in a parametric form  $-C \ln(S_w)$  (Aziz, 1995), where  $C$  is a constant. To use these relations the core was divided into several small blocks. The first and the last blocks were assigned zero capillary pressure. In real situations the capillary pressure may be small but will always be non-zero in the injection lines.

Figures 3.2 to 3.4 show the results of pressure, temperature and saturation distribution from the simulations. The total injection rate is 14 cc/min of water and the steam quality is 0.1. In all the cases the flow was modeled as adiabatic. It is clear that the linear relative permeability curves give lower pressure drops across the core for all injection rates. They also predict lower steam saturations. This is consistent with the higher mobility predicted (equal to unity for all saturations) for the combined flow. In all cases the steam saturation increases marginally towards the production end until the end-effects reverses the trend. This, too, is consistent with the flashing of water into steam as the pressure declines. In all cases the capillary end-effects are very strongly expressed but decrease in each case with increasing flow rate. The results also show that it is possible to have a substantial flat saturation profile for modest injection rates. These curves show clearly that the type of relative permeability used have a significant influence on the results obtained.

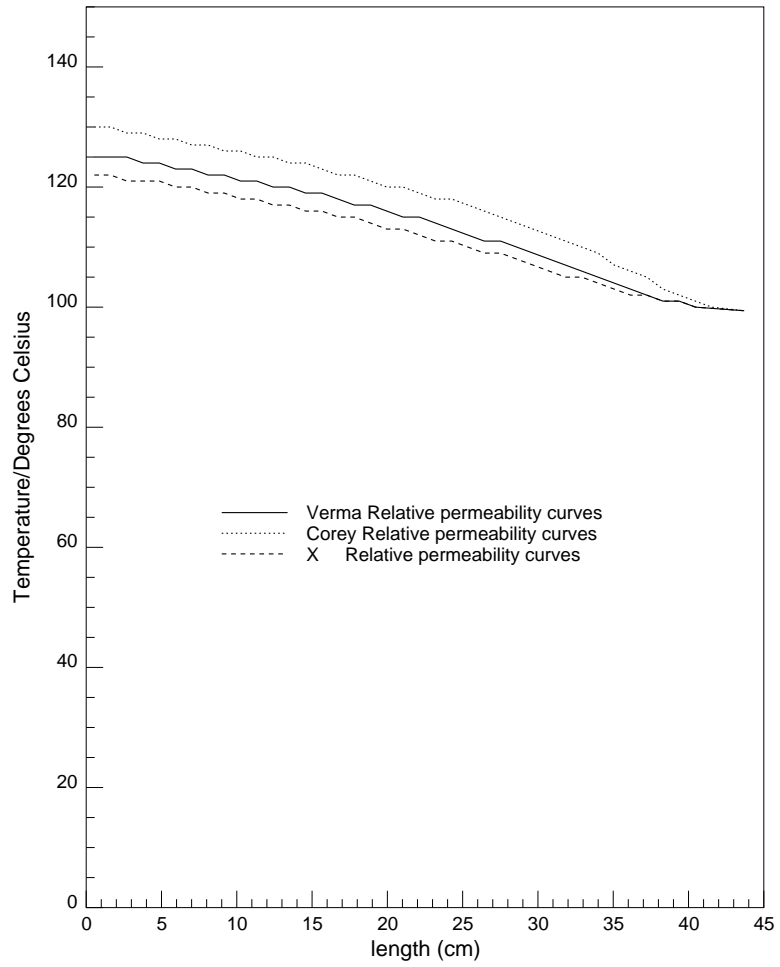


Figure 3.3: Temperature distribution for different relative permeability curves.

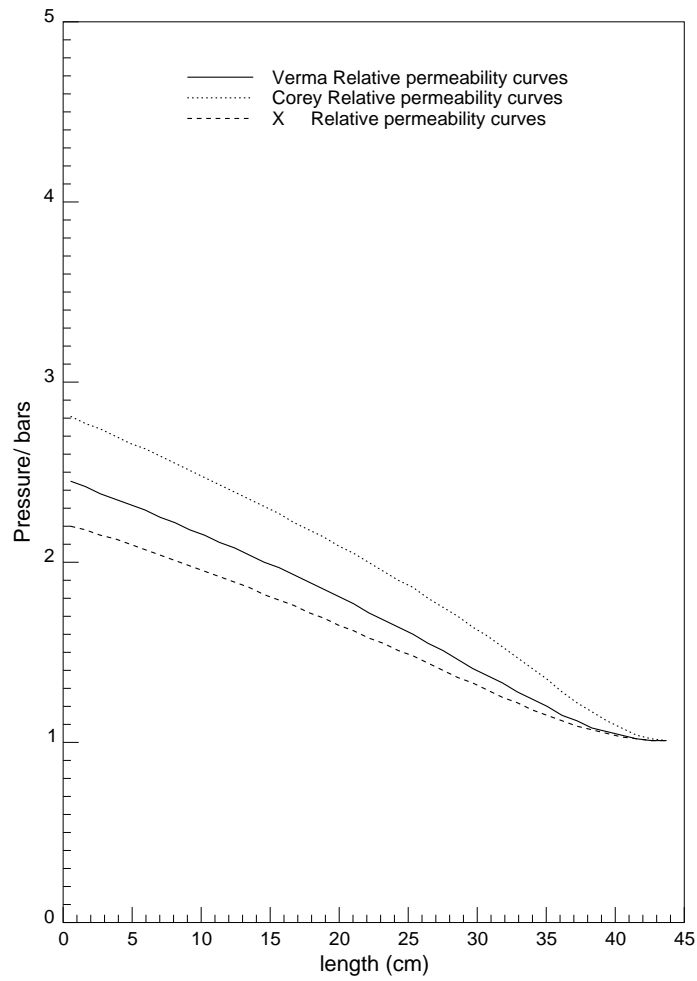


Figure 3.4: Pressure distribution for different relative permeability curves.

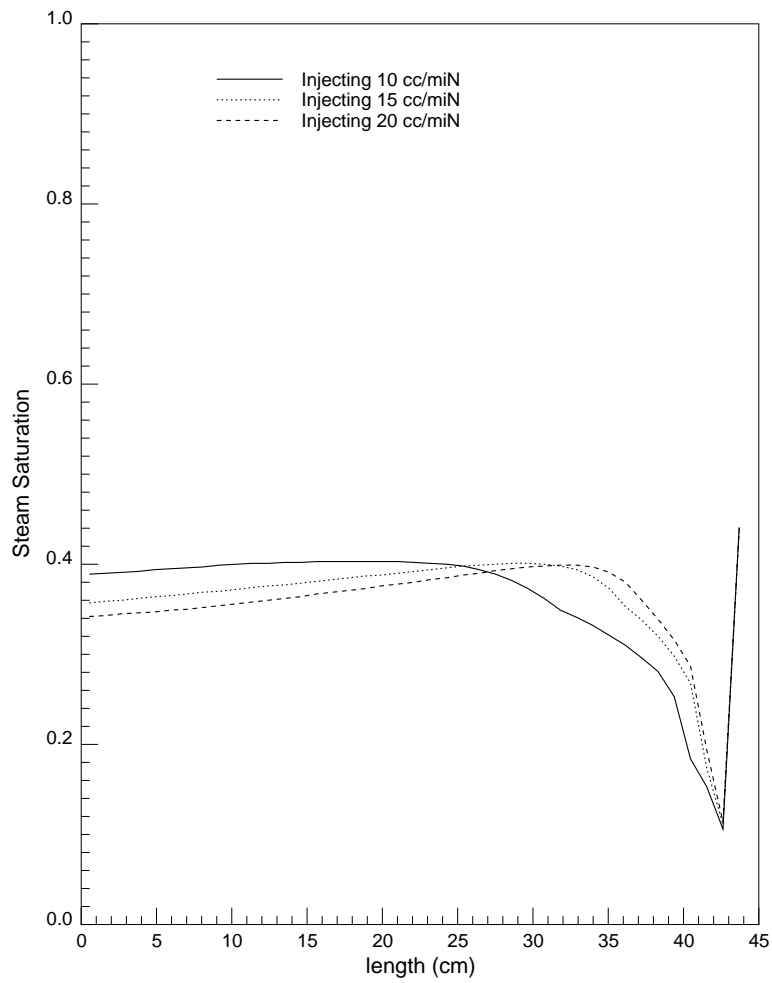


Figure 3.5: Saturation distribution for three different injection rates.

