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SAND REMOVAL FROM A VERTICAL HEAVY OIL WELL

by

Kerry Anne Mazurek ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

Department of CIVIL ENGINEERING

EDMONTON, ALBERTA
FALL 1994

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UNIVERSITY OF ALBERTA

FACULTY OF GRADUATED STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled SAND REMOVAL FROM A VERTICAL HEAVY OIL WELL submitted by Kerry Anne Mazurek in partial fulfillment of the requirements of the degree of MASTER OF SCIENCE.

Dr. N. Rajaratnam (Supervisor)

Dr. J.D. Scott

Dr. S.M. Farouq Ali

DATED: 30 Sept. '94

ABSTRACT

A qualitative study was performed to investigate the mechanics of flow in a vertical heavy oil well. The objective was to determine the flow regimes in the area around the entrance to a progressive cavity pump for both a viscous sand slurry and a water/sand slurry. Sand removal from the well and the mechanisms for blockage of the pump inflow by sand were also observed. The possibility of improving sand removal from the well through a change in the design of the tail joint, a length of tubing attached below the entrance to the pump, was also investigated.

A half well model was used for flow visualization. Three flow rates were tested corresponding to 5, 10, and 15 m^3/day in a prototype well. Both glycerine and water were used as the liquid carrier phase for the fine sand. In the glycerine tests, sand was either continuously mixed with the glycerine to form a homogeneous slurry or added as a separate mass of a glycerine/sand mixture in a slug form. For the water tests, sand was added either continuously or in the form of a slug, where a period of sand addition is followed by a period of no sand addition. Three tail joint designs were examined.

It was found that the slotted tail joint filled with sand up to a level within the top slot for all flow cases. For the other tail joints, flow pattern formation did not occur until the sand level in the well was within a few centimetres of the entrance to the tail joint. For the viscous flow tests, the flow patterns depend on the viscosity of the sand slug. Flow pattern formation was more predictable and there was less tendency to block the tail joint entrance for less viscous sand slugs. Almost all sand was carried out of the well for the viscous, homogeneous slurry. For the water flow, sand removal is greatly dependent on flow rate in the range of flow rates tested. Sand removal was substantially improved from the lowest to the highest flow rate.

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NOTATION

S_g	specific gravity
API	API gravity
Q	flow rate through tail joint
Q_p	flow rate due to pump
Q_i	incremental flow rate
A	cross-sectional area of flow in the tubing.
h	difference in fluid level in the tubing between the times t_1 and t_2t
t_1	initial time
t_2	final time
D_{50}	grain size diameter for which 50 % of the particles are finer
D_{60}	grain size diameter for which 60 % of the particles are finer
D_{10}	grain size diameter for which 10 % of the particles are finer

CHAPTER 1: INTRODUCTION

I. PROJECT EVOLUTION

The work presented in this thesis was commissioned through a larger study undertaken by the Centre for Frontier Engineering Research (CFER). The intention of the CFER study was to develop a comprehensive understanding of the mechanics of solids (sand) production from oil wells situated in heavy oil, unconsolidated (sandstone that is not cemented) reservoirs. It was hoped that drilling, completion and operating strategies could be developed to reduce the costs of producing oil from this type of reservoir. The project was funded jointly by The Natural Sciences and Engineering Research Council and a number of oil companies as an NSERC-Industry Grant. This work includes collection and synthesis of well data for those companies involved in the CFER study; the statistics for these wells provides a basis for some of the work discussed herein.

The work presented here is only a small part of the total study. It is an effort to understand the mechanics of slurry flow of oil, water, and sand in the portion of the well that is near the entrance to a progressive cavity pump. It is an exploratory study of wellbore hydrodynamics as it relates to sand suspension characteristics.

II. COMPONENTS OF THE OIL WELL SYSTEM

The type of oil well under study is the primary, vertical, oil well. The well is cased through the producing part (pay zone) of the reservoir. The well makes use of artificial lift (a pump). Of most interest is that the lift is provided by a progressive cavity pump (also named the progressing cavity, eccentric screw, or Moineau pump). This pump is most often seated beneath the perforations in the well casing, where the flow from the reservoir enters the well. The typical well of the CFER study is depicted in Figure 1-1. Only the components of the well important to this thesis work are shown.

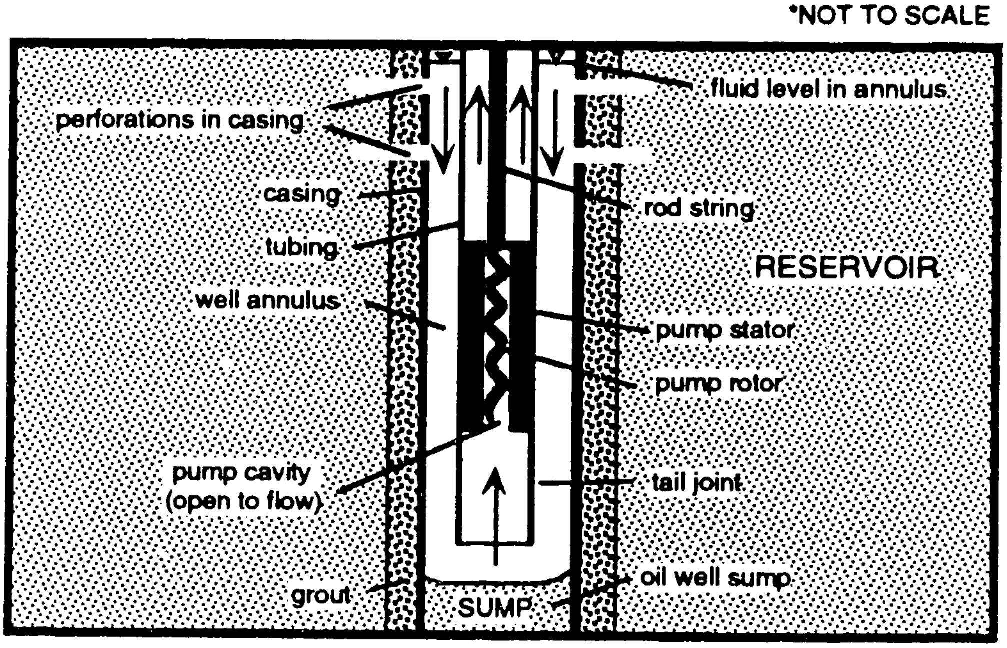


Figure 1-1: Components of the prototype well.

The casing is a pipe that provides support for the wellbore. The tubing encloses the flow moving to the earth's surface. The rod string turns the pump rotor by a torque applied to the top of the rod at the ground surface. The sump is a volume provided at the bottom of the well, used to hold excess sand that comes into the well when it is brought on production. The tail joint is an extra length of tubing added beneath the pump entrance. If the tail joint is not added beneath the pump, it is a "barefoot pump".

III. THE SANDING PROBLEM

Sand production is a potentially serious problem for all wells in unconsolidated sandstone reservoirs. For example, even minimal sand production in high rate gas wells can cause severe damage to production equipment. Sand control methods have been developed to inhibit sand flow into the wellbore. These include mechanical methods such as gravel packs, screens and filters, and chemical consolidation of the formation. Operational methods may also be used such as limiting flow rates. These sand control methods have been very successful at controlling sand production.

It was found, however, that for the wells producing heavy oil in unconsolidated reservoirs, that sand production may significantly increase the total productivity of these wells. Sand production "is considered to be fundamental to the ability of heavy oil wells ... to obtain the high production rates being observed during primary production (McCaffrey, 1990)." Thus, the production philosophy for the heavy oil wells tends to allow sand production while trying to minimize its negative effects.

The problems associated with sand production in the heavy oil reservoirs include the potential for sand to choke the flow within the wellbore and the production equipment. Sand may form bridges within the annulus to block flow from the perforations to the pump entrance. The sand may choke and perhaps totally block flow at the inflow to the pump. The sand may also plug the tubing at the pump discharge. All of these may cause a decrease in production from a well. The latter two may cause the pump to shut down. The well is said to be "sanded in" when these have occurred. Sanding may also accelerate wear to production equipment. The most serious effect of production of sand is the possible failure of the well to operate within its economic limits and therefore its consequent abandonment.

For the average well in the CFER study, sand related well servicing costs average $10 000 per workover. A "workover" is the acting of trying to stimulate production from a well, after its initial startup. Usually this requires that the well be taken "off production" for several days. The study wells averaged one workover every 170 days. Thirty percent of the wells averaged one workover every 50 days. Sixty percent of all workovers performed during the study period were sand related. This represents a significant portion of the operating cost for heavy oil wells drilled in unconsolidated reservoirs (CFER, 1994).

There is also an increasing environmental concern of sand disposal once it has reached ground surface. Typical volumes of sand produced from the wells in the CFER study ranged from 200 to 1200 m^3 during the life of the well. The wells have produced 1000 m^3 of sand on average.

A typical percentage of sand volume produced as a percentage of the bulk fluid is 40 % at the initial startup of production, with a gradual decline to around 3 %.

IV. PROJECT SCOPE

Understanding the mechanics of sand production requires both an understanding of the production the sand from the formation and the mechanics of flow of the fluid/sand mixture within the well. This thesis concentrates on the latter.

The original intent of this study was to seek an understanding of the mechanics of flow from the perforations in the casing to the entrance of a progressive cavity pump. Defining the problem in this way allows for a study of the mechanisms for sanding of the inflow to the pump. As this is an exploratory study, use of a physical model was desirable, specifically use of a visualization model. This project was later defined to study the flow in the area of the entrance to a progressive cavity pump. The goal was to evaluate how the flow regime changes with the flow rate and with the properties of the sand slurry fed to the well. The aim was to gain a qualitative understanding of the phenomena.

The sand slurry to be fed into the model was to use as viscous a fluid as possible within practical constraints. Sand was to be mixed in the slurry in two ways. First, as a homogeneous slurry with sand concentration varying from 5 to 50 % by volume (if possible). Secondly, in the form of a slug, where a period of sand addition is followed by a period of single phase (no sand) fluid flow in the well. As testing proceeded, it was also decided that a water based slurry would also be investigated. This provides a comparison for the results of the viscous slurry tests. It is also a possible (although extreme) situation in the field. Three flow rates for the prototype well of 5, 10, and 15 m^3/day which correspond to the operating conditions for the wells studies in the main CFER work.

After working with the initial setup for the model, it was proposed that perhaps a tail joint could be designed to improve the inflow characteristics of sand into the pump. With the correct tail joint design, sand removal from the well might be improved. This would reduce the potential for sanding at the inflow of the pump. As well, a change in the tail joint design would not effect more critical factors in the design and production of the well such as flow rate and tubing size.

Thus, this study evolved to become a qualitative examination of the mechanics of flow for both a viscous sand slurry and a water/sand slurry near the entrance to a progressive cavity pump. This is done for a varied tail joint design, slurry sand concentration, and method of sand addition at the model flow rates equivalent to the prototype well flow rates of 5, 10 and 15 m^3/day.

A review of petroleum engineering literature suggests that this type of study has not been undertaken previously.

V. OBJECTIVES

The objectives of the study can be summarized as follows:

- To study the mechanics of flow in a heavy oil well in the area around the entrance to a progressive cavity pump for both a viscous sand slurry and a water/sand slurry.
- To study the possible mechanisms for the formation of sand blockages (or sanding) to the inflow to the pump.
- To investigate the possibility of improving sand removal from the well, and hence reduce the potential for sanding of the pump inflow, through a change in the tail joint design.

VI. THE MODEL

A. Flow Visualization

Flow visualization is an effective method for monitoring the deposition and movement of the sand particles within the flow. It is also the general practice in fluid mechanics to perform a visualization study before performing quantitative work. An example of the usefulness of flow visualization is An Album of Fluid Motion, prepared by Van Dyke (1982).

To allow for the visual study of the flow, the use of a half well was proposed. The model well simulates a prototype well that has been cut in half by a vertical plate through its diameter. The practice of modelling a prototype that halved is a common technique for flow visualization. An example of this practice is its use by the consulting firm, Northwest Hydraulics, in the modelling of a conical settling tank for a Syncrude Canada Ltd. tailings stream (personal communication with Dr. N Rajaratnam, 1994).

There are also negative effects in the use of a half-well. The use of the front plate creates a wall in the centre of the well and therefore a no slip boundary for the flow. This shear on the front plate changes the velocity distribution in the annulus and the tail joint. For the flow in the tail joint, there is a decrease in velocity near the front plate and an increase in velocity near the tail joint wall as compared to flow in a fully circular pipe flow. Secondly, the front plate may suppress the formation of vortices because of the boundary it creates. However, the effect of the wall is difficult to assess. Vortex formation is potentially helpful in suspending sand within the tail joint and also in cleaning sand particles from the tail joint entrance. Thirdly, an oscillatory waviness was observed to predominate in the flow regimes for the sand slug tests in glycerine, described in chapter 4. However, no waviness was observed close to the front plate. This may be due to a viscous damping effect of the wall. Finally, it is thought that the intersection of the tail joint with the front plate may influence the formation of certain flow regimes. For example, in the Single Jet Regime for the wide entrance tail joint, again described in chapter 4, the single jet was found only to form against the front plexiglas. This suggests that the front plate may set a preferred location for the formation of the jet.

B. Model Sizing

For the model well used for this study, its dimensions were made as close to that of the prototype well as possible. A comparison of the dimensions of the casing and tubing used in the model well to that of the typical well in the main CFER study is given as Figure 1-2.

Due to practical limitations, the length of flow in the annulus from the perforations in the casing to the entrance of the pump had to be shortened. This length is typically 4 to 7 m for the wells in the CFER study. Note that for almost all the wells in the CFER study, the pump is seated below the perforations. It was assumed that it was not necessary to model this full length of flow. The flow length in the annulus for the model typically ranged from 0.90 to 1.25 m, depending on the length of the tail joint used for testing.

The full sump depth of a prototype well could also not be modelled due to practical limitations. A typical sump depth for the CFER study wells is 30 m. It was assumed (correctly) that the pump will only affect the sand in the sump to some small distance. The maximum depth of sump provided by the model is 0.69 m, when the tail joint length is zero. Typically, the available sump depth during testing was 0.25 m.

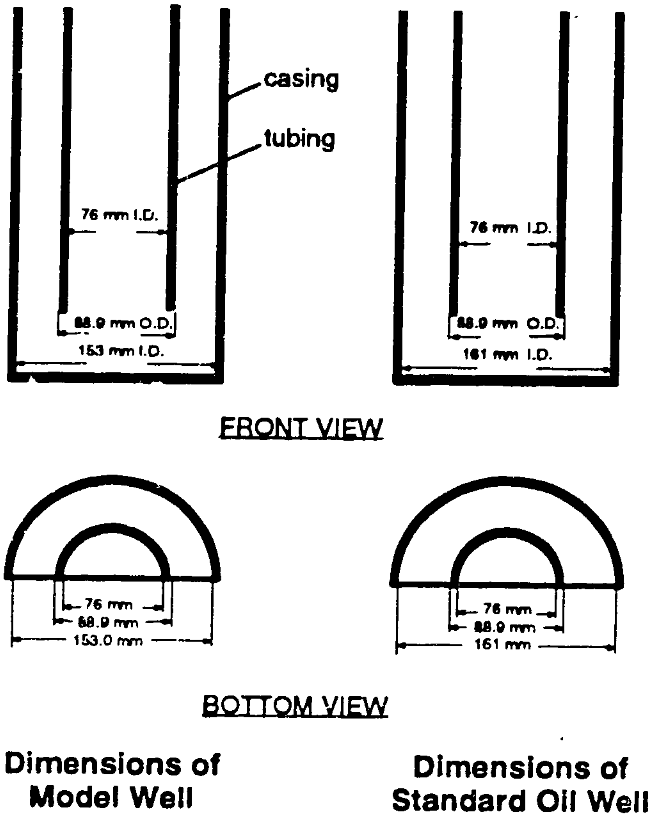


Figure 1-2: A comparison of the casing and tubing dimensions of the model and prototype.