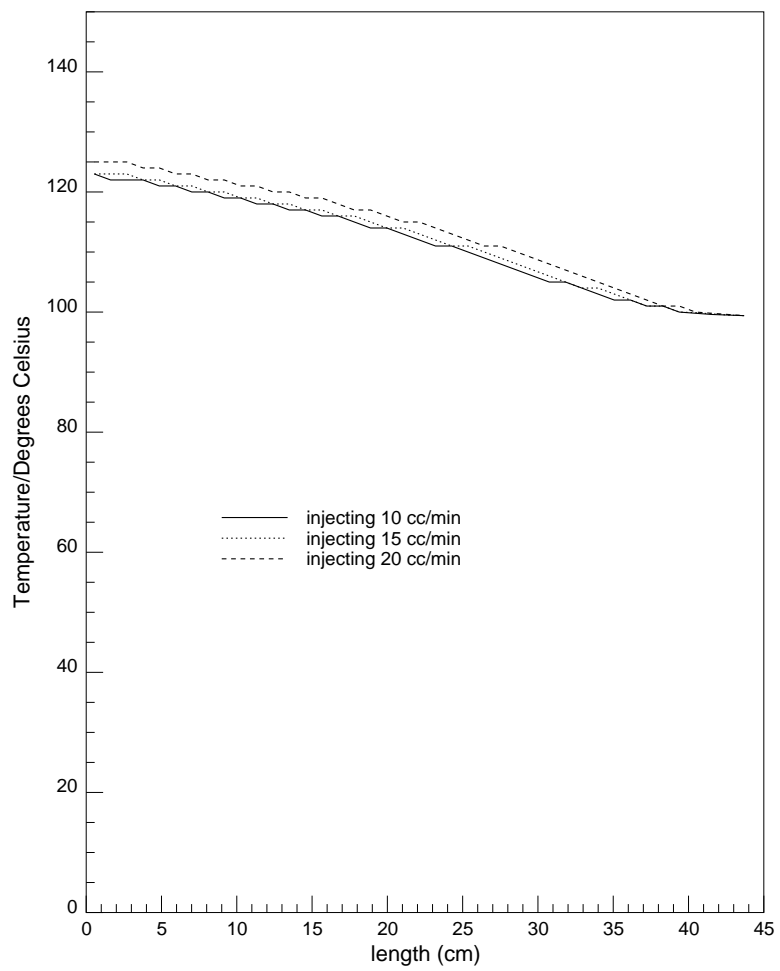


Figure 3.6: Temperature distribution for three different injection rates.

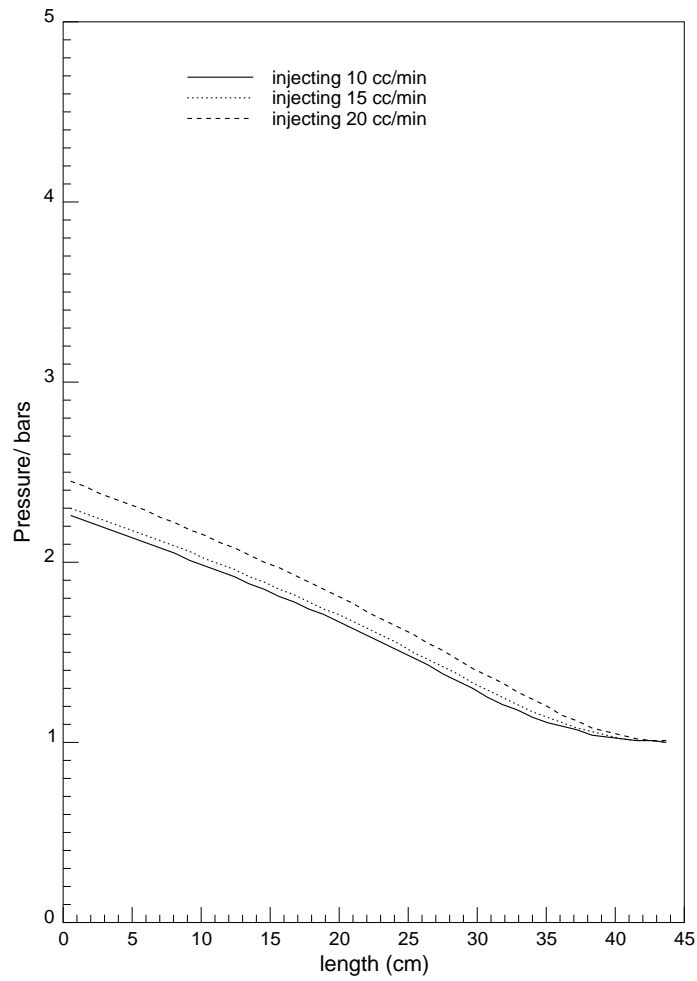


Figure 3.7: Pressure distribution for three different injection rates.

## 3.2 Flow Rates

The curves obtained by Verma (1986) were used to investigate the effect of flow rate. In each case the steam quality was constant and equal to 0.05. The rates were 8, 15 and 20 cc/min. Figures 3.5 to 3.7 show the saturation, pressure and temperature distribution for these three flow rates. The significant factor here is the portion of the curve affected by the end-effects, which decrease as expected as flow rate increases. The pressure and temperature also rise to higher values. Since the expected pressure range for the experiments was about 3 bars these results show that the appropriate length for the core which is not to be affected by end-effects is about eleven inches. Therefore a core length of 17 inches was selected for the experiments.

## 3.3 Heat Losses

To investigate the effect of heat losses on fluid segregation a three-dimensional model was used. The core was divided into a 100x3x3 grid in the -x, -y and -z directions, respectively. Insulation was added around the core as an additional layer in the -y, and -z directions. The thickness of the insulation was set to an inch and the porosity and permeability of the insulation were set to zero. The thermal properties in the simulator were set to those provided by the manufacturer. The curves obtained by Verma (1986) were used to generate results shown in Figures 3.8 to 3.9 for a flow rate of 12 cc/min. The results are for the middle three layers from the uppermost to the lowest. As expected, the temperature and pressure are practically the same for all



blocks at a given cross-section except at the end blocks where there is non-axial flow. Saturations vary only marginally in the vertical direction.

To compare the results to those without heat losses a one-dimensional model was constructed with the same dimensions. A comparison of results from these models are shown on Figure 3.11. There still is a flat saturation profile over most of the early part of the curve but the end-effects are more strongly expressed and start early for non-adiabatic case. Also, the steam saturation does not show the marginal increase observed for the adiabatic cases but is rather simply “flat”. This is an important aspect of these results since only one value of saturation was computed per section, effectively making the experiments one-dimensional. Recognition of this variation in saturation was an important confirmation of acceptable results. This indeed was the case.

These results indicate that heat losses will affect the measurements but the main features will be unaffected. Thus a flat saturation profile, which is required to evaluate relative permeability accurately, is still present and is of sufficient length. However, the flowing fractions will need to be determined from the material and energy balances and the heat losses.

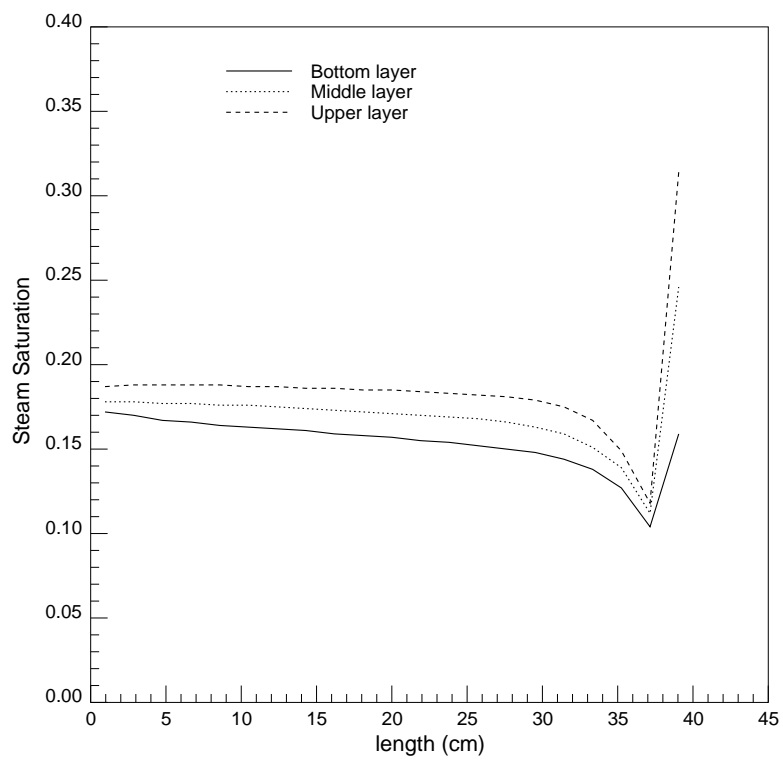


Figure 3.8: Steam saturation in vertical direction.

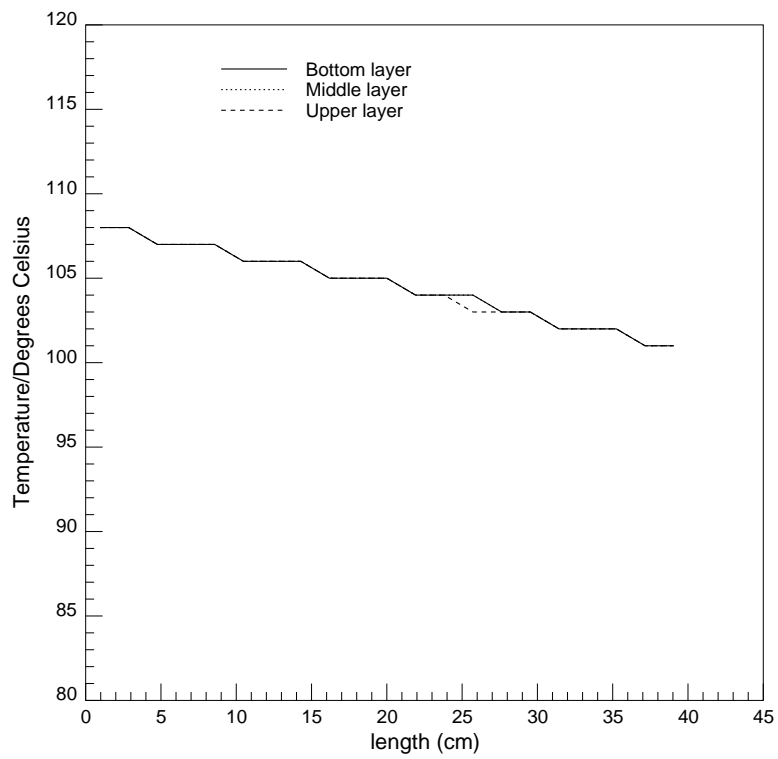


Figure 3.9: Temperature in vertical direction.

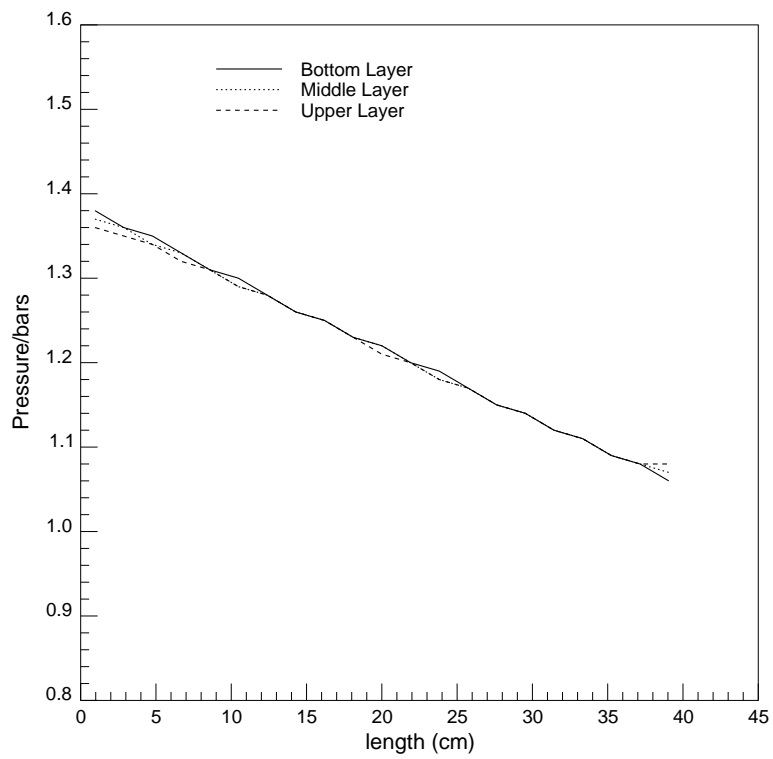


Figure 3.10: Pressure in vertical direction.

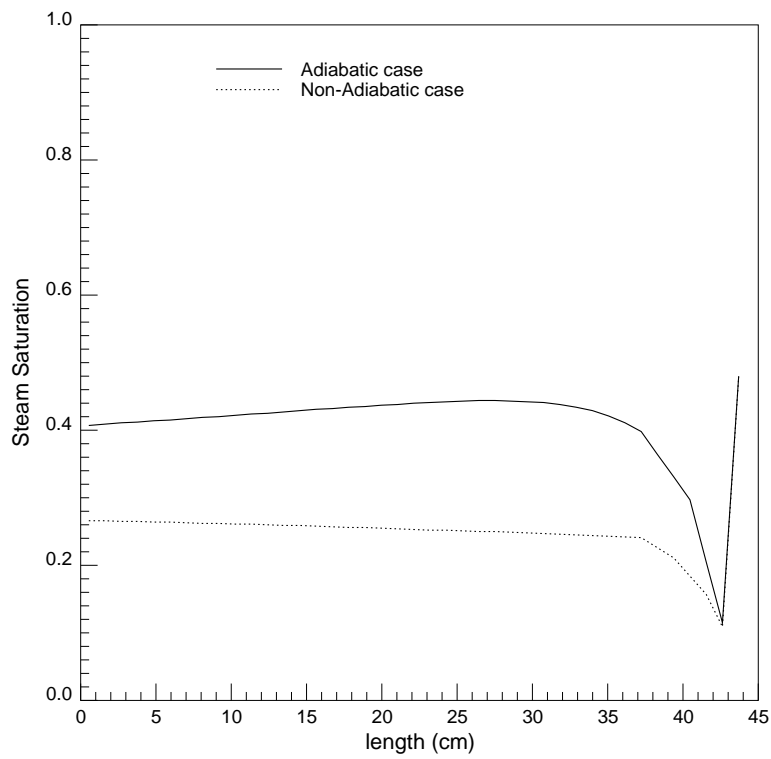


Figure 3.11: Saturation for adiabatic and non-adiabatic cases.

# Chapter 4

## Core Holder Design

As discussed in the introduction, saturations were measured by using an X-ray CT scanner. As a requirement, however, high density materials such as most metals or large pieces of intermediate density materials like some forms of plastics should not be placed in the area being scanned since they are almost opaque to X-rays. This imposed a severe restriction on the types of materials that could be used for making the core holder. A review of previously published literature did not reveal a core holder without any major metal parts that had been used for this type of experiment. Several investigators (e.g. Closmann and Vinegar, 1988) have reported using core holders made of aluminum materials. They however used X-rays at higher energy than the X-ray CT scanner equipment used here. This ruled out the use of similar designs for the experiments. The first step therefore was to design and construct a core holder that could be used in the CT scanner and that could also withstand high temperature and pressure for extended periods of time. In addition, the problems associated with minimizing heat losses had

to be considered since guard heaters, which have been previously used in similar experiments, could not be used (Verma, 1986; Sanchez et al., 1988). Several attempts were made before a successful core holder was ultimately constructed. This section discusses the steps taken before a working model was finally achieved.

By design, the core holder was to have the following properties,

- 1) It must be transparent to X-rays.
- 2) It must be able to hold and withstand high temperature and pressure for an extended period of time.
- 3) It should be possible to measure representative values of pressure and temperature during the experiment.
- 4) It must be perfectly sealing to provide a flow along the core axis (flow is in the horizontal direction).

Property 1 implied that the choice of materials was limited to plastics and epoxies which have low density and produce no artifacts on CT images. Property 2 was more difficult to meet as the range of high temperature plastics and epoxies is limited and the physical properties under circumstances like the ones encountered in steam-water experiments are not well known. In particular, how the materials behave after extended periods of exposure to water at high temperature was important. Property 3 was probably the most important in the evaluation of the relative permeability. The parameters were to be calculated at steady state conditions during which the system

would be in a two-phase state. In this state the temperature and pressure are coupled by the Clausius-Clapeyron equation and therefore measuring one implies the other. However, because of the capillary forces the pressure was also dependent on saturation of the phase.