VII. NATURE OF THE WELL FLUIDS

Fluids in the prototype well consist of a multiphase mixture of a very viscous heavy oil, gas, water, and sand. These fluids may also flow as an emulsion. The fraction of the different phases that make up the bulk fluid produced from the well vary. Knowledge of the composition and behavior of the fluids produced from the wells in the main CFER study was very limited at the start of this thesis work, and was based on the field experience of the oil company personnel involved in the CFER study. A comparison of the viscosity of glycerine to the values of viscosity of the different oils produced from wells in some of the different formations is given as Table 1-1. It is not known how these oil samples were collected, by what method the oil viscosities were determined, or at what shear rates the oils were tested. The specific gravity, S_g, was calculated from values of API gravity by the formula:

$$S_g = \frac{141.5}{131.5 + API}$$

In developing the concept for this model, it was decided that the model well fluids should be very simple at this early stage of the model development. Firstly, the model would not include a gas phase in the flow. Secondly, the fluid used was to have a very high viscosity, as close to the viscosity values of the heavy oils produced from the prototype wells as possible, within practical limits. This single liquid phase was to be mixed with a solids phase (sand) to form a slurry. After model testing with the chosen viscous fluid had begun, it was decided that also using water as a slurry fluid would provide a useful comparison. It is not unreasonable, for the produced fluid in the heavy oil wells in the CFER study to produce large quantities of water. The upper limit of water production as a percent of the bulk fluid produced from these wells is 100 % (not including the produced sand).

In a two phase solid-liquid flow, characterization of the solids phase becomes important. Again, there was very little information on the sand produced from the formations in the main CFER study. However, a range for the formations under study of 0.1 to 0.2 mm was given by CFER, suggested from their work with the oil companies involved in the main CFER study. Therefore, it was desirable to use a sand with an average grain size in this range, with a uniform grain size distribution. The specific gravity of the sand grains used in testing and of those produced from the oil well should not vary significantly.

Table 1-1: A comparison of the viscosity and specific gravity of glycerine to that of produced heavy oils (adapted from data collected by the Centre for Frontier Engineering Research).

Formation	Absolute Viscosity (cpoise)	Kinematic Viscosity (cstokes)	API	Specific Gravity	Ratio of dynamic viscosity of oil to glycerine	Ratio of kinematic viscosity of oil to glycerine
Glycerine (22°C)	1250	992	-19	1.26		
Basal Mannville	7700	7591	8	1.01	6.2	7.7
Clearwater	54981	54981	10	1.00	44.0	55.4
Cummings	16632	16750	11	0.99	13.3	16.9
Duperow	2232	2311	15	0.97	1.8	2.3
G.P.	5140	5176	11	0.99	4.1	5.2
Lloydminster	3672	3828	16	0.96	2.9	3.9
McLaren	5608	5727	13	0.98	4.5	5.8
McMurray	57600	53529	0	1.08	46.1	54.0
Sparky	7812	7757	9	1.01	6.2	7.8

CHAPTER 2: LITERATURE REVIEW

I. BACKGROUND

In pursuing literature on the thesis topic described in chapter 1, it was found that there is little published literature relating directly to the flow of a sand laden heavy oil mixture within a vertical oil well. In particular, there is no published literature for this type of flow for the boundary conditions (the tail joint design) used in this work. However, there are several subjects that aid in understanding this flow and, specifically, aid in understanding the simplified flow used in the described model. The relevant literature is vast and comprises several hundred papers. Therefore, only general treatises on these subjects are discussed herein.

II. PHYSICS OF FLOW

Flow of very viscous fluids at low flow rates falls under the regime of low Reynolds number flows. This subset of laminar flow is generally referred to as "creeping flow". The single phase fluid flow at low Reynolds numbers is discussed by Schlichting (1979). Happel and Brenner (1965) present an extensive mathematical treatment of creeping flow. This includes a discussion of the low Reynolds number motion of a single particle moving through an infinite fluid; the motion of a few interacting particles; the effect of simple boundaries such as the wall of a cylinder; and the settlement of concentrated suspensions. They also deal with the subject of fluidization and the viscosity of suspensions.

The physics of a single particle moving through a fluid (or the fluid moving past the particle) is discussed in Schlichting (1979) and Raudkivi (1990). Raudkivi goes on to discuss the settling of a group of dispersed particles (hindered settling) and the settling behavior of particles in a group.

III. RELATED SUBJECTS

Sediment transport (e.g. for the suspended load in rivers), generally deals with particle laden water at low particle concentrations in natural channels of small slope. A review of the mechanisms of sediment transport are given by Raudkivi (1990) and Vanoni (1975). However, these mechanisms are somewhat different from this thesis work, as in the physics of sediment transport, the vertical sand settling acts in a direction normal to the main horizontal flow.

Work on the topic of slurries also discusses the flow of particle laden fluids. Reviews are provided by Wasp et al (1977), Shook and Roco (1991), and Brown and Heywood (1991). Generally, the study of slurry transport is concerned with sand or coal laden water flow at high particle concentrations (as compared with the subject of sediment transport) in horizontal pipes.

Considerably less attention has been paid to the flow of slurries in vertical pipes or the similar topic of hydraulic hoisting. Shook and Roco (1991), Govier and Aziz (1972), and Brown and Heywood (1991) give only brief accounts of vertical slurry flow in each of their treatise on slurry flow. It has been found that the delivered particle concentrations (the concentration of particles out the outlet of flow) differs (it is less) from the particle concentration within the pipe for particles with a density greater than that of the carrier fluid in an upward flow. A buildup of the particle concentration within the pipe potentially can occur. Newitt et al (1961) state that the delivered concentration in an upward, vertical pipe flow is only significantly different from the concentration of particles in the pipe when the ratio of the mean velocity of the fluid to the settling velocity of the particles is small. They did not put limits on this ratio. However, Govier and Aziz (1972) recommend that the operating conditions for slurry flow in a vertical pipe be that the minimum mean velocity is at least two times greater than the terminal settling velocity of the largest particle (or the particle with the greatest settling terminal settling velocity). They do not take particle concentration effects on the settling velocities into account; however, their use of the single particle terminal settling velocity would result in a conservative operating condition.

Most studies of the conveyance of solids in vertical pipes try to predict the head losses for flow (see, for example, Newitt et al (1961)). However, Shook (1988) discusses the problem of segregation of particle mixtures and plug formation in hydraulic hoisting. His presentation reviews intermittent or slug slurry flow in which hydraulic hoisting processes frequently operate. His slurry consists of a high concentration mixture (45 % particle concentration by volume) of two particles of differing sizes but equal density. His numerical work predicts a redistribution of the particles, as the coarser particles settle through the fines. If the concentration of the particles rises high enough, because of differential settling, a plug can form in the pipe. Shook defines a plug as "not an impervious barrier, but a mixture which offers a very high resistance to motion". This definition of plug is essentially equivalent to that considered as "sanding of the tail joint entrance" for the water tests described in the following chapters. Shook's treatment was concerned with the concentration profiles along the length of the slug with time. Only the flow conditions leading up to plug formation were considered. He does not predict the formation of a plug, although he warns that plugs can occur when a situation is allowed where coarse or more dense particles settle through fine or less dense particles.

Slurry flow in horizontal pipes is categorized into homogeneous and heterogeneous flows. This classification is based on the concentration gradient of the particles across the diameter of the pipe (along its height). The ratio of the particle concentration at 80 % of the height of the pipe diameter to the particle concentration at the pipe's centre is not less than 80 % for a homogeneous flow (Wasp et al, 1967). Homogeneous slurries, tend to behave similarly to single phase fluids, although they exhibit non-Newtonian behavior as the concentration of the particles in the fluid increases. Shook and Roco (1991) comment that any time the time scale for particle settling in the fluid is much less than the time scale of flow, it is likely that slurry will behave as a combined fluid (like a single phase flow) rather than as two distinct, separate phases. Knowledge of the behavior of homogeneous slurries is important for the continuous sand feed tests in glycerine for this thesis work.

The flow behavior and properties of non-Newtonian fluids are discussed in detail by Skelland (1967) and in other works such as Wilkinson (1960) and Patel (1983). Also, included in these works are discussions on the determination of non-Newtonian fluid viscosities. A review of the work on the rheological properties of suspensions is provided by Jeffrey and Acrivos (1976). A description of the rheology of coarse settling suspensions is provided by Clarke (1967).

The flow of fluids of varying density, or stratified flow, also is related to this thesis work. Discussions of this topic are given by Simpson (1987) and Harleman (1961). A fluid with a varying concentration gradient particles of a different density than the carrier fluid, may be thought as a stratified flow since the density of the combined fluid will vary with particle concentration.

The mechanics of fluidization is also significant to this work. It encompasses flow through high concentrations of particles and particle suspensions in a vertical flow. Fluidization is reviewed by Davidson (1963), Kunni and Levenspiel (1969) and Howard (1989). Shook and Roco (1991) also briefly discuss this phenomenon. An incipiently fluidized bed can be considered to be equivalent to vertical slurry flow, as solids are supported only by fluid drag.

CHAPTER 3: EXPERIMENTAL SETUP & TESTING PROGRAM

I. THE MODEL WELL

A. Experimental Setup I

The first experimental setup developed isolates a 1.35 m section around the pump entrance. The model simulates a vertical section taken through the diameter of the well. A schematic is given in Figure 3-1. Plexiglas is used for the casing and tubing of the well to provide for the visual monitoring of the flow. The comparison of the model well dimensions to the standard size of the prototype well was given in Figure 1-2. The model well is shown in Plate 3-1.

This apparatus requires only one pump to circulate the fluid in the system. The fluid flows from storage bin 2 located above the well, to the "mixing section" of the apparatus. There it can be mixed with sand supplied by a Vibrascrew sand feeder. This mixture then flows into the annulus of the well. Within the well, the fluid/sand slurry flows down the annulus and through the tail joint towards the pump outlet. A 1.15 m long tube of 1.5 inch inside diameter connects the well at this outlet to a small progressive cavity pump. The pump returns the slurry to storage bin 1, where the sand settles and the fluid clarifies. The fluid then returns for use to storage bin 2.

The tail joint length in the model is adjustable. The tubing is held in place by five screws that are bent to wrap around the tubing. Bolts on the outside face of the front plexiglas sheet tighten to hold the tubing against the plexiglas. The tail joint length can be adjusted by loosening these bolts and sliding the tubing within the screws. The tubing can also be completely removed from the model when necessary.

The fluid storage bins are 32 US gal plastic garbage bins. Metal connectors, of 1.5 inch diameter, are provided at the base and 15 cm below the top of each bin. Flow moves into a bin through the connector at its base. Fluid moves out of a bin through the top connector. It is atmospheric pressure at the fluid surface within the bins. The tubing that connects the entire system is the same 1.5 inch inside diameter, plastic, flexible tubing that connects the well and the pump.

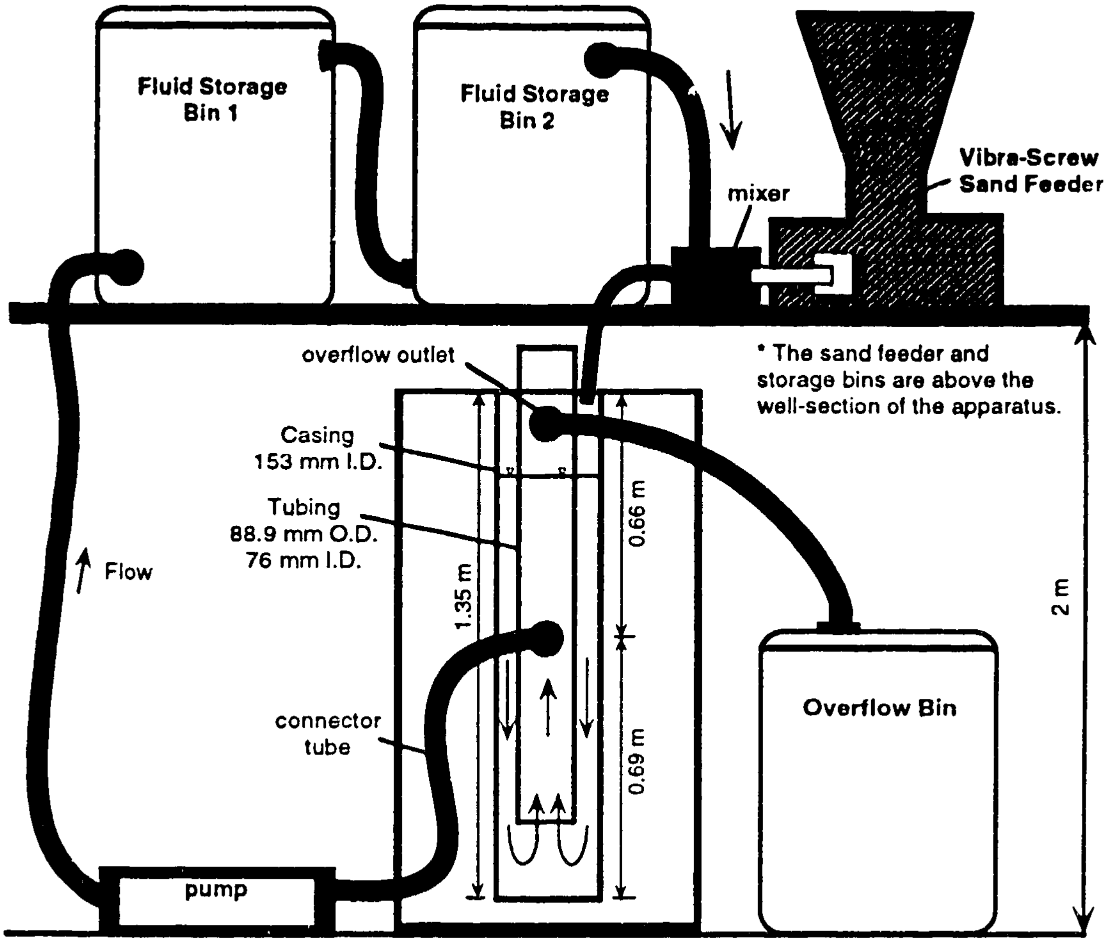
The overflow outlet was provided to ensure that the fluid in the well did not flow out the top of the well. The outlet is located 10 cm below the top of the well. A flexible rubber tube connects the overflow outlet to a 20 L pail that serves as the overflow bin.

The mixing section and pump are discussed in their own separate sections.

B. Experimental Setup II

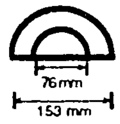
1. Reasons for a Change in Setup

As testing progressed, it was found that it was necessary to modify the original experimental setup. This was due to several reasons. The first is that the flow rate through the tail joint could not be held constant. The sand acted as additional flow component to the constant recirculating flow caused by the pump. This additional flow overflows through the overflow outlet at the top of the tubing. Therefore, the addition rate of sand is an undesired additional flow rate through the tail joint. The increase in flow rate provides an increase in velocity through the tail joint and therefore an increase in the capacity of the fluid to carry sand. This was considered undesirable because in the



FRONT VIEW

Note: The arrows denote the direction of flow.



BOTTOM VIEW

Figure 3-1: Experimental Setup I.