Given the simulation results (Figures 3.10 and 3.11), which showed similar values of temperature on the outer and inner layers, it was decided that measuring pressure on the core surface would give accurate readings. The thermocouples were placed at the same points.

Property 4 was necessary to ensure that there was no flow between the core and the core holder. This, in fact, was one of the reasons for the use of a real core rather than an artificial core where flow channeling has been suspected to lead to enhanced steam flow and to give misleadingly higher relative permeability for the gaseous phase (Verma, 1986). Thus some form of sealing ability was required for the core holder. It was not possible to establish which materials met all these qualities from published data on plastics and epoxy and the final design was arrived at by a combination of deliberate design and trial and error. Following is a chronology of the various models that were tried before the final working design was achieved. The purpose of reporting unsuccessful designs is as an aid to experimenters who wish to attempt similar experiments.



## 4.1 The Plastic and Epoxy Core Holder

In the first design, the core holder had an oil jacket around it to act both as an insulator and to minimize beam hardening effect in the scanning area. However after difficulties in constructing a leak-free configuration the oil jacket was removed from the design.

The alternative design for the core holder had a simple structure that involved two plastic end plugs at the ends of the core, held to the core by high temperature epoxy, while the rest of the body was covered completely by the same epoxy. Confining pressure was not intended for the core as the outer epoxy was sufficiently thick and rigid. The plastic brand name was known as Hydlar Z. Although rated for use at 170<sup>0</sup>C our own test showed that the plastic crystallizes at about 155<sup>0</sup>C after a few hours and therefore had a lower temperature rating. The front side of the plastic, the surface facing the core, was machined into small groves radiating from the center for an even fluid distribution. The edge of the plug was raised to form a socket in which the core would fit by leaving little room to be filled by epoxy. The rear side of the end plug had three holes intended originally for measuring temperature and pressure and injecting fluids. Each of these holes were fitted with threaded metallic fittings which were connected to the supply tubes.

The brand name for the epoxy we used is Duralco-4461 and is manufactured by Cotronics Inc. of New York. This particular brand is relatively viscous (600 centipoise) and flows if uncontained for up to a few hours after mixing. It cures at room temperature over a 24 hour period and therefore does not

require any equipment to prepare at any stage. Because of its viscosity it had to be applied onto the core in stages in order to avoid penetration into the core body. First, a thin layer was applied over the core surface and allowed to cure for 4 hours. Additional layers were applied until a layer 5 mm thick was formed over the core. Eight pairs of  $\frac{1}{8}$  inch diameter holes 2 inches apart were then drilled into the core body. A pressure tube (plastic) and a thermocouple were placed at each pair of holes and fixed in place with epoxy.

The core was tested at room conditions for leaks. During the tests the core holder withstood pressures of 200 psi at room temperature. This core was also used successfully for experiments on nitrogen and water which were routinely run at 30 psi and occasionally at 60 psig (Satik et al., 1994). However during warm up at 70<sup>0</sup>C in steam-water experiments the core failed repeatedly at the connection between the end plugs. Our investigations eventually established that these failures were due to the higher thermal expansion of the plastic end plugs whose linear thermal coefficient of expansion is  $10^{-4}$  m/C. This is about an order of magnitude higher than that for the epoxy and the core (sandstone) both of which had comparable thermal expansion coefficients.

As a quick correction, the manufacturers of the epoxy suggested the use of a flexing additive that could make the epoxy more elastic thus effectively increasing the thermal expansion coefficient to about that of the plastic. Trials of various proportions of the additive improved the temperature at which the plastic parted from the core body (to about 110<sup>0</sup> C). Apart from this

temperature being lower than that expected during the experiments, further tests revealed that the flexed epoxy had lower bonding capabilities and could not withstand high pressure ( $>30$  psi) even at room temperature conditions. Tests on using this brand of epoxy were abandoned and similar tests on an alternative high temperature epoxy, Duralco-4703, were conducted. This brand of epoxy is paste like at room conditions but can remain in that state for several days without hardening and therefore requires a three-stage heating process to cure to optimum properties. As in the previous case failures occurred between the core and the end plugs during either the curing process or during the cooling stage after curing. Thus this epoxy was never tested under experimental conditions. The tests however did show that the epoxy had stronger bonding characteristics that later proved to be very valuable. Trials using this brand of epoxy with a flexing additive showed that the epoxy hardened very rapidly after being mixed with the additive and could not be spread out properly on the core surface.

## **4.2 Ceramic End Plates**

Following these two experiences, an alternative material with lower coefficient of thermal expansion was sought for the end plugs. The first material to be tested that also proved to be the last was a ceramic material that has thermal expansion properties similar to the sandstone. Unlike the plastic used originally the ceramic material has high density and therefore absorbs X-rays. It was therefore not possible to use the socket type shape for fitting

the core and the end plate was machined with flat faces only. The end plugs were fixed on to the face of the core by epoxy as in the previous case but with additional layers of epoxy at the sand face. Eight pairs of holes for thermocouples and pressure ports were drilled and fitted with tubing as in the previous case.

Prior to attempting complete experiments with the core trial runs in the laboratory under conditions close to those in the real experiments were conducted. After successfully heating the core to experimental conditions for about 3 hours the core was able to take 8 gm/min of a mixture of steam and water at about 120<sup>0</sup>C for most day before a break on the core body was discovered. It was not possible to establish how long the core had been able to take sustained flow since the failure occurred during the night. However our estimates placed the time at about fourteen hours. This was encouraging and two cores were prepared in a similar way for full-fledged experiments.

During experiments with the first core it was possible to heat the core and conduct one full equilibrium step successfully. However when the steam fraction was increased with change in pressure one of the pressure ports started leaking profusely and the experiments had to be abandoned. Further inspection of the core revealed several other smaller leaks on the body and close to the end plugs making it clear that several aspects were still not adequate for complete use of the design in the experiments. It was still unclear up to this point whether the failure was due to epoxy fatigue or to improper handling of the epoxy during the preparation or during the heating process.

To help establish the modes and the nature of the failures a second similar core was used for another experiment with similar results except that this time the failures occurred after a much longer injection period with at least two complete steps. A closer look at the CT images for saturation distributions also revealed steam channeling at the edge of the core, presumably caused by separation between the epoxy and the core (Ambusso et al., 1996).

These issues taken together implied that though the epoxy had the correct properties it could not endure the long periods of the tests. It is not clear to date why this is so. Our suspicion is that the epoxy has a water absorption property and loses its bonding capabilities with time when in contact with hot water for a long period of time. Thus we tried the Duralco-4703 epoxy with similar cores. The first test was conducted on a miniature core 5 inches long. Since the epoxy has to be cured at high temperature it presented special problems in preparation and some Duralco-4461 epoxy had to be used for fixing the end plugs onto the core. A small leak was detected after more than 16 hours of continuous injection of a two-phase mixture at pressures of about 3 bars (30 psig). The failure was at the end plugs which were held in place by the Duralco-4461 epoxy.

This result was a clear indicator that the Duralco-4703 epoxy was more hardy and could endure higher temperatures and pressures for a longer period. The next step was to use this brand of epoxy alone on a core holder. This was done but unfortunately the epoxy developed large cracks while being cured the second time to fit the end plugs. It was also discovered that though the

epoxy held on well during trials with the miniature core it had also cracked apparently on cooling. Thus it was concluded that the epoxy, though with better water absorption properties, was inelastic and responded badly to thermal shock. This implied that the epoxy could not be used by itself on the core as situations where temperature was likely to change suddenly were numerous. A final change in epoxy usage was to apply the Duralco-4703 first and then cover it with a thin layer of Duralco-4461. This turned out to be the final solution to the epoxy selection. This design still required a number of other changes to other features of the core holder, namely the pressure ports and the location for the thermocouples. These are discussed in the next section.

### **4.3 Final Design**

As discussed in the previous section the final design of the core holder used the Duralco-4703 which had a low water absorption property but was inelastic and cracked when exposed to rapid thermal stress. The remedy was to cover it in a layer of the more elastic Duralco-4461. To achieve this was still a challenge since the pressure ports and thermocouples had to be fixed on the core body.

The first step in the construction was to apply a thin layer of Duralco-4703 to the core and cure it to optimum conditions before covering it with a thick layer of Duralco-4461. This was achieved by inserting the core, covered in

Duralco-4703, in a Teflon sleeve sealed at one end and pouring the elastic epoxy to cover the core completely except for the injection and production ends. The epoxy was allowed to cure for the required time after which the holes for the pressure ports and the thermocouples were drilled. The holes for thermocouples were drilled on the outer layer of epoxy. Those for the pressure ports were drilled through to the core after which tubes were fixed by applying epoxy carefully so that the epoxy never entered into the body of the core nor sealed the tubes.