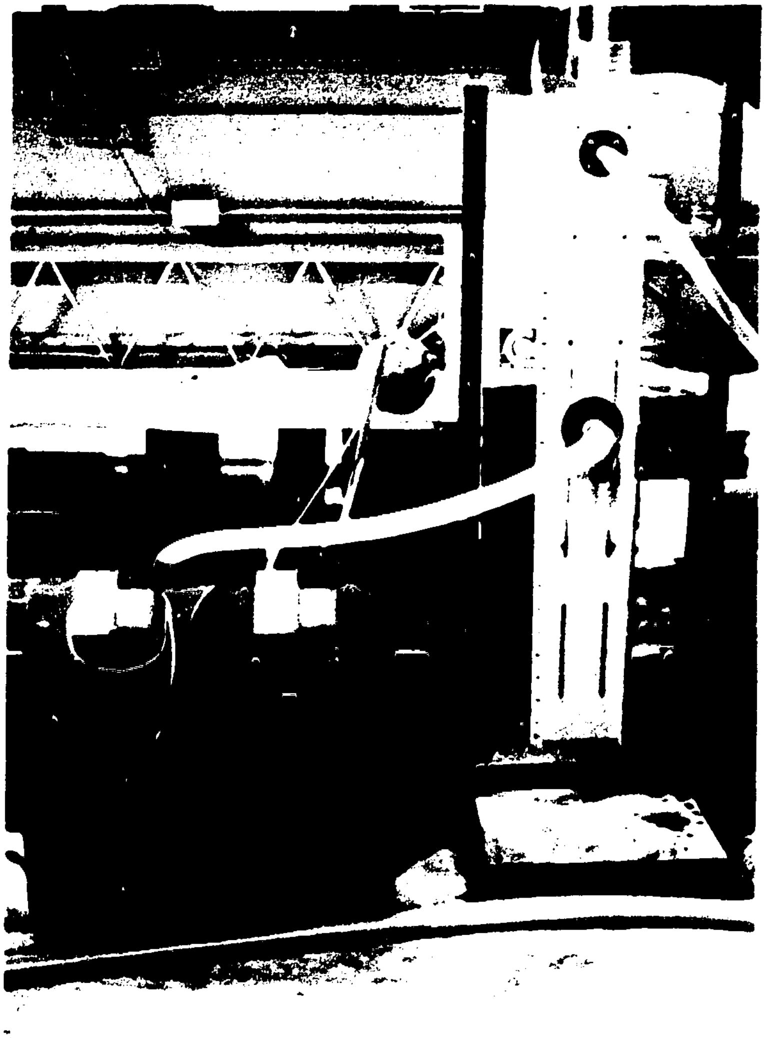


Plate 3-1: The model well.

prototype well, the pump removes fluid from the tail joint at a relatively constant rate, the pumping rate.

The other main problem with the previous setup is that with the storage bins raised above the well section of the apparatus (they were located on a platform 2 m above the base of the well) it is an unwieldy task to clean the sand out of the bins. Frequent cleaning of these bins is required. In order to speed the completion of testing and to provide for a more ergonomic setup, a better method of cleaning the bins was necessary.

The considerations for the design of the second experimental setup can be summarized as follows:

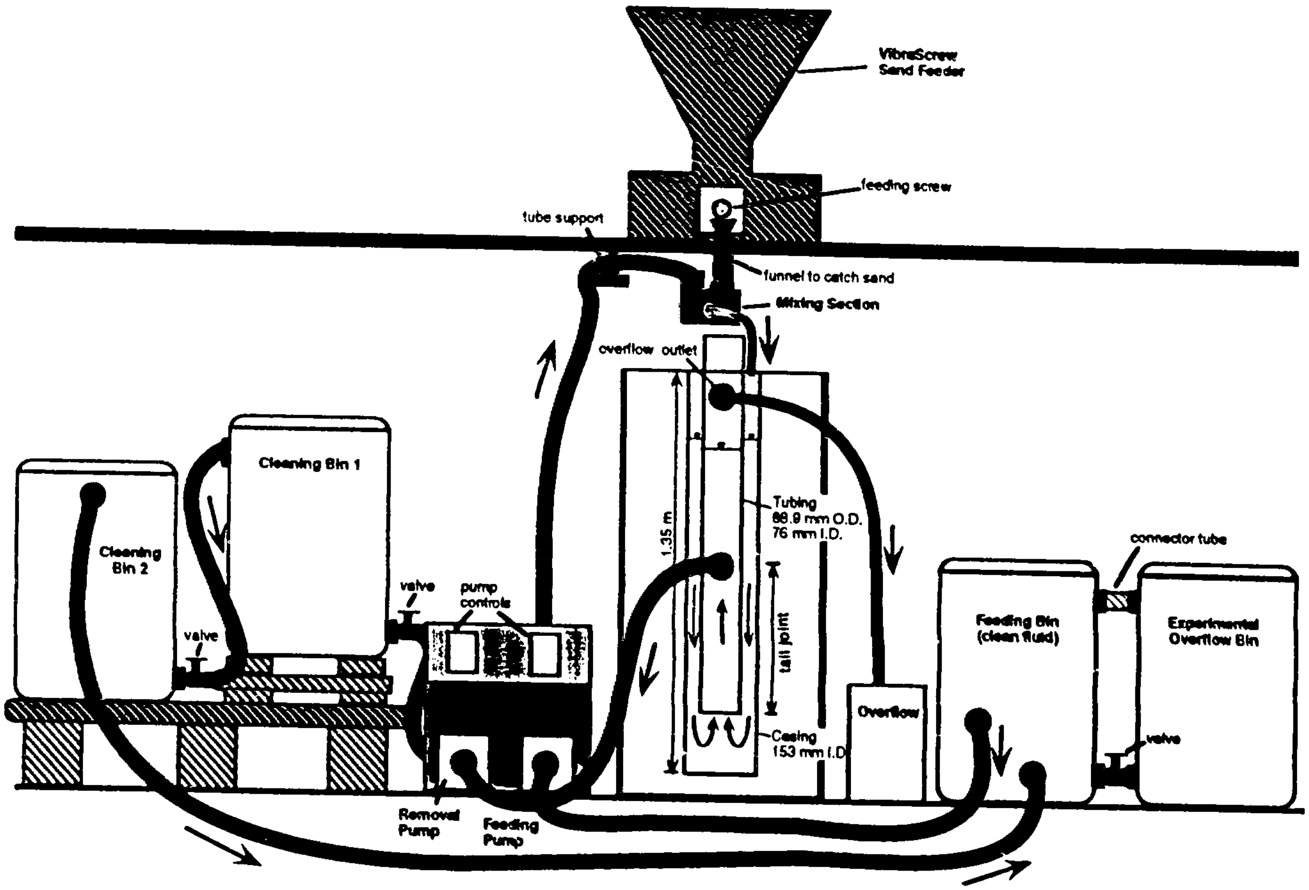
- The apparatus must provide a constant (homogeneous) slurry flow rate through the tail joint.
- The apparatus must be relatively easy to clean and the storage bins must be easily assessable.
- The duration of the test must be maximized before a shutdown for cleaning is required.
- It must be simple to change base fluids in the apparatus from the viscous fluid to water.
- It must be permit the different types of sand addition to the well.
- It must minimize changes to the existing design.

2. Design and Operation of Setup

This experimental setup uses the same "well section" of Experimental Setup I. It differs from the first setup in that it makes use of two identical progressive cavity pumps, one for feeding the fluid into the well (the "feeding pump"), and the other for removing the fluid from the well (the "removal pump") at the pump outlet. The removal pump is also responsible for moving the slurry to the cleaning bins. A schematic of this apparatus is given in Figure 3-2. Plate 3-2 gives the layout of this setup. The feeding and overflow bins are in the lower left corner of this picture. Plate 3-3 shows the Vibrascrew sand feeder and the mixing section of the apparatus.

This experimental setup, as in the first setup, depends on the recirculation of the base fluid. Clean fluid (the base fluid) is taken out of the feeding bin by the feeding pump. The feeding pump then pushes the fluid either to the mixing section of the apparatus or directly into the well annulus, depending on the type of sand addition. Within the well, the fluid flows down the annulus and through the tail joint. It is taken out of the well when it reaches the pump outlet by the removal pump. This pump pushes the fluid into the bottom of cleaning bin 1. It is here that most of the sand settles out of the slurry. To aid in clarifying the fluid, another cleaning bin was added. The fluid overflows from the top of cleaning bin 1 to the bottom of cleaning bin 2. The overflow of the second bin is returned (by gravity) to the feeding bin. If desired, more cleaning bins can easily be added to the system. As well, the system sometimes operated with only one cleaning bin while the other was cleaned. This is the case in Plate 3-2.

To correct the problem of additional flow through the well when the sand is added, the pumping rate of the feeding pump can be adjusted to correspond to the addition rate of sand. This provides a constant flow rate through the tail joint, as there will no longer be overflow. For example, it is desired that there be a constant flow rate through the well at 5.0 m^3/day, with a sand concentration by volume of 50 %. The removal pump is set at 5.0 m^3/day. The sand feeder is then set to provide sand at 2.5 m^3/day. Therefore, the



FRONT VIEW

Note: The arrows denote the direction of flow.

Figure 3-2: Experimental Setup II.

Plate 3-2: Layout of Experimental Setup II.

Plate 3-3: The Vibrascrew sand feeder and mixing section of the apparatus.

feeding pump must be set at 2.5 m^3/day to give a constant mixture flow rate of 5.0 m^3/day. The flow rate of 5.0 m^3/day is first pumped to the cleaning bins and then returned to the feeding bin. However, only 2.5 m^3/day is being removed from the feeding bin by the feeding pump. This results in an extra flow rate at the bin of 2.5 m^3/day. This extra flow is collected in the experimental overflow bin.

An additional value of the use of the two progressive cavity pumps is that a test could be shut down almost immediately upon shutting off the pumps. With the one pump system, and the use of the weir system at the cleaning and feeding bins to provide fluid to the well, the fluid was still fed into the well for about 20 min after the pump had been shut down. Sometimes this flow would be greater than the flow through the overflow outlet, and the fluid would spill from the top of the well annulus.

Another new characteristic of the second setup from the first, was that a T-valve was provided at the outlet of the removal pump. This allowed for sampling of the slurry removed from the well.

C. Materials Used

1. Fluids

a. General

The term "fluid" used in the previous description of the operation of the apparatus refers to either glycerine or water. Glycerine was used to provide a viscous, laminar flow. Water was used to gain an understanding of how the conditions change when the fluid in the well is relatively inviscid and flow becomes turbulent.

b. Glycerine

Glycerine (or glycerol) is a very viscous, Newtonian, clear fluid. It was required that the fluid used be clear so that the transport of sand could be monitored visually. The viscosity of pure glycerine at 22°C (test temperature) is approximately 1250 cp. The specific gravity of glycerine at this temperature is 1.260. Glycerine was chosen for the experiments because of its high viscosity, transparency, availability, relatively low cost, and low toxicity. It is also miscible with water, which makes the apparatus easier to clean. A comparison of the viscosity of pure glycerine at 22°C to the viscosity of some heavy oil produced from various formations is given in Table 1-1. The viscosity of glycerine is very sensitive to temperature. A plot of this relationship is given in Figure 3-3.

Unfortunately, as testing proceeded, it was discovered that glycerine is hygroscopic. As well, the absorption of water vapour occurred rapidly (partly due to the high humidity conditions associated with a hydraulics laboratory). The drop in viscosity on the absorption of relatively small amounts of water is large. Figure 3-4 gives the relationship between the viscosity of glycerine at 22°C and water content. The viscosity at this temperature was linearly interpolated from viscosity values given at 20 and 25°. Figure 3-5 gives the variation of the density of glycerine at 22°C with water content by weight. The glycerine used was 99.7 % pure glycerol (0.3 % water by weight).

The lowest measured viscosity of the glycerine used during testing was 900 cp and averaged 1115 cp for the tests. The average specific gravity was 1.258. The flow patterns observed when using "older" or less viscous glycerine varied from those when

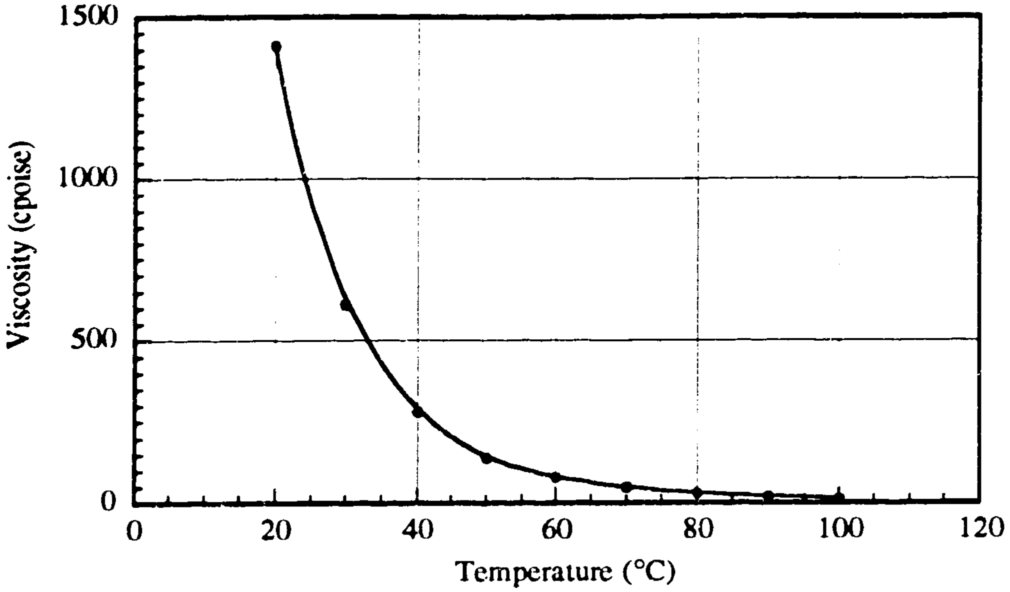


Figure 3-3: Variation of the viscosity of pure glycerine with temperature (from Segur and Oberstar, 1951).

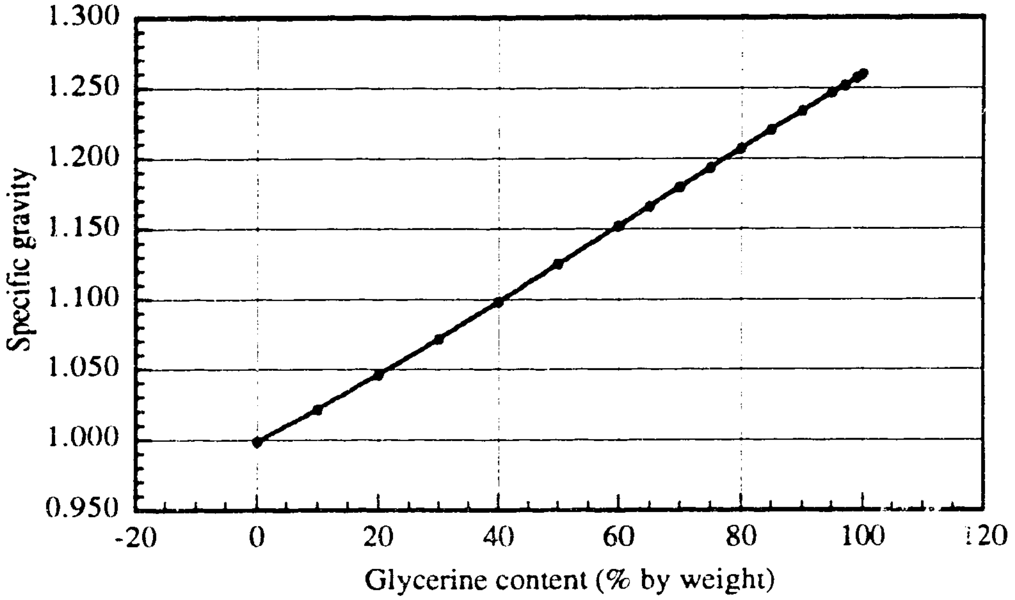


Figure 3-4: Variation of viscosity with water content given in % glycerine by weight (from Segur and Oberstar, 1951).

"newer" or more viscous glycerine was used. However, this change in behavior may be looked upon positively, as a broader range of viscosities, and therefore Reynolds numbers, have been tested.

In their use of glycerine for the analysis of fluid flow, Hsieh and Rajamani (1991) report that both glycerine and glycerine and water solutions are Newtonian fluids.

c. Water

The viscosity of water at 22°C is 0.96 cp. Its density at this temperature is 0.998 g/cm^3. These are linearly interpolated values between the temperatures of 20°C and 25°C and are taken from the viscosity tables given in Streeter and Wylie (1985).

2. Sand

The grain size distribution of the fine sand that was used in most experiments is given in Figure 3-6. It is designated as 70-140 frac sand. The average grain size is 0.17 mm. The coefficient of uniformity, defined as the ratio of the diameter of the particle that 60 % of the material is finer than to that diameter which 10 % of the material is finer (D_{60}/D_{10}), is 1.4. The range for a typical formation sand grain size, suggested by the CFER well data, is 0.1 to 0.2 mm.

D. Mixing of the Homogeneous Slurry

1. Glycerine Slurry

Mixing for the homogeneous glycerine/sand slurry, required for the continuous sand feed tests, is provided by means of a drill with a long bit. Plates 3-3 and 3-4 show the mixing section for this homogeneous slurry. A schematic is given as Figure 3-7. A 50 cm long, 4 cm inside diameter, copper pipe acts as a mixing chamber. A 37.5 cm long, helical, wood bit of 6 cm pitch and groves of 3 cm width, carries and mixes the slurry within the pipe. A drill, driven by compressed air, turns this bit. The glycerine is first to be supplied to the mixing chamber. The sand enters the chamber when it falls into the funnel from the Vibrascrew sand feeder and through the feeding pipe. When the sand reaches the mixing chamber it mixes with the glycerine. The slurry is forced out of the copper pipe and is directed by a short piece of flexible tubing into the well annulus.

This mixing system works most effectively for mid range glycerine flow rates (5.0 m^3/day) even at high concentrations of sand. The slurry produced appears to be fairly homogeneous. For low glycerine flow rates, this system tends to clog, and therefore break down, as there is not enough fluid to mix and carry the high concentrations of sand. However, when the system does work correctly, a homogeneous slurry is achieved. The mixing system also tends to clog at high flow rates (7.5 m^3/day), regardless of the slurry sand concentration, as the capacity of the drill/drill bit system, turning at the maximum rotational speed of the drill, is not enough to carry all the flow pumped into the chamber. As well, the homogeneity of the slurry appears to be reduced, as strangely sometimes dry sand deposited in the well annulus. It has not been determined how this could occur.

2. Water Slurry

For the continuous sand feed tests in water, the drill system that mixed the viscous slurry was not used. The sand supplied by the Vibrascrew feeder was carried in a long, V-shaped channel and deposited directly into the well annulus. Upon hitting the water

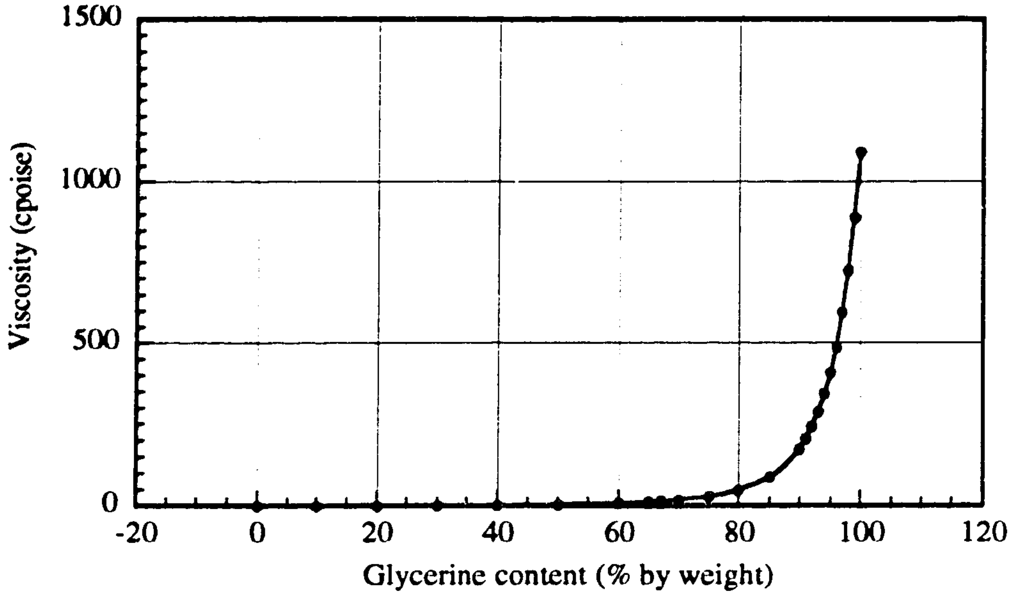


Figure 3-5: Variation of density of glycerine with water content % by weight (from Bosart and Snoddy, 1928).

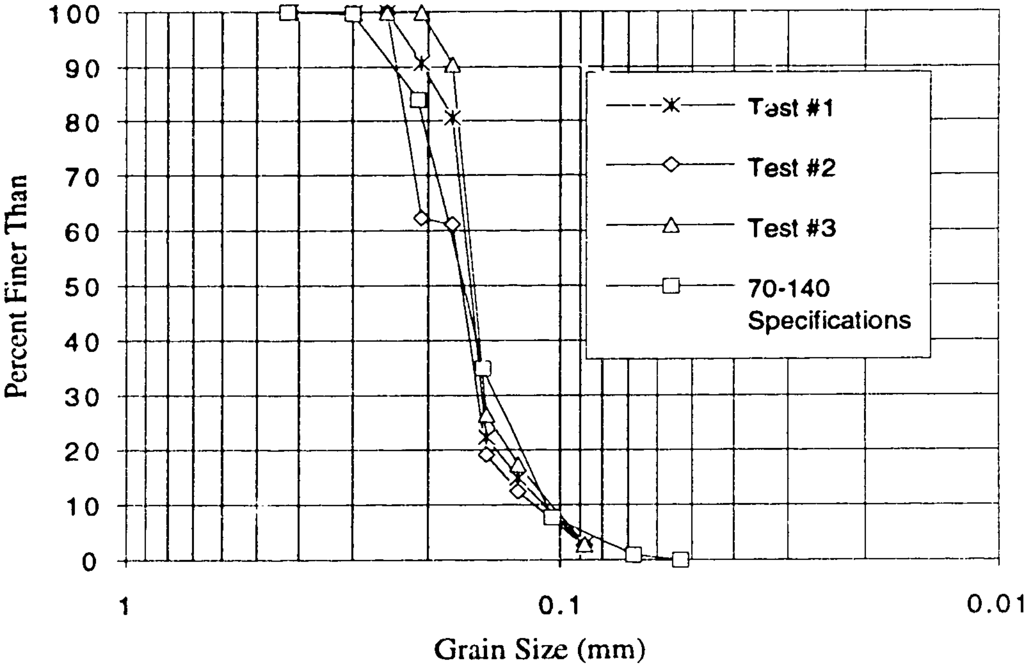


Figure 3-6: Grain size distribution of the 70-140 frac sand used in testing.

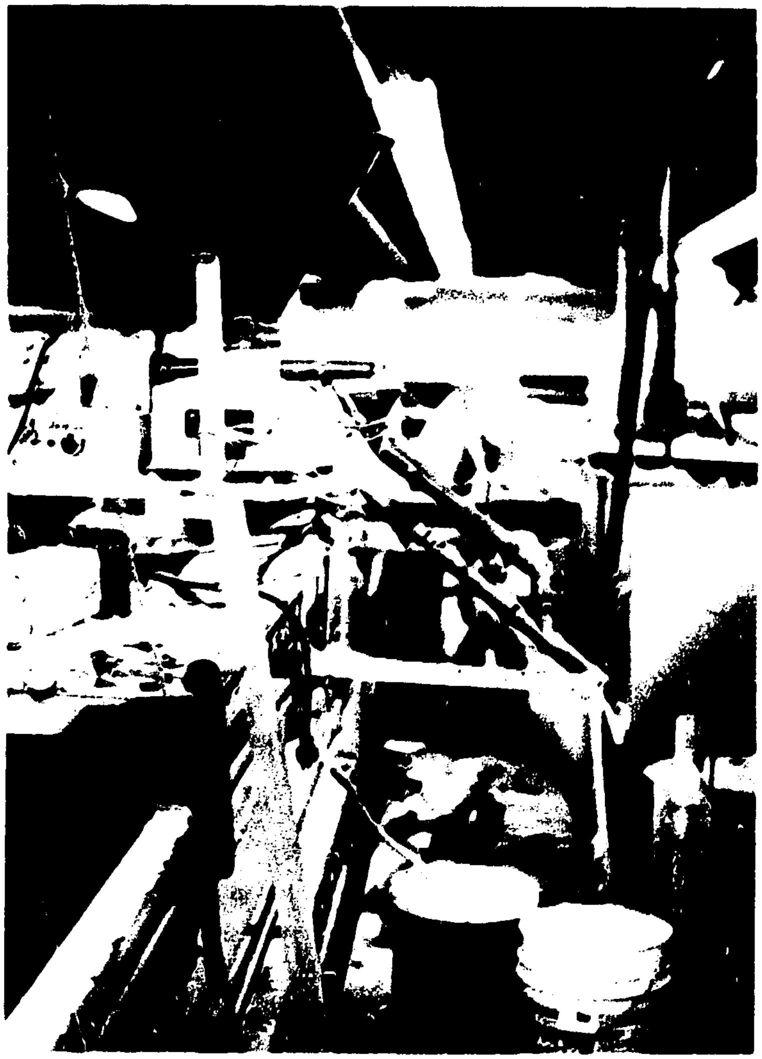


Plate 3-4: Mixing system for the viscous slurry.

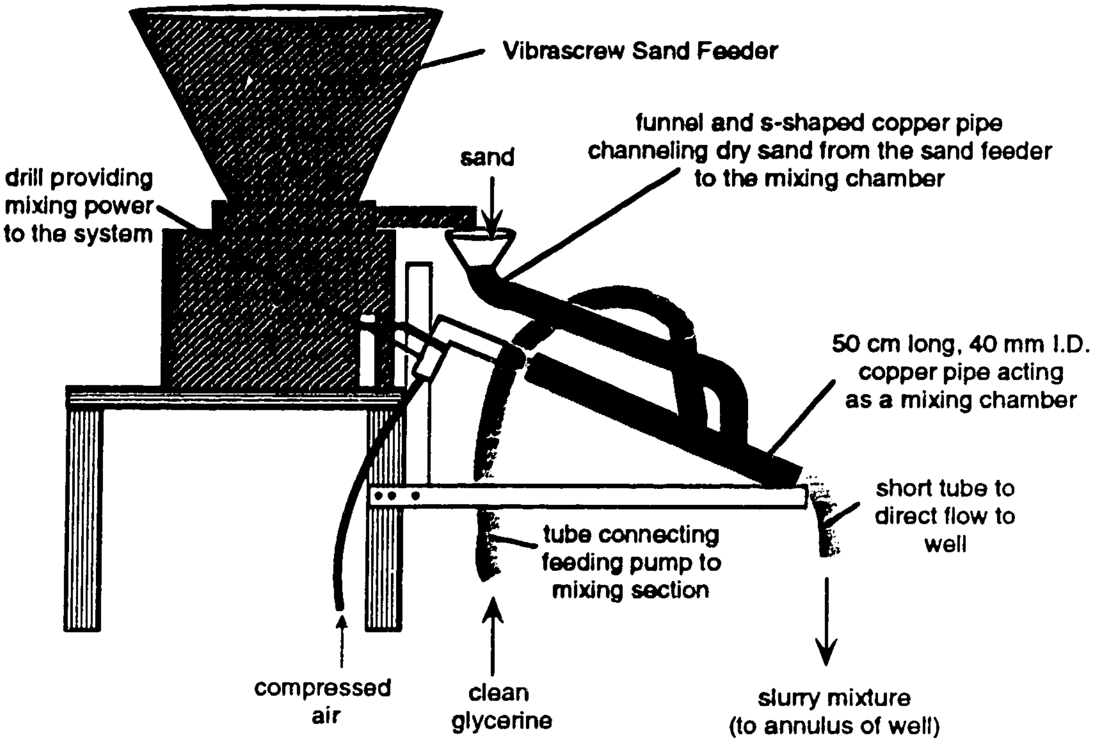


Figure 3-7: Schematic of the mixing system for the viscous slurry.

surface, the sand dispersed throughout the well. The water was fed into the well annulus directly from the feeding pump. Thus, no mechanical mixing system was required. To avoid sand buildup at the top of the annulus, the water level in the well was kept at a high level. Once the sand becomes wet, it falls into the well annulus. Plate 3-5 shows this setup.

E. Pumping of the Model Fluids

The pump(s) used in the two different experimental setups were small progressive cavity pumps. The model type of these pumps is a Seepex size 1, 6 L pressure stage, BN range eccentric screw pump. These pumps have a variable speed drive. As well, the pump is directly coupled to the drive unit. A transistorized invertor was connected to each pump, complete with a parameter unit to monitor the frequency of the current "fed" to the pump motor. This frequency is digitally displayed on a parameter unit. Changing the frequency, changes the motor speed, and thus increases or decreases the pumping rate. The pumping rate was calibrated with this current frequency readout on the parameter unit. Thus, the flow rate could be controlled by inputting the frequency, corresponding to the desired flow rate, into the parameter unit. No extra equipment to monitor flow rate was used.

Progressive cavity pumps consist of two parts, a rotor rotating eccentrically inside a stationary stator. Typically, the rotor is a single helical gear inside a double helix stator of the same minor diameter and twice the pitch length (Saveth and Klein, 1989). A sketch of the pump components is given in Figure 3-8. As the rotor rotates, sealed cavities are formed, 180° apart, by the contact of the rotor with the stator. The result is that the fluid inside the cavities is slowly "squeezed" upwards from the pump entrance to its outlet. At the pump entrance, an area is always open to flow as the rotor moves within the stator. This is depicted in Figure 3-9. Thus, the pump provides a continuous, non-pulsating flow when operating at a high efficiency (Wild, 1991).

Wild (1991) discusses fluid flow into the pump. At the pump entrance, the opening of the cavity produces an opening or void space into which the fluid flows. The amount of fluid to flow into the opening depends on the fluid viscosity, the differential pressures across the opening, the time this cavity is open to flow, and the size and shape of the opening. Theoretically, the lowest pressure to exist within a cavity is vacuum pressure. If the pressure difference across the pump entrance is great enough for the voids to fill completely, the pump operates at its full displacement. If this pressure is not enough to fill the cavity, "cavitation occurs as the fluid pressure drops within the cavity. When cavitation occurs, part of the cavity will be filled with vapor which is condensed after the rotor closes behind it and applies positive pressure (Wild, 1991)." The result is a pulsating, erratic, and potentially noisy flow.

A discussion of the use of progressive cavity pumping systems in heavy oil reservoirs is given in Lea et al (1987).

II. THE TESTING PROGRAM

A. Test Variables

1. Flow Rate

The flow rates used for testing were 2.5, 5.0, and 7.5 m^3/day. These rates correspond to 5, 10, and 15 m^3/day in the prototype well.