This design proved to be better than the previous construction but failed twice after several hours of use, each time at the pressure ports. On each occasion the failures looked minor enough to be repairable by redrilling and reapplying the epoxy. However attempts to dry the core for resumption of the experiments resulted in the development of extensive cracks on the core body. A closer look at the cracks showed that the cracks always started or terminated at the ports drilled for the pressure tubings. This implied that the holes acted as stress concentrators and drilling was probably the cause of these problems. Furthermore, direct attachment of the tubes to the core body also put a restriction on the type of tubes to be used; Teflon tubes could not be used since they are epoxy repellent.

To overcome this weakness the final choice was to use threaded nylon nuts to which Swagelok pressure fittings could be attached. The nuts were fixed on the body of the core after the initial application of the epoxy Duralco-4703 at the designated points for pressure ports. The nuts were held on the core

by coating the Duralco-4461 epoxy on to one face of the nuts and allowing it to cure. The other face of the nut was covered by a removable tape to prevent entry of the Duralco-4461 epoxy during the subsequent application of the core surrounding epoxy using the sleeve. The faces were cut out immediately the last layer of epoxy cured but before it hardened completely and the sealing paper removed. The correct Swagelok fittings were then placed with some application of epoxy to improve the sealing.

This design proved robust and was able to last for a week of pre-experiment test without failure at pressures above 60 psig and temperatures in excess of 140<sup>0</sup>C. Parts of the core holder between the core and the end plugs failed at a pressures of about 70 psig. This established the limiting pressure at which the core holder could be used without failure. This pressure was twice the value expected for the experiments. To date this design has been able to withstand all pressures applied on all occasions and was used for the actual experiments.

One additional modification was to change the way the thermocouples were placed by avoiding drilled holes which are potential stress concentrators. Ceramic tubings were used for this purpose and had to be fixed at the same time as the nylon nuts. These tubes performed well without failing. However the readings from the ports were always less than expected from the pressure readings using Clausius-Clapeyron equation. This is because the ceramic tubes were placed in the outer layer of the core holder. This will require improvement in the future.



## 4.4 Mounting the Core

To finally assemble the core for the experiments it was required that the tubings for pressure measurement and for injection and production be connected at the inlet and outlet. The thermocouples were connected at the assigned places. Heat flux sensors were placed along the body starting from the injection end and uniformly spaced towards the production end. Four heat flux sensors were used. The sensor readings were corrected for curvature of the surface and gave the heat loss required for calculation of the flowing fractions.

The entire assembly was then covered in four layers of insulation made from ceramic blanket, forming a one inch layer around the core. The blanket was carefully wrapped around the core with no air pockets to avoid any draught cooling due to air circulation. For safety, plastic rods were used to hold the end plugs in place against any blow out. The entire unit was then mounted on to a wooden frame that was placed on the movable couch of the X-ray CT scanner.

# Chapter 5

## Experiments and Results

### 5.1 General

As discussed earlier the single core dynamic method was used for the measurement of the relative permeability. This required that a two-phase mixture be injected into the core. By changing the flowing fractions and letting the system adjust itself to steady state conditions the relative permeability relations were determined from the knowledge of the flowing fractions and the measured pressures and temperatures.

To determine the flowing fractions it is necessary that the enthalpy of the injected fluid be known accurately. Thus it is important that the injected fractions of the components in the core be known before injection and the phase change accompanying pressure drop be considered. Though it has been suggested that in the porous media the process of boiling and phase change may require more energy due to capillary forces (Udell, 1980), experiments

by Miller (1952) with light gasoline showed that the temperature and pressure follow values close to those for flat surface thermodynamics. For this reason steam table values were used to compute flowing proportions in the core.

Two methods were used to inject fluids of predetermined enthalpy. The first was to inject a two-phase mixture that was heated to high temperature but always keeping the pressure above saturation so that the fluid always remained in the liquid phase upstream of a throttle valve set to release fluid only after some threshold pressure has been reached. The enthalpy of the two-phase mixture would be the same as that of the liquid water corrected for heat losses along the line, the kinetic energy being negligible in this case. This method is a modification of that used by Miller (1951) and Arihara (1976) who injected the fluid as a single phase into the core. For these experiments this method was used for injection of fluid at low enthalpy to produce low steam fractions and proved useful since steam table values could be used to determine the enthalpy given either the temperature or the pressure.

The second method was to mix streams of steam and water. Due to difficulty in keeping both streams close to saturation, steam was superheated by a few degrees and liquid water was kept a few degrees below boiling point. This too enabled the use of steam table values for computation of fractions. This approach was used at high steam fractions.

The temperature logging unit consisted of a thermometer which could take

up to twelve readings simultaneously. This unit was connected to a computer for storing and displaying the temperature data. The thermometer gathered readings from the eleven J-type thermocouples, eight of which were located on the core while the other three were on the steam generator, the water line and the mixing point for the steam and water at the injection end of the core.

The pressure measuring unit consisted of eleven transducers each with its own read-out screen. Some of the transducers were connected to a chart recorder. This enabled direct monitoring of pressure which together with the temperature readings were used to determine when steady state conditions had been reached.

## 5.2 Experiments

After assembling the core and the auxiliaries, the experiment was initiated by first determining the porosity of the core. This was done by taking X-ray CT scans of the core at various locations while it is dry and when fully saturated with water. A steady stream of carbon dioxide was passed through the core for several hours after the initial scan, referred to as the *dry scan*, before injecting a steady stream of water at low rate (5 cc/min) for twelve hours. A second scan, the *wet scan*, was then conducted. By analyzing these two sets of images at every point scanned it was possible to determine the porosity of the core, which was found to be 20% for all points. These scans also revealed that the core had a few vugs identified as points with higher

Table 5.1: Permeability at different flow rates

Rate cc/min	Pressure psi	Pressure psi	Permeability md
10	7.8	6.5	944
15	10.2	8.5	1082
20	13.1	10.8	1102

porosity from the bar scale.

After the porosity distribution had been determined the absolute permeability was determined by flowing water at different flow rates and measuring pressure along the core. Three rates were used and the results are summarized in the Table 5.1. The results were taken after an hour of pumping. The readings show that there is a small dependence of permeability on injection rate. The range is somewhat small and it is not clear whether this variation is due to other parameters.

After determining the absolute permeability, the core was brought to experimental conditions by injecting hot water. This was done in stages to avoid problems of rapid thermal expansion and shock. These heating stages at low flow rates provided an additional opportunity to check the permeability of the core at higher temperatures. The values were found to be within the range of those measured at room conditions giving credence to the assumption that permeability does not change with temperature.

Once the temperature for the experiments had been reached, the core was allowed to attain thermal equilibrium before readings were taken. For the first four steps only the water line was used. The steam fraction was adjusted by changing the injection temperature and the flow rate. For the subsequent five steps both the steam and water lines were used.

These experiments were aimed at determining the drainage relative permeability curves and were conducted in steps of increasing steam saturation. Between the steps this was achieved by increasing the injection temperature and reducing flow rates for the steps where only water was injected. For the steps where both water and steam were injected this was achieved by increasing the steam fraction and reducing the water.

In practice a number of other variables made perfect control of injection temperature and fractions difficult. This was because the steam generators took time to reach thermal equilibrium each time the flow rate or temperature was changed. As a result the steam fractions being injected were initially either less than or more than intended for the next step. This was the same when water flow rate was changed. In addition the pressures within the core body were limited to values that did not surpass the limit determined in the laboratory in the pre-experiments. This might have affected some of the drainage features of the results.

Steady state conditions were recognized by the constant values of tempera-

ture and pressure. Typically this took three to five hours, though the readings reported here were taken after at least eight hours. Once a steady state had been confirmed, the readings of temperature and pressure were recorded together with the voltage measurements of the heat flux sensors. The X-ray CT scans were then taken at locations where the the dry and wet scans. had been taken. These scans were then processed into images using the software ct2tif.exe which generated the files with the density profile of the images. These profiles were then processed with the dry and wet scans to give the saturations at each point.

The saturation profiles presented in this report were from average values over the entire core surface. To determine whether the distribution was uniform each image had to be examined. In general all the images showed very uniform saturations for most sections for all flow rates.