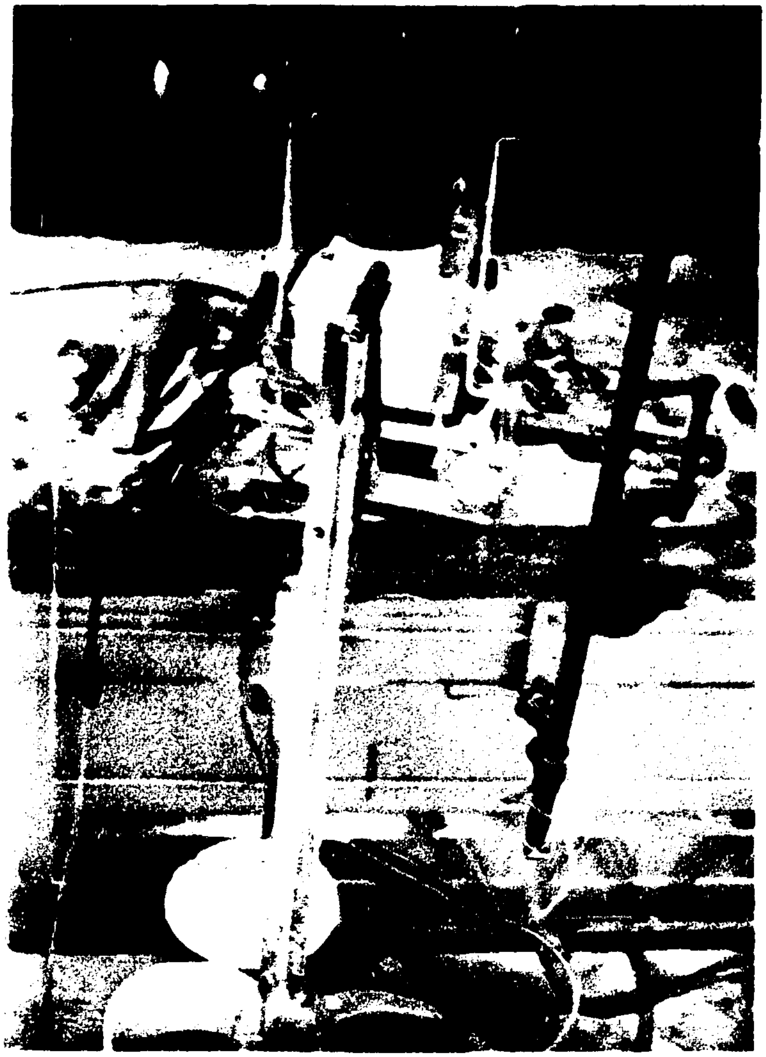


Plate 3-5: Setup for the continuous sand feed into the well for the water tests.

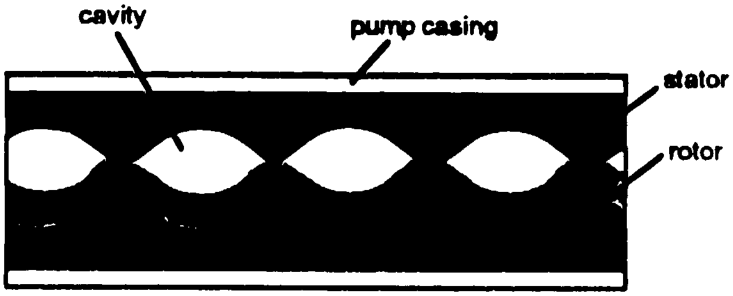


Figure 3-8: The components of a progressive cavity pump (adapted from Saveth and Klein, 1989).

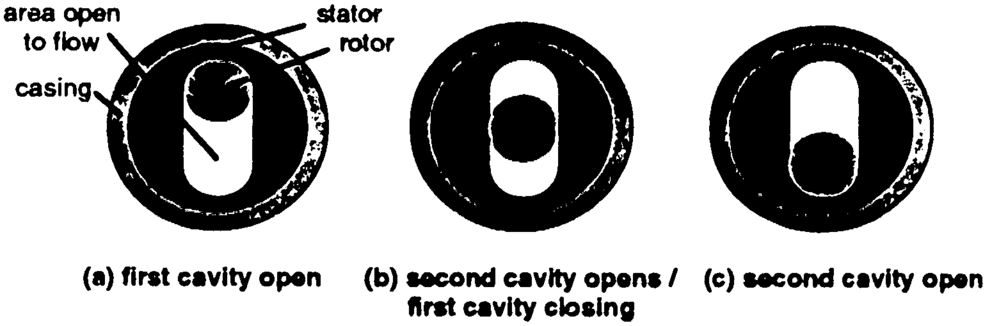


Figure 3-9: Movement of the rotor within the stator at the pump entrance (adapted from Saveth and Klein, 1989).

2. Sand Addition

Sand was added to the flow by two methods. The first is the "continuous sand feed", where the sand is continuously fed into the well at a constant rate and is mixed to form a homogeneous slurry. This method of sand addition makes use of the Vibrascrew sand feeder. Mixing of the slurry occurs in the "mixing section" of the apparatus, which is described in the section "Mixing of the Homogeneous Slurry". The flow rate of the feeding pump is adjusted to account for the addition rate of sand. Sand percentages for these tests have varied from 5 to as high as 50 % by volume of the slurry flow.

High sand concentration, continuous sand feed tests were not performed for the 5.0 and 7.5 m^3/day flow rates. This is mainly due to the inability of the Vibrascrew sand feeder to supply the required flow rate of sand. Tests at the 5.0 m^3/day flow rate were limited to a sand concentration of 20 %. Tests at the 7.5 m^3/day were limited to a sand concentration of 10 %. Another problem in performing the higher sand concentration tests for the larger flow rates is the total volume of sand required to run these tests for a significant length of time. For example, to perform a test at 7.5 m^3/day and 30% sand concentration for a half an hour would require 124.2 kg of sand. This is beyond the capacity of this experimental setup.

The second method of sand addition is the sand slug. A period of sand addition is followed by a period of no sand addition. The flow rate is not adjusted to account for the additional of volume of sand in the flow. For the water tests, the time between slug additions was typically about 4 min. For the glycerine tests, this time was typically 5 min.

For the glycerine tests, the "slug" was added as a cohesive mass of glycerine wet sand. The properties of these slugs depend on their percentage of glycerine. A sand slug that contains a higher percentage of glycerine (and is fully saturated) will flow easily under the application of a stress. It will also mix with the surrounding fluid when added to the well. The cohesion between the sand particles is not strong. The concentration of sand in this type of slug is in the range of 35 to 45 % sand by volume. A dense sand slug exhibits a strong cohesion. It can be molded into a ball shape and will not lose this form for several minutes. The concentration of sand in this slug is close to 60 %. This type of slug may not be fully saturated with glycerine. This extra phase may cause an additional cohesion between the sand particles in the form of interfacial tension. The dense sand slug does not flow easily and does not quickly mix with the surrounding fluid once added to the well. The size of the slugs ranged from about 125 mL to 500 mL. Their size had to remain small because of their great tendency to block flow to the pump and therefore to cause the apparatus to overflow. These slugs were added by hand at the top of the annulus, near where the fluid enters the well.

For the water tests the sand slug, which is fully saturated with water, is added to the main flow. The slug sand was held in a container above the well and washed into the well using the main flow. The sand becomes well dispersed throughout the well annulus quickly. Slug sizes varied greatly. Their volume ranged from 0.28 L to 5.5 L. Since the fluid flow rate from the feeding pump was not adjusted to account for the addition of slug sand, the "slugs" are in addition to the main flow through the well. Table 3-1 gives the slugs sizes, length of time for slug addition, and the time averaged additional flow rate to the well for the different flow rates tested. It also gives the ratio of the total flow (main flow plus sand addition rate) to the intended or main flow. It should be noted, however, that this does not necessarily give the increase in flow rate through the well. This is because of storage effects in the well annulus and other mechanisms to be discussed in the section "Mechanisms of Flow in the Well". Consistency of the slug sizes was based on the mass of the water saturated sand.

Water saturated sand was used for these slugs primarily because a large quantity of water wet sand was available from previous tests. If dry sand was to be used for slugs, new sand would have had to be used for each test or the sand from the previous tests would have to be dried. Due to the large volumes of sand used, this would be expensive and/or time consuming.

3. Tail Joint Design

Three main designs for the tail joint were investigated. The first is the slotted tail joint. The design for this tail joint was adapted from a Pan Canadian Petroleum Ltd. design. It is a tubing with a completely open bottom, two half-slots cut into the side at the mid-point of the tail joint, and another full slot cut out of the pipe, very near the pump outlet. The second type of tail joint has been named the wide entrance. It a length of tubing with a completely open bottom and no slots (a length of pipe). The last tail joint has been named the small hole entrance. It is a piece of tubing that includes a bottom piece with a 32 mm diameter semi-circular hole. Figure 3-10 depicts these three tail joint designs.

Two other types of entrances were tested briefly. The first is the barefoot pump. Here the bottom opening of the small hole entrance was brought to the level of the pump outlet in hopes of simulating the situation where the pump has no tail joint. However, tests with this entrance seemed to yield unreliable results. As well, it was felt that this setup would not adequately simulate the eccentric movement of the pump rotor across the diameter of the pump. The second type of entrance was called the clayed entrance. It is so named because clay was used to provide a 32 mm diameter semi-circular opening through the entire height of the tail joint. This entrance was used only for a few water/sand slug addition tests. The purpose was to help determine whether the ability of the small hole entrance to remove sand could be improved by increasing the velocity of the fluid through the entire length of the tail joint instead of just at the bottom opening. However, work with the clayed entrance was left for later research.

4. Test Duration

a. Average Test Duration

The duration of the glycerine tests with a continuous sand feed was generally just over 30 min. This duration was arbitrarily chosen, however, large amounts of sand (more than enough to sand in the entrance) will have been added to the well by the end of that time. The test duration may have been smaller than 30 min if many problems were encountered with the mixing section at that test flow rate and sand concentration. If the test duration was smaller than 10 min, the test was redone. If the test duration was greater than 20 min when a breakdown of the system occurred, the test was not redone. If the test duration was between 10 and 20 min, the test was redone if it had not be retried several times prior to the most recent breakdown.

The duration of the water tests with a continuous sand feed typically lasted 10 min. However, a test of this type may be only a few minutes in length if the tail joint becomes plugged with sand. If that occurred, the test was stopped.

The sand slug tests using both glycerine and water typically averaged 45 min in length.

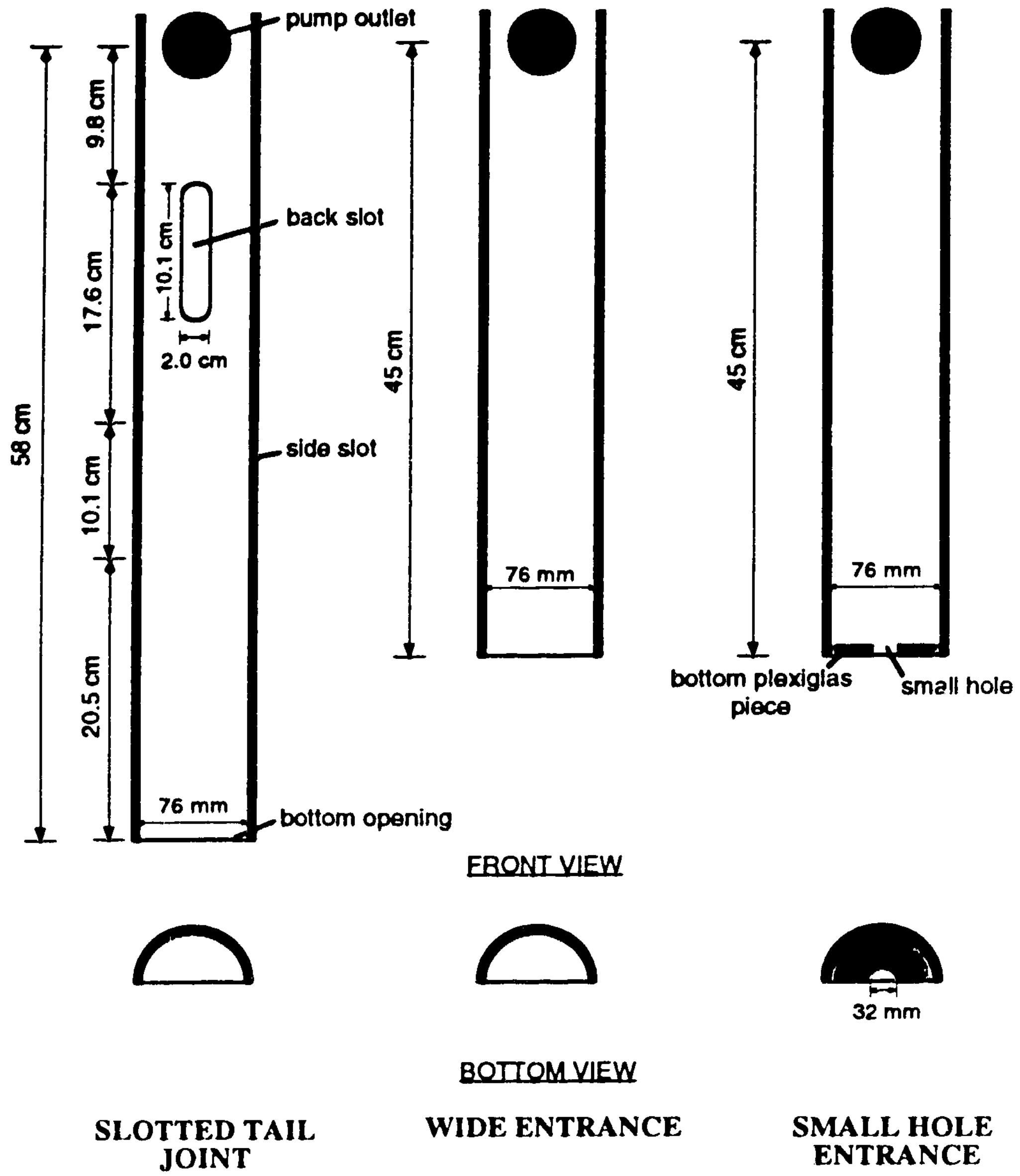


Figure 3-10: The three tail joint designs used in testing.

b. Limits to Testing Times

The duration of the tests depended very much on the total volume of sand added to the flow, as there is a limited capacity for sand storage in the system. The theoretical testing times for the continuous sand feed tests are given in Table 3-2 for each flow rate used. The maximum testing time is based on a usable storage bin volume of 60 L. The absolute maximum testing time is based on a storage volume in the bins of 80 L. After the absolute maximum test duration, a storage bin should be filled with sand and its use as a settling basin is inhibited. The rate of sand filling of the bins is based on the volume of the sand grains plus an additional volume for the void space in the sand (assuming a porosity of 35 %).

B. Observations

1. Visualization of the Flow

Almost all tests were video recorded. To aid visualization of the flow patterns a number of methods were used.

Dye was added to the flow to determine whether the flow was laminar or turbulent. It was also useful in determining the depth of flow underneath the tail joint entrance for the wide and small hole entrance tail joints. This gives an approximation to the pump suction depth. It was also used for the slotted tail joint to determine if there was flow through the side slots and/or the bottom opening.

Bubbles were prevalent in the glycerine flow. They were useful in determining that the flow was laminar. They were also useful in determining the streamlines of flow and in estimating the pump suction depth.

Black colored pepper flakes were added to the sand because their movement could be easily monitored against the background of sand particles. The pepper was used mainly to help monitor the movement of the sand particles within the different flow regimes for both the glycerine and water tests.

Poppy seeds are black and round, with a diameter of about 0.5 mm. The seeds were used in the same manner as the pepper flakes. However, they have the additional property that they are heavier than water, but lighter than a sand/water suspension. Thus, when they are added to a sand slug during a water test, the seeds float on the top of the sand suspension and act as an interface marker between the end of the slug sand and a return to a single phase water flow.

The sand particles themselves were useful for flow visualization. They help determine whether the flow is laminar or turbulent. They trace the structure of the flow i.e. vortices. As well, the sand particles are a part of, and therefore help determine, the flow regime.