### 5.3 Analysis

The data collected during the experiments were reviewed for consistency. This was done by evaluating the data for application of the results to general flow situations of steam and water flow in porous media. We also compared the data to the simulation predictions.

#### Dry Scans

In general all the images gave an average porosity of  $20.0 \pm 0.5$  %, which is very acceptable for a field sample like the core that was used for the ex-

periments. In spite of this uniform value some images had regions of local variations in porosity. Figure 5.1 shows selected images of the dry core. Some of the images show zones with different porosity. It is not clear whether the anomalous zones are due to larger pores or due to a different packing of sand grains. Otherwise, most of the core is very close to the average porosity. This core can therefore be considered as a close approximation to a uniform porous medium. The regions of nonuniform porosity such as those with vugs provided the a useful check for repeatability of the locations of the images.

### Saturation

Figure 5.2 shows a plot of all the saturation profiles obtained during the experiments. In general all saturations show a trend of decreasing values from the injection end to the production end which is what is expected from the numerical simulation of the non-adiabatic case. The first and second steps of injection show a few irregular trends at 17 cm and at 25 cm from the injection point. These trends are also repeated to a lesser degree at the same points at higher saturations. These anomalies are probably due to inhomogeneities in permeability or porosity. These are however minor and the saturations still reflect the general trend. In addition, the values of saturation are never really constant but change gradually. Thus the flat saturation profiles are not always flat. However the values change very little over most of the core length and can be averaged over an interval to a representative value. In addition, from previous experience with other experiments (e.g oil and water) relative permeability typically changes monotonically with saturation by small amounts. Therefore relative permeability computed over regions where



Figure 5.1: Selected images from the dry scan.

saturations vary by less than  $\pm 2\%$  can be considered to be constant.

The saturation profiles reveal a number of other interesting features. The capillary end-effects are observed for low steam flow rates with high steam fraction. This can be seen for steps that are different in rates but have the same steam fractions (e.g. Steps 4 and 5). This supports some of the results obtained from the simulation where the end-effect is very strong for small flow rates.

#### Heat Losses

Heat losses on the core body were measured by using heat flux sensors. These sensors are made up of thermopile which magnifies the current created by the individual thermocouples. In general the heat loss is highest on the injection end of the core and decreases towards the production end of the core. This is expected since the temperature profiles decrease in the same direction. In addition, the heat losses show dependence on the body temperature. These are small since the experiments were conducted within a narrow temperature range.

#### Temperature and Pressure

Figures 5.3 and 5.4 show steady state temperature and pressure profiles respectively for the injection steps. As described in chapter 4 the thermocouples were inserted in ceramic tubes within the outer most layer of the epoxy. Thus the thermocouples did not make direct contact with the core. This led to lower temperature readings than expected.

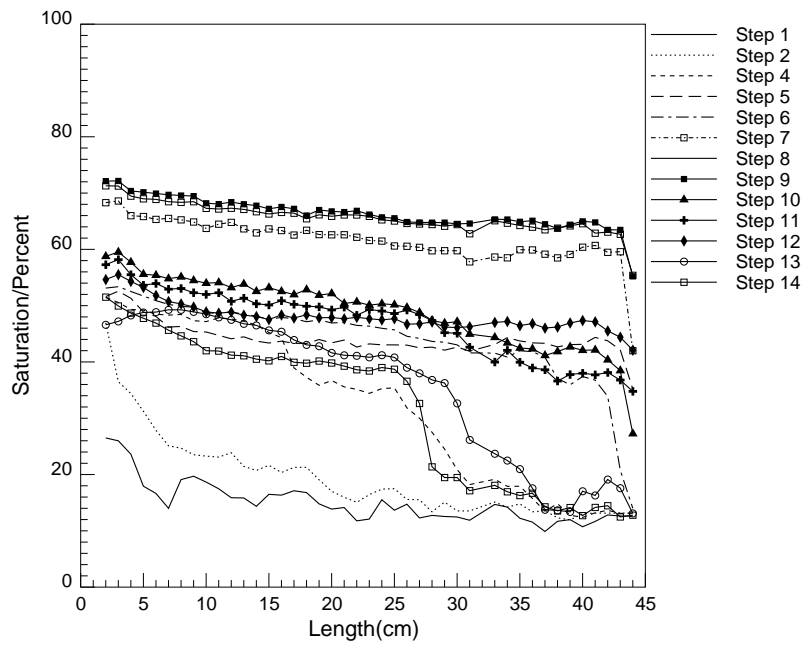


Figure 5.2: Saturation profiles for all scans.

The pressure readings were taken using tubes fixed on the core body. To ensure that the readings were for the water phase these tubes were filled with water. In this way water in the tubes were in contact with the water in the core. In general all the pressure measurements reflected what was expected i.e decreasing values along the core from the injection end. The values were however read by gauges that had a minimum scale division of 1 psi. The error was therefore about  $\frac{1}{2}$  psi. This value was taken into account when computing the relative permeability thus giving a range of values.

## 5.4 Interpretation of Results

Since it was not possible to use guard heaters the experiments were not conducted under completely adiabatic conditions. Thus the interpretation of the results must take heat losses into considerations. This requires that the heat lost through the system be accounted for and the flowing fractions corrected accordingly. Heat losses were measured only on the body of the core. In the steam and water line, the heat losses were only estimated by recording the temperature drop while flowing a known amount of fluid. Since the heat loss rate is only governed by the temperature difference between the material being considered and the surrounding (Newtons law) these results could be extended to the case of any other fluid under similar conditions. This was done to estimate the heat lost from the injection lines before and after mixing.

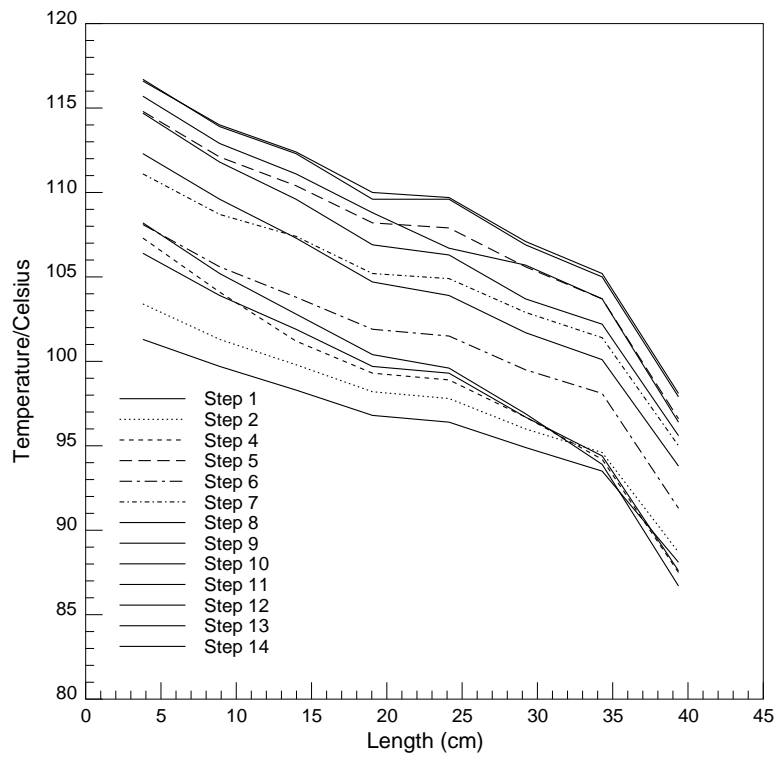


Figure 5.3: Temperature profiles for all steps.

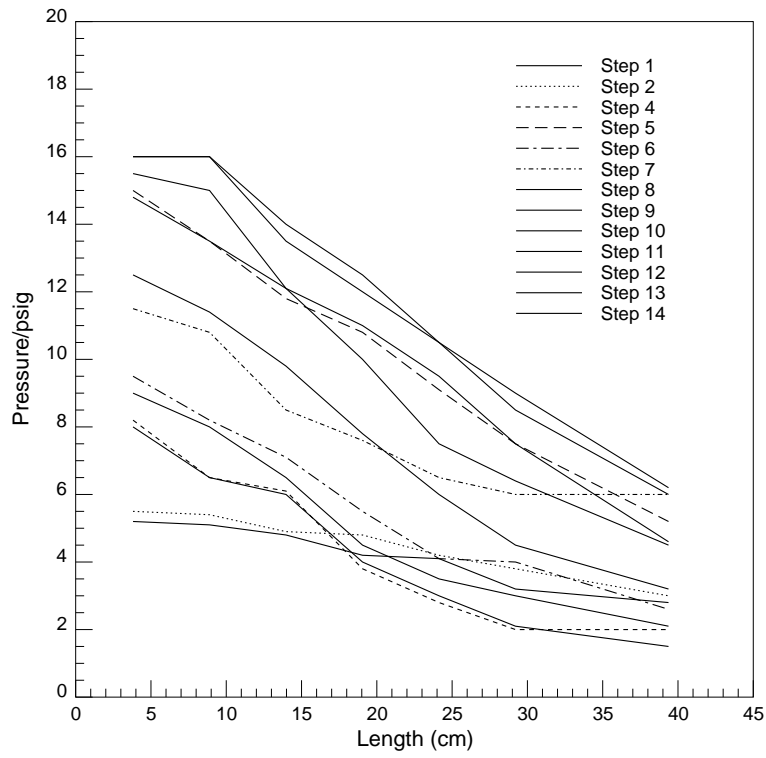


Figure 5.4: Pressure profiles for all steps.

Following are the two derivations of the equations for the steam fractions. One is for the adiabatic case, modified for the heat losses to give results for the non adiabatic flow. The latter results are used for interpretation of the experimental results .

Adiabatic case

The starting point of this derivation are the conservation equations for mass and energy fluxes:

$$m_t = m_v + m_l \quad (5.1)$$

$$m_t h_t = m_v h_v + m_l h_l \quad (5.2)$$

where  $m$  and  $h$  refer to mass flow rate and enthalpy respectively and the subscript  $t$  refers to total,  $v$  to vapor phase and  $l$  to the liquid phase.

Then using flat interface thermodynamics the steam fraction ( $x$ ) in the flow at any time would be given by:

$$x = \frac{h_t - h_l}{h_{lv}} \quad (5.3)$$

$h_{lv}$  is the latent heat of vaporization at the prevailing temperature and pressure.

The corresponding Darcy's equations for each phase in terms of the mass

flow rates are:

$$k_{rl} = -\frac{(1-x)m_t\mu_l v_l}{kA\frac{\Delta p}{\Delta x}} \quad (5.4)$$

$$k_{rv} = -\frac{xm_t\mu_v v_v}{kA\frac{\Delta p}{\Delta x}} \quad (5.5)$$

Thus a knowledge of the values of flowing mass fractions in the above equations and pressure drop along a column of the core with constant or flat saturation provides a value for the relative permeability.

#### Non-Adiabatic case

For the non-adiabatic case the energy flux term is the only one that needs to be modified to take account the condensing steam that changes to water thereby reducing the steam fraction and increasing the water fraction. The energy flux equation can be modified thus by adding a term representing all the heat losses as follows:

$$m_t h_t = m_v h_v + m_l h_l + Q \quad (5.6)$$

$Q$  is the total heat lost upstream of the point being considered. The steam fractions can thus be shown to be given by:



$$x = \frac{h'_t - h_l}{h_{lv}} \quad (5.7)$$

where  $h'_t$  is the total enthalpy of the mixture corrected for heat lost,  $h_t - \frac{Q}{m_t}$ .

This can be written out in terms of the uncorrected values as:

$$x = \frac{m_t(h_t - h_l) - Q}{m_t h_{lv}} \quad (5.8)$$

The equations for the relative permeability parameters are the same as those for the adiabatic case but the values of  $x$ , the steam fraction is different in each case. These are repeated here,

$$k_{rl} = -\frac{(1-x)m_t\mu_l\nu_l}{kA\frac{\Delta p}{\Delta x}} \quad (5.9)$$

for the liquid phase and for the vapor phase:

$$k_{rv} = -\frac{xm_t\nu_v\mu_v}{kA\frac{\Delta p}{\Delta x}} \quad (5.10)$$

Critical to the evaluation of the flowing fractions is the knowledge of the injected enthalpy and the heat losses. The heat losses on the body of the core can be computed from the measurement of the heat flux directly. Heat losses in the injection lines were a major challenge to determine and were estimated from the temperature drop while injecting water during the heating process. Figure 5.5 shows the heat loss per minute taken as a product of the

Table 5.2: Heat loss from injection line.

Rate (q) cc/min	Upstream Temp. °C	Downstream Temp. °C	change in enthalpy ( $\Delta H$ ) Joules	q( $\Delta H$ ) Joules/min
10	58.4	55.8	10.882	108.82
10	68.3	64.9	14.246	142.46
10	100.9	94.6	26.601	266.01
15	105.9	102.1	20.266	303.99

enthalpy change per gram for the measured temperature drop between the back pressure valve and the mixing point. The values lie on a straight line which lends credibility to the approach. By projecting the graph heat losses at higher temperatures can be inferred.

Table 5.2 shows the values of the estimated heat losses based on temperature drop. These values, though high, represented less than 5 % for high flow rates and were twice this for low flow rates. For the heat losses on the core, graphs of the heat loss were constructed from the measured values corrected for curvature of surface. These were then used to determine the heat lost at points in between the heat flux sensors.

Table 5.3: Heat loss rate from sensors J/min inch<sup>2</sup>

Step	Sensor 1	Sensor 2	Sensor 3	Sensor 4
2	14.568	4.68	4.245	4.3
4	14.66	5.696	4.849	4.26
5	14.68	5.74	4.83	4.28
6	14.986	5.37	4.143	5.248
7	15.57	5.94	5.42	4.6
8	16.148	6.2	5.173	5.248
9	16.148	6.4939	5.04395	5.149
10	15.818	6.2	5.173	4.9196
11	15.49	6.33	5.438	5.458
12	15.79	6.28	5.42	5.51
13	14.92	6.12	5.32	4.8
14	14.72	5.86	4.97	4.41

To determine the flowing fractions at a particular point, the heat losses upstream of the point under consideration was evaluated and subtracted from the total energy at the injection point. The heat lost in the injection line was estimated from the Figure 5.5. The second component was the heat lost on the core before the fluid reached the point under consideration. This could be estimated from the heat flux sensor measurements which indicated how much was being lost in the radial direction. In the direction of flow, the

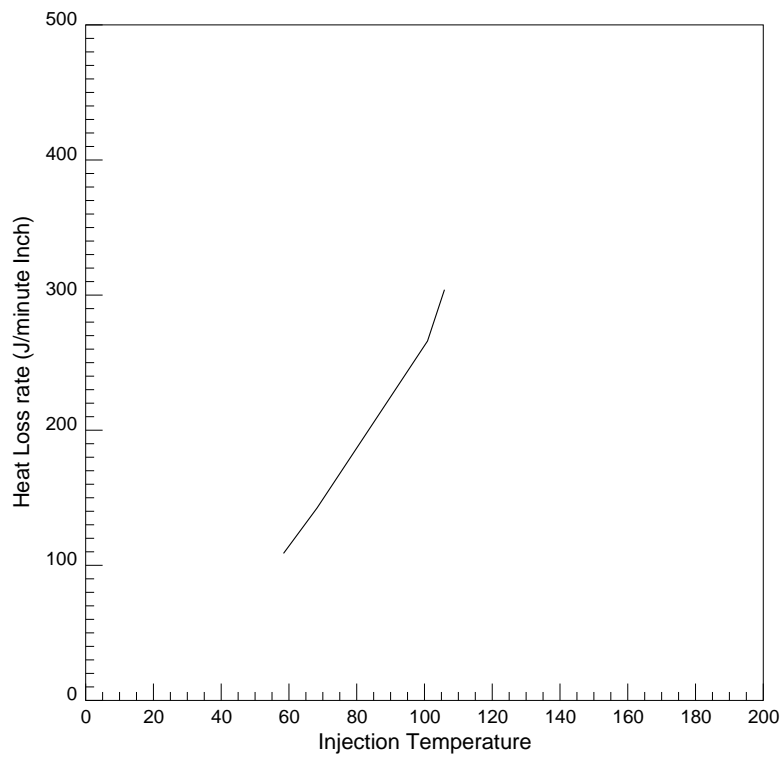


Figure 5.5: Heat loss curves from the injection line

temperature gradient also leads to conductive heat loss. This component is negligibly small compared to heat lost in the radial direction and was neglected in the computations.

To use the heat losses from the heat flux sensors, it was found convenient to convert the readings into graphs that gave the cumulative heat lost as the fluid moved along the core. This was done for each set of measurements and the results are plotted on Figure 5.6.