2. Sand Level in the Sump

The height of sand in the sump (or sump level) as compared to the height of the tail joint entrance was originally thought to be an important variable to be measured. Therefore, initially this level was monitored closely. However, it was soon found that the sump level was not significant. It rises to within a few centimetres of the tail joint entrance in the glycerine tests, and a few millimetres of the entrance in the water tests, before any significant amount of sand is carried out of the well by the flow. (Actually, this is true for all tests except the glycerine tests using a continuous sand feed, where the sand in the slurry does not settle quickly enough for this to occur). The level of sand in the sump was noted during each test. However, it will not be reported in the thesis as it largely does not affect the flow patterns observed.

3. Slurry Sand Concentration

The concentration of sand in the pump out slurry was monitored for the glycerine tests with a continuous sand feed. Samples were taken every 2.5 min in a 500 mL graduated cylinder from by opening the T-valve sampler, located at the outlet of the removal pump (see the description of experimental setup II). A hydrometer was used to measure the specific gravity of the sampled slurry. By comparing the specific gravity of the slurry to that of glycerine, the sand concentration can be calculated. These sand concentrations will not be reported in this thesis.

Sampling of the concentration of sand in the slurry pumped out of the well could not be done for the water tests. Sand settled out of the slurry in the tubing connecting the pump outlet and the removal pump (see the description of experimental setup II). This makes it impossible to obtain an accurate measure of the slurry concentration.

4. Fluid Properties

Before each glycerine test (as well as after for the glycerine, continuous sand feed tests) the viscosity, specific gravity, and temperature of a 1 L glycerine sample were recorded. The viscosity was measured using a Brookfield DVI+ Digital Viscometer. The spindle was a cylindrical spindle with an effective radius of 0.9421 cm and effective length of 7.493 cm (given by Brookfield in their manual associated with the operation of the viscometer). The spindle guard was used for all tests, as the viscosity readings on the viscometer are calibrated by the manufacturer for its use. The rotational speed of the spindle was 3.0 rpm. The viscometer test was carried out in a 1 L beaker of 10.0 cm diameter.

Specific gravity measurements were taken using an appropriately scaled hydrometer in a 500 mL graduated cylinder.

5. Fluid Levels in the Well

The fluid levels in both the well annulus and tubing were monitored during most tests. This aids in recognizing when the flow into the tail joint has been restricted by the sand. These values will not be reported in this thesis. However, their significance is discussed in the section, "Mechanisms of Flow in the Well".

C. The Testing Program

The following describes the tests performed. It summarizes the fluid, sand addition, and experimental setup used as well as what measurements were taken for each phase of testing (test group). A summary of the type of tests performed in given in Table 3-3. A detailed overview of all tests is given in Table 3-4.

1. Group A - Initial Glycerine Tests

In this initial set of tests with glycerine, both slug and continuous feed sand addition were used. The glycerine was very viscous for most of these tests and the sand slugs had a high concentration of glycerine (they were "flowable"). These experiments were formed using Experimental Setup I and were helpful in determining the operational performance of the model. Only the sump level was monitored during these tests (not including the video record of the tests).

2. Group B - Water Tests

These tests were performed with water using slug sand addition. Experiments were performed using Experimental Setup I. The quantitative measurements included the difference in fluid levels in the annulus and tubing and sump sand level.

3. Group C - Glycerine Tests

These glycerine tests were performed using a continuous sand feed. Experimental Setup II was used. The feeding pump flow rate was adjusted to account for the sand feed rate into the flow, so that the mixture flow rate through the well was constant. Measurements of the viscosity of glycerine, density, and temperature of the glycerine were taken before and after each test. Other quantitative measurements included a sampling of the concentration of sand removed from the well with time; monitoring the fluid levels in the annulus and tubing; and measurement of the sump level and shape with time.

4. Group D - Glycerine Tests

These glycerine tests were performed using sand slug addition. The glycerine for these tests became increasingly less viscous. Most sand slugs used had a high concentration of sand (they were "dense"). Slugs of varying "flowability" were also tested. These tests were performed using Experimental Setup II. Measurements included the fluid level in the annulus and the tubing and sump level.

5. Group E - Water Tests

These water tests were performed using a continuous sand feed into the well. The pumping rate of the feeding pump was adjusted to account for the sand feed rate. The change in sump level with time was monitored. Experimental Setup II was used for these tests.

III. MECHANICS OF FLOW IN THE WELL

A. The Model Well

1. Single Phase Flow

When the pump removes flow from the model well, the reduced pressure likely only affects a small area around the pump outlet. The flow through the tail joint is driven by the pressure difference at the tail joint entrance, due to the fluid levels in the annulus and the tubing (refer to Figure 3-11). The pressure or head difference, assuming a constant flow through the tail joint equal to the pumping rate, depends on this flow rate, the losses due to friction along the pipe walls, the losses at the tail joint entrance, the density of the fluid columns in both the annulus and tubing, and gravity.

Due to the free surface in the tubing, the flow through the tail joint, Q, can be different than the pump driven flow, Q_p. The incremental flow rate, the difference between the flow rate Q and Q_p, is given by the increase in fluid level within the tubing (multiplied by the constant cross-sectional area of the tubing) with time, by the principle of the

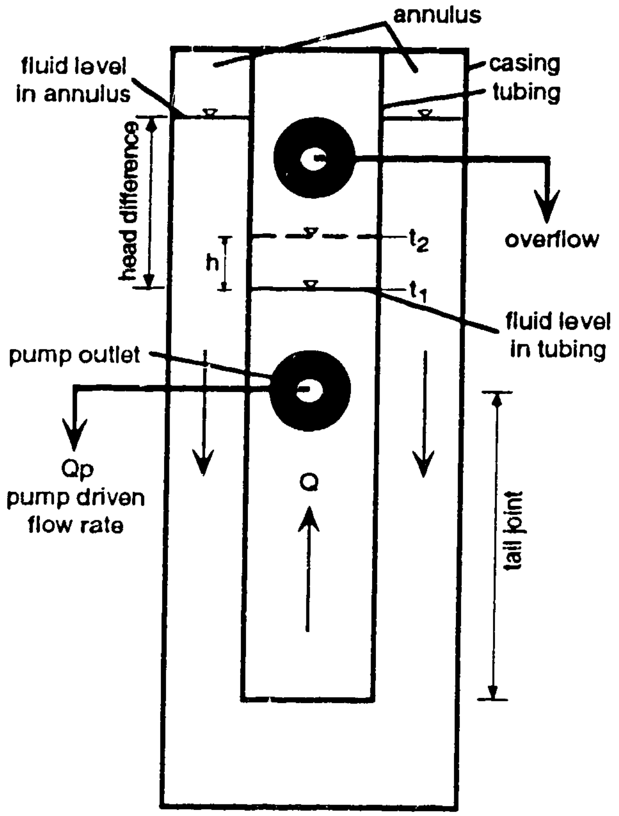


Figure 3-11 A sketch of the flowing model well.

conservation of mass. Using this same principle, a decrease in fluid level in the tubing signifies a flow rate through the tail joint of less than the constant pump driven flow. The incremental flow rate, Q_i, over an arbitrary time span, $t_2 - t_1$, can be given by:

$$Q_i = A\frac{dh}{dt} = A\frac{h}{t_2 - t_1}$$

where A = cross-sectional area of flow in the tubing.
h = difference in fluid level in the tubing between the times t_1 and t_2.
t_1 = initial time.
t_2 = final time.

2. Sand Slug Addition

The flow rate of the fluid fed into the well was not adjusted to account for the additional flow rate caused by the sand for the slug sand addition tests. However, the rate of sand addition may not correspond to a change in flow rate through the tail joint because of storage effects in the annulus. Other factors affecting the flow include a sand blockage of the tail joint entrance.

An example of a possible variation of the flow rate through the entrance with the addition of a sand slug, based on experience and observations of the fluid level in the tubing is given in Figure 3-12. The initial time is the time at which the first part of the slug of sand flows into the well annulus. The line designated as Q_p gives the flow rate created by the pump. Initially, as the sand travels down the annulus, the flow rate through the tail joint increases beyond the pumping rate, due to an increase in the fluid level in the annulus. As the sand reaches the tail joint entrance, it partially blocks flow into the tail joint. This results in a flow rate through the tail joint that is smaller than the pumping rate, shown by a decrease in the fluid level in the tubing. As this occurs, the fluid level in the annulus rises. The head difference between the fluid columns in the annulus and tubing soon becomes great enough to clear at least some of sand out of the entrance. The flow rate through the tail joint quickly increases to a value greater than the pumping rate. This flow rate slowly decreases to the pumping rate as the fluid levels in the annulus and tubing become stable. When the flow through the tail joint has been completely blocked with sand (it has sanded in), the subsequent rush of flow into the tail joint when some of the sand is removed may be many times greater than the pumping rate.

For the water tests, there is potential for a variation in flow rate because of the volume of the sand slugs used was large. The variation in flow rate caused by the glycerine slugs may also be large, although slug volumes were small at about 250 mL. This is due to their high propensity to plug the tail joint entrance. The fluid levels in the annulus and tubing could reach their respective maximum and minimum heights in the model well (for safe operation of the apparatus). The associated increase in flow rate when the sand was moved out of the entrance was large. If the slug is not substantially block the entrance in the glycerine tests, the increase in flow rate due to the extra sand volume in the flow is minimal.

This variation in flow rate may not be important to the flow patterns and sanding mechanisms as one would intuitively expect, considering that the increase in velocity in the tail joint, increases the flow's capacity to carry sand. The same type of flow regimes and sanding mechanisms were seen for the water slug tests and the flow rate adjusted continuous sand feed tests in water. For the glycerine tests, it is not directly known how this increase in flow rate affects the flow regime formation.

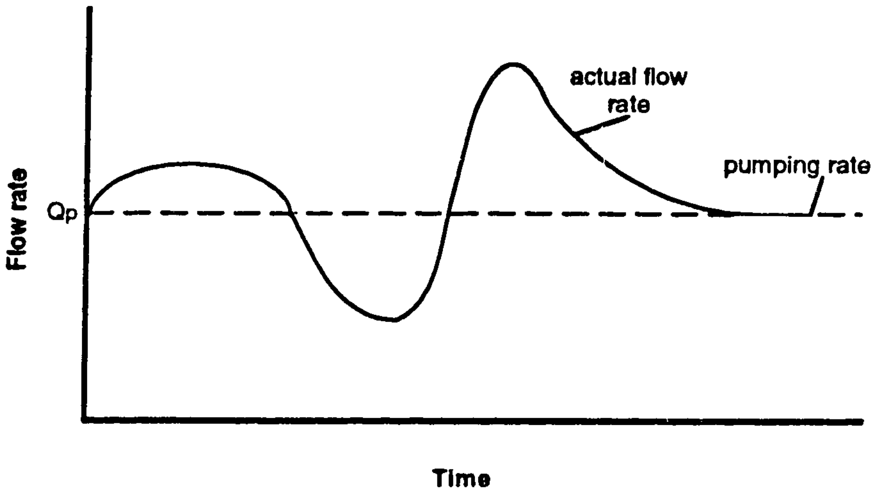


Figure 3-12: The variation in flow rate after the addition of a sand slug.

B. The Prototype

In the prototype well (see Figure 1-1) all the fluid that flows through the tail joint must move into the pump. This differs from the model, where fluid that has moved through the tail joint may also be stored in the fluid column in the tubing above the pump outlet.

The potential pressure difference across the tail joint entrance is much greater in the prototype than in the model. Bottomhole pressure in the prototype (from CFER well data) average from 100 to 200 kPa. Bottomhole pressure is defined as the pressure in a well at a point opposite the producing formation (Leecraft, 1983). If the pump is seated, on average, 5.5 m below the perforations in the casing, and assuming a specific gravity of the well fluid of 1.0, there is a potential for pressure difference of 150 to 250 kPa across the entrance area to the pump. This compares to a maximum possible pressure difference across the entrance of the tail joint, due to the difference in level between the fluid in the annulus and in the tubing, of about 6 kPa for a single phase water flow and 7.5 kPa for a single phase glycerine flow.

IV. MECHANICAL PROBLEMS WITH THE SETUP

There were many difficulties experienced in the mechanical operation of the described model. Some of this problems were already discussed within the relevant sections.

For the water tests, sand deposits in the tube connecting the pump outlet and the removal pump. This caused two main problems. The first occurs in the area of the pump outlet of the model well, where a pile of sand fills the outlet. Sand continuously spills from this "pile" into the tail joint. This volume of sand is not large. However, as a result, a small amount of sand will remain in the tail joint long after the sand from, for example, a sand slug was removed from the well. The other problem caused by the deposition of sand in this tube, was that as the sand builds up, it will suddenly fall as a large slug into the initial pump cavity. The pump could handle this large influx of sand and shut down. This was a serious operational problem for the water tests at the 2.5 m^3/day flow rate.

Another problem was that for the continuous sand feed tests in glycerine, the sand did not completely settle out of the pumped out slurry before returning for use in the feeding bin. Thus, as the fluid in the system is recirculated, the concentration of sand in the slurry pumped into the well tended to increase through the duration of the test. The values for the sand concentration (by volume) in the glycerine at the end of the test is reported in Table 3-4. This concentration is based on a simple comparison of the specific gravities of glycerine samples (taken from the T-Valve sampler) before and after each test. It ignores the effect of a change in temperature (and possibly water content) between the two samples.

Flow, moving into the tail joint at the intersection of the tail joint wall and the front plexiglas, occurred if the screws holding the tubing in place were not tightened sufficiently. It was not possible to prevent this flow across the front plexiglas if the tail joint used was very long. Thus, the tail joint length used in testing for the small hole and wide entrances typically was about 45 cm (measured from the bottom of the tail joint to the centre of the pump outlet). A longer length was used for the slotted tail joint to accommodate the back slot.

A potential problem with the use of glycerine is the potential for mold growth. Segur and Oberstar (1951) note that this occurs for glycerine water solutions with a water content (by weight) of 50 % and greater. This did not tend to be a problem within the experimental setup as glycerine was never purposely mixed with water. However, any glycerine that spilled from the model tended to mix with water from the air and other sources (such as leaks from the other hydraulics experiments). Significant mold growth occurred in the area surrounding the model.

V. REYNOLDS NUMBERS

Reynolds numbers and particle Reynolds numbers are given for a variety of flow situations in Table 3-5. For consistency, the hydraulic radius is used for the length scale in the Reynolds numbers due to the variety of the shapes of the flow areas. The effect of the front plexiglass sheet in calculation of the hydraulic radius is ignored. Glycerine kinematic viscosity is based on the 1115 cp viscosity and 1.258 specific gravity that were the average measured properties of the glycerine during testing. Viscosity of the water is based on its properties at 22°C. The Reynolds numbers are given for flow in the annulus; in the tubing; through the small hole in the small hole entrance (a 32 mm semi-circular hole); through an opening of 20 % of the area of the back slot at the top of the slot; and through a rectangular opening 2.0 cm by 0.5 cm just beneath the tail joint entrance for a wide entrance that has been partially blocked with sand. The particle diameter used in the particle Reynolds number is the average grain size of the sand used in testing, 0.17 mm. The settling velocity of the particle was determined using the drag coefficient for a sphere.

Table 3-1: Water Test Slug Addition.

2.5 m^3/day (1.74 L/min)							
Mass added	Volume added	Average addition time for 3 trials	Increase in Flow Rate		Total Flow rate		Ratio of total flow to intended flow
(Kg)	(L)	(s)	(L/min)	(m^3/day)	(L/min)	(m^3/day)	
0.53	0.28	9.33	1.77	2.55	3.51	5.05	2.02
1.06	0.55	14.33	2.30	3.32	4.04	5.82	2.32
1.59	0.83	21.33	2.32	3.34	4.06	5.84	2.33
2.12	1.10	28.00	2.36	3.39	4.10	5.89	2.35
2.65	1.38	29.33	2.81	4.05	4.55	6.55	2.62
3.18	1.65	32.00	3.09	4.46	4.83	6.96	2.78
3.71	1.93	36.33	3.18	4.58	4.92	7.08	2.83

5.0 m^3/day (3.47 L/min)							
Mass added	Volume added	Average addition time for 3 trials	Increase in Flow Rate		Total Flow rate		Ratio of total flow to intended flow
(Kg)	(L)	(s)	(L/min)	(m^3/day)	(L/min)	(m^3/day)	
0.53	0.28	5.00	3.30	4.75	6.77	9.75	1.95
1.06	0.55	10.00	3.30	4.75	6.77	9.75	1.95
1.59	0.83	13.33	3.71	5.35	7.18	10.35	2.07
2.12	1.10	18.00	3.67	5.28	7.14	10.28	2.06
2.65	1.38	19.33	4.27	6.14	7.74	11.14	2.23
3.18	1.65	23.00	4.30	6.20	7.77	11.20	2.24
3.71	1.93	26.00	4.44	6.40	7.91	11.40	2.28
4.24	2.20	28.33	4.66	6.71	8.13	11.71	2.34
4.77	2.48	39.00	3.81	5.48	7.28	10.48	2.10
5.30	2.75	41.00	4.02	5.80	7.49	10.80	2.16
6.36	3.30	47.67	4.15	5.98	7.62	10.98	2.20
7.42	3.85	58.67	3.94	5.67	7.41	10.67	2.13
7.95	4.13	61.00	4.06	5.84	7.53	10.84	2.17
8.48	4.40	63.33	4.17	6.00	7.64	11.00	2.20
9.01	4.68	71.67	3.91	5.64	7.38	10.64	2.13
10.60	5.50	102.33	3.22	4.64	6.69	9.64	1.93

7.5 m^3/day (5.21 L/min)							
Mass added	Volume added	Average addition time for 3 trials	Increase in Flow Rate		Total Flow rate		Ratio of total flow to intended flow
(Kg)	(L)	(s)	(L/min)	(m^3/day)	(L/min)	(m^3/day)	
0.53	0.28	4.67	3.54	5.09	8.75	12.59	1.68
1.06	0.55	7.67	4.30	6.20	9.51	13.70	1.83
1.59	0.83	11.00	4.50	6.48	9.71	13.98	1.86
2.12	1.10	14.00	4.71	6.79	9.92	14.29	1.90
2.65	1.38	17.33	4.76	6.85	9.97	14.35	1.91
3.18	1.65	19.00	5.21	7.50	10.42	15.00	2.00
3.71	1.93	21.67	5.33	7.68	10.54	15.18	2.02
4.24	2.20	23.67	5.58	8.03	10.79	15.53	2.07
4.77	2.48	36.67	4.05	5.83	9.26	13.33	1.78
5.30	2.75	39.33	4.19	6.04	9.40	13.54	1.81
6.36	3.30	44.33	4.47	6.43	9.68	13.93	1.86
7.42	3.85	52.00	4.44	6.40	9.65	13.90	1.85
8.48	4.40	57.33	4.60	6.63	9.81	14.13	1.88
9.01	4.68	59.00	4.75	6.85	9.96	14.35	1.91
9.54	4.95	73.00	4.07	5.86	9.28	13.36	1.78
10.60	5.50	79.33	4.16	5.99	9.37	13.49	1.80

Table 3-2: Theoretical Testing Times.

Flow Rate (m3/day)	7.5					
Flow Rate (L/min)	5.208					
Sand Concentration (%)	Sand particle volume flow rate (L/min)	Sand mass flow rate (kg/min)	Rate of sand filling bin (L/min)	Max. Testing Time (min)	Total amount of sand used in 30 min testing (kg)	Absolute Max. Testing Time (min)
5	0.26	0.69	0.40	149.8	20.7	199.7
10	0.52	1.38	0.80	74.9	41.4	99.8
15	0.78	2.07	1.20	49.9	62.1	66.6
20	1.04	2.76	1.60	37.4	82.8	49.9
25	1.30	3.45	2.00	30.0	103.5	39.9
30	1.56	4.14	2.40	25.0	124.2	33.3
35	1.82	4.83	2.80	21.4	144.9	28.5
40	2.08	5.52	3.21	18.7	165.6	25.0
45	2.34	6.21	3.61	16.6	186.3	22.2
50	2.60	6.90	4.01	15.0	207.0	20.0

Flow Rate (m3/day)	5.0					
Flow Rate (L/min)	3.472					
Sand Concentration (%)	Sand particle volume flow rate (L/min)	Sand mass flow rate (kg/min)	Rate of sand filling bin (L/min)	Max. Testing Time (min)	Total amount of sand used in 30 min testing (kg)	Absolute Max. Testing Time (min)
5	0.17	0.46	0.27	224.6	13.8	299.5
10	0.35	0.92	0.53	112.3	27.6	149.8
15	0.52	1.38	0.80	74.9	41.4	99.8
20	0.69	1.84	1.07	56.2	55.2	74.9
25	0.87	2.30	1.34	44.9	69.0	59.9
30	1.04	2.76	1.60	37.4	82.8	49.9
35	1.22	3.22	1.87	32.1	96.6	42.8
40	1.39	3.68	2.14	28.1	110.4	37.4
45	1.56	4.14	2.40	25.0	124.2	33.3
50	1.74	4.60	2.67	22.5	138.0	30.0

Flow Rate (m3/day)	2.5					
Flow Rate (L/min)	1.736					
Sand Concentration (%)	Sand particle volume flow rate (L/min)	Sand mass flow rate (kg/min)	Rate of sand filling bin (L/min)	Max. Testing Time (min)	Total amount of sand used in 30 min testing (kg)	Absolute Max. Testing Time (min)
5	0.09	0.23	0.13	449.3	6.9	599.0
10	0.17	0.46	0.27	224.6	13.8	299.5
15	0.26	0.69	0.40	149.8	20.7	199.7
20	0.35	0.92	0.53	112.3	27.6	149.8
25	0.43	1.15	0.67	89.9	34.5	119.8
30	0.52	1.38	0.80	74.9	41.4	99.8
35	0.61	1.61	0.93	64.2	48.3	85.6
40	0.69	1.84	1.07	56.2	55.2	74.9
45	0.78	2.07	1.20	49.9	62.1	66.6
50	0.87	2.30	1.34	44.9	69.0	59.9

Table 3-3: A general overview of the tests performed.

GROUP A - Glycerine Tests

	Continuous Sand Feed								
	Small Hole Entrance			Slotted Tail Joint			Wide Entrance		
Flow rate (m3/day)	**2.5**	**5.0**	**7.5**	**2.5**	**5.0**	**7.5**	**2.5**	**5.0**	**7.5**
Continuous feed	5						5	5	
sand concentration							10	10	
(by volume) %							15	15	
							20		
							25		
	Slug Sand Addition								
	Small Hole Entrance			Slotted Tail Joint			Wide Entrance		
Flow rate (m3/day)			7.5	2.5	5.0	7.5	2.5	5.0	7.5

GROUP B - Water Tests

	Slug Sand Addition								
	Small Hole Entrance			Slotted Tail Joint			Wide Entrance		
Flow rate (m3/day)	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5

GROUP C - Glycerine Tests

	Continuous Sand Feed								
	Small Hole Entrance			Slotted Tail Joint			Wide Entrance		
Flow rate (m3/day)	**2.5**	**5.0**	**7.5**	**2.5**	**5.0**	**7.5**	**2.5**	**5.0**	**7.5**
Continuous feed		5							
sand concentration	10	10	10	10		10	10	10	10
(by volume) %	20	20			20			20	
	30			30			30		
	40						40		
	50						50		

GROUP D - Glycerine Tests

	Slug Sand Addition								
	Small Hole Entrance			Slotted Tail Joint			Wide Entrance		
Flow rate (m3/day)	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5

GROUP E - Water Tests

	Continuous Sand Feed								
	Small Hole Entrance			Slotted Tail Joint			Wide Entrance		
Flow rate (m3/day)	**2.5**	**5.0**	**7.5**	**2.5**	**5.0**	**7.5**	**2.5**	**5.0**	**7.5**
Continuous feed	10		10	10		10	10		10
sand concentration	30			30			30		

Table 3-4 (a): Detailed Test Overview - Glycerine Tests

TEST NO.	Tail Joint	Flow Rate (m3/day)	Sand Addition	C.F. Sand Conc. (%)	Q Adjusted for Sand?	Viscosity measured?	Viscosity Before (cp)	Sg Before	Temp. Before (°C)	Viscosity After (cp)	Sg After	Temp. After (°C)	% Sand in Fluid after test	Videotape Number
A1	wide	7.5	slug		no	no	1100							1
A2	wide	5.0	slug		no	no	1100							1
A3	wide	2.5	slug		no	no	1100							1
A4	small hole	7.5	slug		no	no	1100							1
A5	small hole	2.5	continuous feed	5	no	no	1100							2
A6	wide	2.5	continuous feed	5	no	no	1100							2
A7	wide	2.5	continuous feed	10	no	no	1100							2
A8	wide	2.5	continuous feed	15	no	no	1100							2
A9	wide	2.5	continuous feed	20	no	no	1100							2
A10	wide	2.5	continuous feed	25	no	no	1100							2
A11	wide	5.0	continuous feed	5	no	no	1050							3
A12	wide	7.5	slug			no	1050							3
A13	wide	5.0	slug			no	1050							3
A14	wide	2.5	slug			no	1050							3
A15	wide	5.0	continuous feed	10	no	no	1050							3 and 4
A16	wide	5.0	continuous feed	15	no	no	1050							4
A17	wide	2.5	continuous feed	25	no	no	1050							4
C1	small hole	5.0	continuous feed	5	yes	yes	1230	1.258	21.2	1210	1.260	21.0	0.1	10
C1A	small hole	5.0	continuous feed	5	yes	yes	1322	1.261	20.3	sand feed problems				10
D1	small hole	5.0	slug			yes				1244	1.280	21.4		11
C1C	small hole	5.0	continuous feed	5	yes	yes	1208	1.260	20.7					11
D1A	small hole	5.0	slug	10	yes	yes	1204	1.260	21.4	1170	1.270	22.2	0.7	11
C2	small hole	5.0	continuous feed	10	yes	yes	1200	1.258	21.2	1058	1.261	21.5	0.2	12
D2	small hole	2.5	slug			yes	1060	1.260	21.5					12
C3	small hole	2.5	continuous feed	20	yes	yes	1200	1.259	20.5	1160	1.259	22.0	0.0	12
C4	small hole	2.5	continuous feed	10	yes	yes	1255	1.254	21.0	1200	1.259	20.5	0.4	13
C5	small hole	2.5	continuous feed	30	yes	yes	1280	1.258	20.5	1250	1.282	21.0	1.7	13
C6	small hole	2.5	continuous feed	40	yes	yes	1220	1.257	21.0					13
C7	small hole	2.5	continuous feed	50	yes	yes	1170	1.258	21.0					13
C8	small hole	5.0	continuous feed	20	yes	yes	1170	1.258	21.0					14
C8A	small hole	5.0	continuous feed	20	yes	yes	1060	1.258	20.5	1622	1.453	21.5	14.0	14
C9	wide	2.5	continuous feed	40	yes	yes	1120	1.257	21.0	sand feed problems				14
C9A	wide	2.5	continuous feed	40	yes	yes	1156	1.255	21.0	sand feed problems				14
C10	wide	2.5	continuous feed	10	yes	yes	1110	1.255	21.0	no recirculating flow				14
C11	wide	2.5	continuous feed	50	yes	yes	1070	1.252	21.0	sand feed problems				14
C12	wide	2.5	continuous feed	30	yes	yes	1070	1.252	22.1	no recirculating flow				15
C12A	wide	2.5	continuous feed	30	yes	yes	1074	1.253	22.0	sand feed problems				15
C12B	wide	2.5	continuous feed	30	yes	yes	1070	1.252	21.0	sand feed problems				15
C13	small hole	7.5	continuous feed	10	yes	yes	1150	1.259	20.5	1232	1.294	21.0	2.5	16

Table 3-4 (a) cont'd ...

TEST NO.	Tail Joint	Flow Rate (m3/day)	Sand Addition	C.F. Sand Conc. (%)	Q Adjusted for Sand?	Viscosity measured?	Viscosity Before (cp)	Sg Before	Temp. Before (°C)	Viscosity After (cp)	Sg After	Temp. After (°C)	% Sand in Fluid after test	Videotape Number
D3	small hole	7.5	slug			yes	1194	1.254	21.0					16
D4	wide	7.5	slug			yes	1000	1.254	22.0	1080	1.261	21.2	0.5	16
D5	wide	5.0	slug			yes	1000	1.255	21.0	not measured				16
D6	wide	2.5	slug			yes	1060	1.254	21.5	not measured				16
C14	wide	7.5	continuous feed	10	yes	yes	1110	1.256	22.0	1080	1.342	22.0	6.2	17
C15	wide	5.0	continuous feed	20	yes	yes	1100	1.277	21.5	not measured				17
C16	wide	5.0	continuous feed	10	yes	yes	1090	1.258	21.5	1350	1.334	22.0	8.8	17
C17	slotted	2.5	continuous feed	30	yes	yes	1014	1.255	23.0	998	1.278	23.5	1.6	18
C18	slotted	2.5	continuous feed	10	yes	yes	1212	1.262	20.3	1400	*1.342*	20.5	5.8	18
C19	slotted	7.5	continuous feed	30	yes	yes	1030	*1.265*	19.5	sand feed problems				18
D7	slotted	2.5	slug			yes	1100	*1.246*	20.0	not measured				18
C20	slotted	5.0	continuous feed	20	yes	yes	1008	*1.265*	20.5	1324	*1.401*	21.0	8.8	18
D8	slotted	7.5	slug			yes	966	1.271	20.0	930	1.283	21.5	0.8	18
D9	slotted	5.0	slug			yes	952	1.257	20.0	not measured				18
C21	slotted	7.5	continuous feed	10	yes	yes	900	1.266	22.6	sand feed problems				18
						Average:	1115	1.258						

Notes:

(1) Specific gravities given in italics were measured by taking the total sample mass by the total sample volume instead of the hydrometer.
(2) Viscosity values given when it has been noted that the viscosity was not measured is an estimated value based on experience in working with the fluid.
(3) The average values for viscosity and specific gravity of the glycerine are taken for only those values directly measured before the test.

* Please contact the author if it is desired to view any videorecorded test.