Thus to compute the flowing fractions, Equations 5.8-5.10 were used after  $Q$  had been calculated from the summation of the heat lost on the body and the heat lost on the line. These were then converted into volumetric flow rates for the prevailing temperature and pressure. Since the pressure changed along the core and therefore the specific volume of steam, the volumetric flow rate was computed for all the points along the core and the average value over the interval used. The volumetric flow rates were surprisingly similar and generally differed by no more than 2 % over 2.0 inch intervals.

The next parameter of interest was the temperature dependent viscosity particularly for water which varied between 252 and  $211 \times 10^{-6} \frac{kg}{ms}$ . The arithmetic mean of the values at the two end points was used for a given interval. A final correction to the results was to include the errors due to pressure measurements. This was done for all the intervals. The error assumed in each case was  $\pm 1.0$  psi. Table 5.4 shows a summary of the essential data from all the steps.

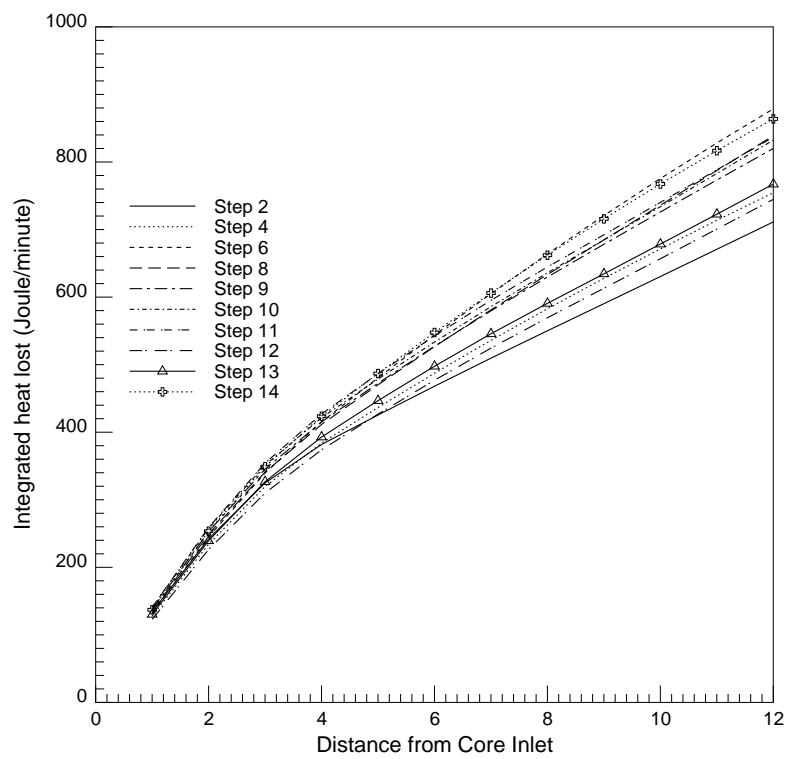


Figure 5.6: Curves for heat loss from the core body.

Table 5.4: Summary of important results.

Step	Injection rate cc/min	Corrected enthalpy Joules/gm	Steam Saturation Percent	$k_{rw}$	$k_{rs}$
1	15	464	10-15	916	-
2	14	474	22	846	99.2
4	8	567	38	365	564
5	8.35	631	50	331	809
6	4.0	764	53	227	711
7	2.25	1285	64	94	908
8	1.3	2264	68	27	987
9	1.33	2262	68	34	974
10	5.05	940	63-54	164	752
11	5.0	624	52-49	198	783
12	6.4	695	49	219	736
13	6.0	548	45-39	306	658
14	8.0	527	43	396	549

The relative permeability computed from the data are shown on Figure 5.6. The relative permeability for the steam phase varies approximately linearly with saturation. The liquid phase on the other hand has a curved variation with saturation somewhat reminiscent of the Corey curves (1954) and those derived by Verma (1986). The curvature is rather small and may change to linear at high temperature as the interfacial tension between water

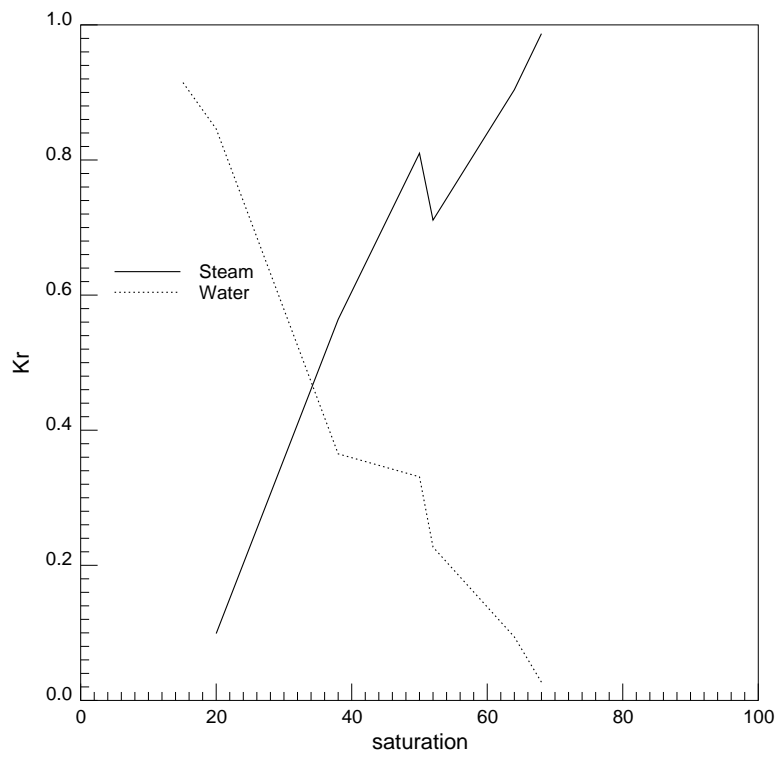


Figure 5.7: Relative Permeability for Steam and Water



and steam reduces.

# Chapter 6

## Conclusion

The relative permeability curves presented in the previous section have been derived from experiments in which the saturations within the core have been measured very accurately. Furthermore the saturation profiles have been shown to follow very closely what is expected from the numerical simulation. The residual limits are not well defined in the experiments. This is because it was not possible to inject steam at 100% quality due to condensation in the injection line. It was also not possible to estimate the steam relative permeability at low saturations as the correction for the enthalpy of the injected fluid was very close to the correction in heat lost from the injection line and the core body. These end points can however be inferred from the relative permeability curves and are about 20% for water and less than 10% for the steam phase.

Analysis of the X-ray CT images from the porosity scans and the images of low flow rate saturation show that the core had some inhomogeneity in

porosity and probably also in permeability. However these are small and the results may be applied to homogeneous porous material of uniform properties. The most likely sources of error in these results are, 1) the heat losses from the injection lines that were only estimated indirectly from the temperature drop along the line and, 2) the pressure readings due to the scale of the gauges used.

Several relative permeability relations for flow of steam and water in porous media derived from experiments have been proposed in the past (Chen et al, 1979; Council and Ramey, 1980; Verma, 1986; Clossman and Vinegar, 1988). In all the curves reported the relative permeability for one or more of the phases have tended to follow the relations obtained by Corey (1954) for nitrogen and water. However none of the investigators have measured saturation directly in the manner of the experiments reported here. As a result, none of them has measured the pressure of a single phase alone over any interval. Unlike previous investigations these results show that the relative permeability for both phases are enhanced in comparison to relations obtained by Corey (1954) which is a major departure from any of the results reported previously.

The main difference between the results obtained from these experiments is the linear variation of the relative permeability of the steam phase with saturation. Though a number of investigators reported enhancement of relative permeability of the steam phase none of them obtained a linear relation between steam phase relative permeability and saturation (Verma, 1986; Clossman and Vinegar, 1988). It is however worth noting that Verma (1986)

reported that the gamma ray densitometer only accessed 5% of the sample and it is possible that his measurements were inaccurate. Also Clossman and Vinegar (1988) used samples that were only 6 inches long. For such lengths capillary effects will dominate and the flow of the wetting phase will be retarded. The relative permeability will therefore be underestimated.

The liquid phase relative permeability still shows resemblance to those obtained by Corey (1954) and Verma (1988). To verify whether the results obtained here can be applied generally, further experiments will be required. These experiments could be done on rocks with different wetting characteristics. It will also be of interest to increase the temperature in the experiments to establish whether the water relative permeability will become linear at higher temperature.

# Chapter 7

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