Table 3-4 (b) - Detailed Test Overview - Water Tests

TEST NO.	Tail Joint	Flow Rate (m3/day)	Sand Addition	C.F. Sand Conc. (%)	Q adjusted for sand?	Videotape Number
B1	wide	5.0	slug			4A
B2	wide	5.0	slug			4A
B3	wide	5.0	continuous feed	20	no	4A
B4	wide	2.5	slug			4A
B5	wide	7.5	slug			5
B6	wide	2.5	slug			5
B7	slotted	2.5	slug			5
B8	small hole	2.5	slug			5
B9	small hole	5.0	slug			5
B10	small hole	7.5	slug			6
B10A	small hole	7.5	slug			6
B11	small hole	2.5	slug			6
B12	small hole	5.0	slug			not videotaped
B13	wide	5.0	slug			6
B14	wide	7.5	slug			7
B15	wide	2.5	slug			7
B15A	wide	2.5	slug			7
B15B	wide	2.5	slug			8
B16	slotted	5.0	slug			8
B16A	slotted	5.0	slug			8
B17	slotted	7.5	slug			not videotaped
B18	slotted	2.5	slug			not videotaped
B19A	clayed	5.0	slug			9
B20	clayed	2.5	slug			9
B20A	clayed	2.5	slug			9
B21	clayed	7.5	slug			9
B22	barefoot	5.0	slug			9
B22A	barefoot	5.0	slug			10
E1	small hole	2.5	continuous feed	10	yes	19
E2	small hole	2.5	continuous feed	30	yes	19
E3	small hole	7.5	continuous feed	10	yes	19
E4	wide	7.5	continuous feed	10	yes	19
E5	wide	2.5	continuous feed	30	yes	19
E6	wide	2.5	continuous feed	10	yes	19
E7	slotted	7.5	continuous feed	10	yes	19
E8	slotted	2.5	continuous feed	10	yes	19
E9	slotted	2.5	continuous feed	30	yes	19

Table 3-5: Reynolds Numbers and Settling Velocities

Location of Flow	**Flow rate (m3/day)**	**Flow Reynolds numbers**	
		water	**glycerine**
annulus	2.5	79	0.09
	5.0	158	0.17
	7.5	237	0.26
tubing	2.5	252	0.27
	5.0	504	0.55
	7.5	756	0.82
small hole	2.5	598	0.65
	5.0	1197	1.30
	7.5	1795	1.95
top 20 % of the area of the back slot	2.5	464	0.50
	5.0	929	1.01
	7.5	1393	1.51
2.0 cm by 0.5 cm rectangular opening	2.5	602	0.65
	5.0	1203	1.31
	7.5	1805	1.96

Particle Reynolds Numbers		**Single D50 Particle Settling Velocity (m/s):**	
water	**glycerine**	**water**	**glycerine**
3.5	3.80E-06	0.02	2.0E-05

Flow Rate (m^3/day)	**Mean Velocity (m/s)**	**Ratio of Mean Velocity to Settling velocity**	
		water	**glycerine**
2.5	0.006	0.32	319
5.0	0.013	0.64	638
7.5	0.019	0.96	957

CHAPTER 4: ANALYSIS - FLOW PATTERNS

PART 1: VISCOUS, LAMINAR FLOW - SLUG SAND ADDITION

I. BACKGROUND

The flow patterns described in the following sections for the wide and small hole entrances are based upon the assumption that the sand level in the sump or "sump level" is near (within about 2 to 3 cm) of the tail joint entrance. Flow regimes do not form until enough slugs have been added to raise the sump level to near the tail joint entrance. If a slug is added to one of these entrances when the sump level is far from the tail joint entrance, the slug will fall to the sump and remain there without changing the pattern of the overall viscous flow.

This phenomena is due to the limited suction depth of the pump. Withdrawal of fluid from a point will affect only a small area around that point in a reservoir. It has been found during testing, that there is no flow into the tail joint from below a depth of about 3 cm beneath the tail joint entrance. The depth to the "dead zone" increases with increasing flow rate. In Plate 4-1, poppy seeds that have been added to the flow as tracers, mark the lowest flowing streamline. It is 3.5 cm below the tail joint entrance for the 5.0 m^3/day flow rate.

Slug addition to the flow for the slotted tail joint is described separately in section IV.

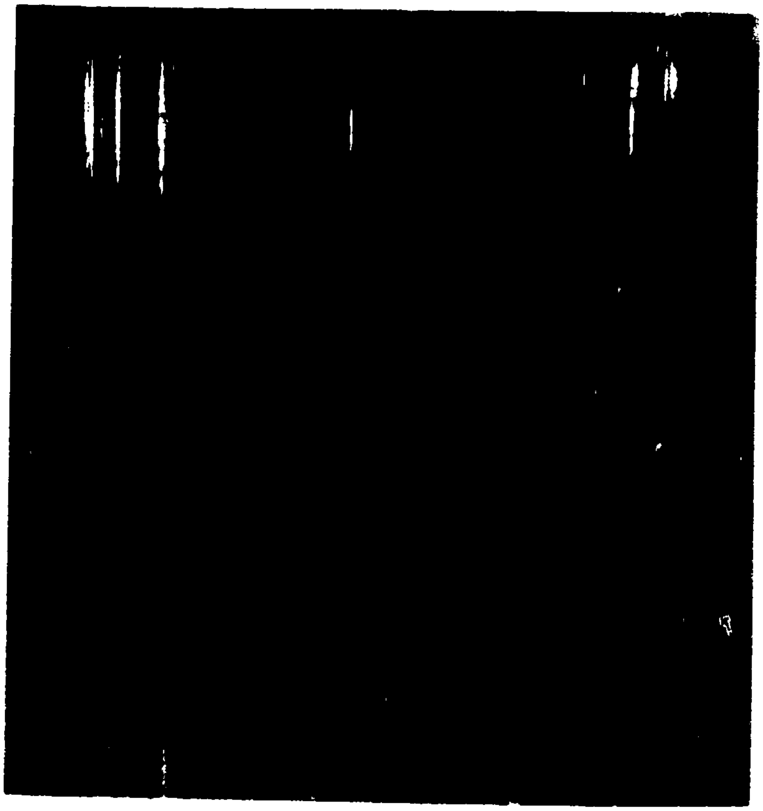


Plate 4-1: Poppy seeds trace the flow of glycerine in the small hole entrance.

Intuitive names were given to the flow regimes described to below to allow for easier recognition of their features.

II. WIDE ENTRANCE

A. Primary Sand Removal Regimes

1. Small Hill Sand Removal Regime

The Small Hill Sand Removal Regime is characterized by a small, rounded mound of sand in the sump, which is located in the centre of the tail joint and bisected by the front sheet of plexiglas. Within this mound, circulation exists. This circulation is caused by the shear of the passing flow on the sand particles. Some sand particles are carried by the passing flow into a small band of sand at the apex of the mound. The sand in this band is carried upward to the pump outlet. The Small Hill Regime is shown in Figure 4-1 and in Plate 4-2.

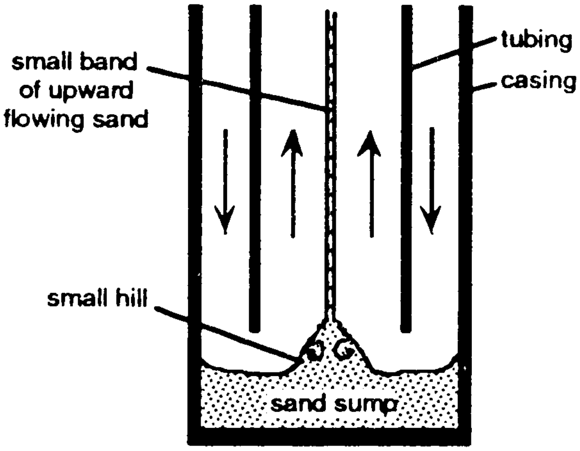


Figure 4-1: The Small Hill Sand Removal Regime.

The circulation of the sand particles within the small hill appears as separate cells of opposite circulation through the front plexiglas. These cells have a very definite, rounded appearance. In three dimensions, the cells are equivalent to a vortex ring. Figure 4-2 depicts these circulation cells.

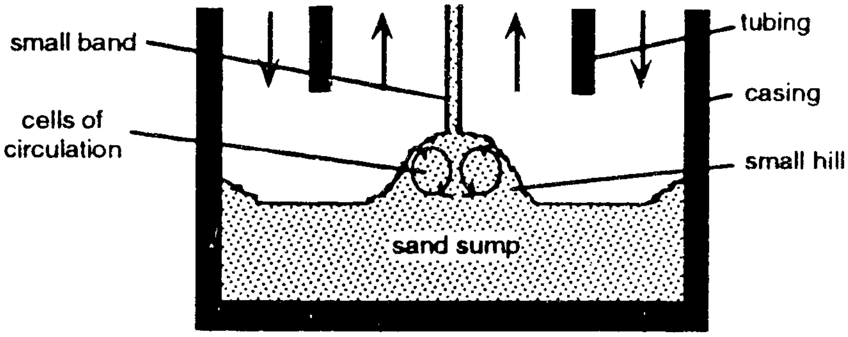


Figure 4-2: Sand particle circulation within the small hill of the Small Hill Regime.

The Small Hill Sand Removal Regime is a form of the Wide Band Sand Removal Regime.

Plate 4-2: The Small Hill Sand Removal Regime.

2. Wide Band Sand Removal Regime

The Wide Band Sand Removal Regime is characterized by a wide band of a dense glycerine/sand mixture that develops in the centre of the tubing. The centre of this band circulates downwards with a velocity observed to be greater than the settling velocity of the sand in glycerine. The sides of the wide band are carried upward by the shear stress caused by the surrounding upward glycerine flow. Most of the sand particles caught in the upward moving portion of the wide band recirculate within the band when they reach the band apex. However, some of the sand particles on the outside of the wide band are not trapped in the downward circulation. They are carried into a small band whose base is at the apex of the wide band. There is no downward component to the sand flow in the small band. All sand that enters the small band will be carried to the pump outlet. The Wide Band Sand Removal Regime is depicted in Figure 4-3 and is shown in Plate 4-3. The downward circulation pattern has been observed in a wide band even when the apex of the band is very near the pump outlet.

The wide band is semi-cylindrical in shape. The width of the wide band is in the order of 40 mm with its depth into the tail joint approximately 35 mm. The width of the small band is generally not larger than 4 mm (24 times the average sand grain diameter) with a minimal depth into the flow. The ratio of the width of the wide band to the width of the small band is typically 10 to 1.

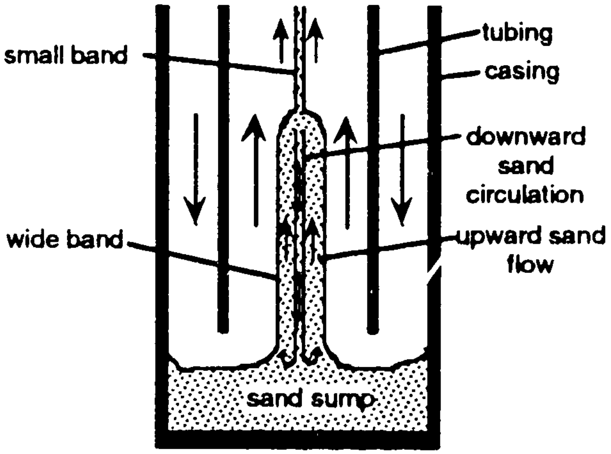


Figure 4-3: The Wide Band Sand Removal Regime.

It has been observed that the wide band will sometimes exist without the presence of the small band at its apex. It also will often exhibit a core of clear glycerine with a diameter of about 5 mm. Typically, the clear glycerine core will not exist if a fully developed small band is present. The lack of the small band, and therefore an upward flowing sand particle suspension, may allow for entrainment of glycerine in the downward circulation and thus establishment of the clear core.

Another interesting feature of the wide band is that it exhibits an oscillatory waviness. These waves are sinusoidal in shape. They appear to travel within the band, but do not seem to transport significant amounts of sand considering the mass of sand they contain. The wide band tends to grow in height when these waves are "readily observable". The waves are readily observable if it is obvious that they exist when the videotape of the test is viewed at the normal playback speed. Playing recordings in fast forward may show that oscillatory waviness actually is present in the wide band when it cannot be detected at the normal speed (real time). In this case, the waviness is "not readily observable".

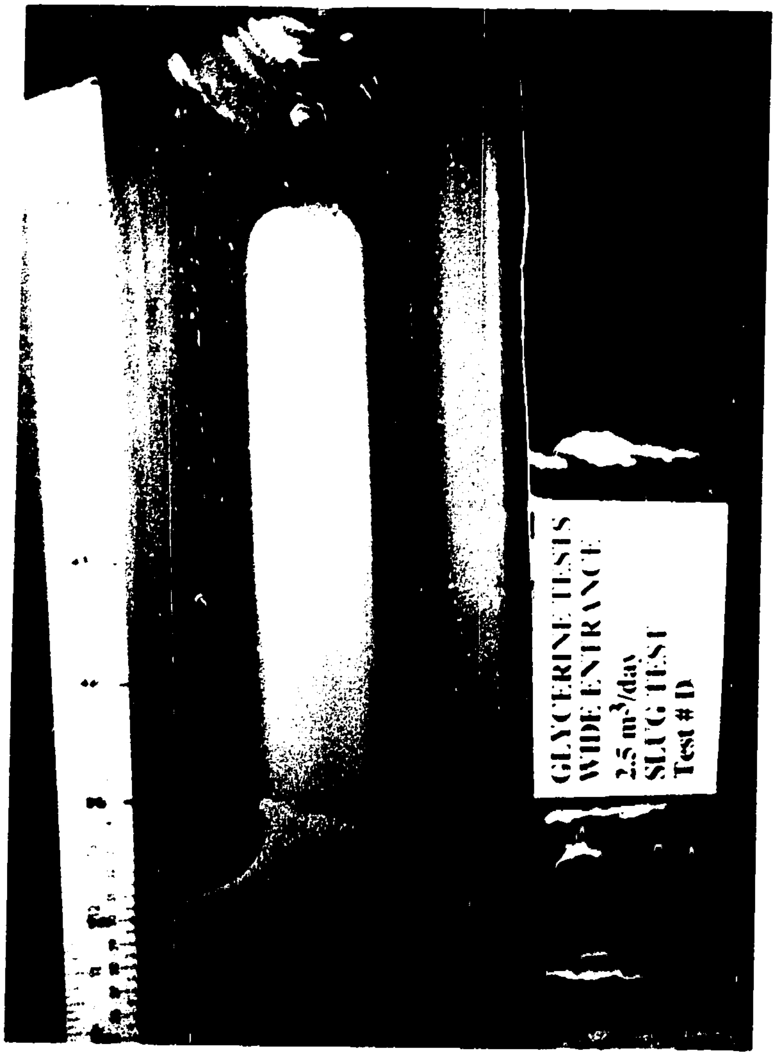


Plate 4-3: The Wide Band Sand Removal Regime.

Another characteristic of the oscillatory waves is that they take up only a portion of the wide band's depth into the tail joint, as the sand closer to the front plexiglas sheet remains stationary. However, in this instance, the shear stress on the front plate may cause damping of the waviness. The top or end of the wave form can be seen to move from side to side within the width of the wide band as the different phases of the wave reach the band apex. The oscillatory waviness is depicted in Figure 4-4. This waviness is more prevalent at the higher flow rates tested. It is often not observable at the 2.5 m^3/day flow rate, even at fast videotape playback speeds. The oscillatory waviness is also more prevalent when the height of the band increases and/or approaches the pump outlet.

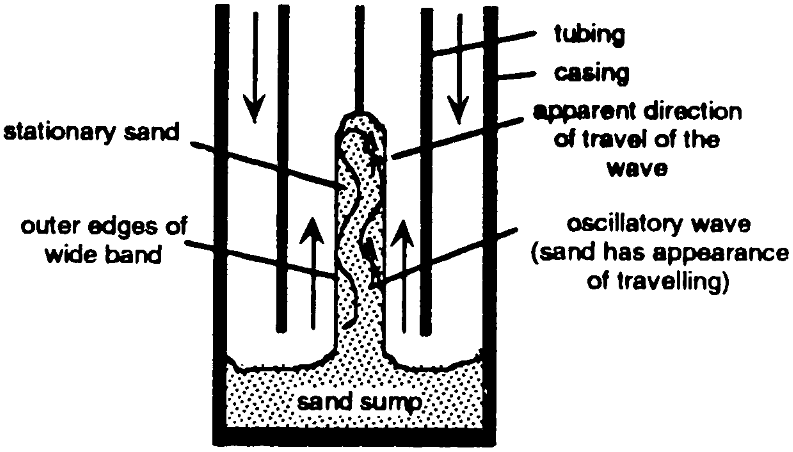


Figure 4-4: The oscillatory waviness in the wide band.

B. Transitions Between the Primary Sand Removal Regimes

More than one transitional process can occur at one time. However, the transitions that are described in the following represent the dominant processes observed to occur. Often one process proceeds another or more than one transitional process occurs in combination to change the sand removal regime from one state to another.

The time for each transition to occur was observed to be inversely proportional to the flow rate. Values for the time of transition are given only to provide an appreciation for the time scale (the order of magnitude) of the process.

1. Transitions from the Small Hill to Wide Band Sand Removal Regime

These transitions will occur only if a glycerine wet sand slug is added to the flow.

a. Type 1 - No Waviness

When sand is added to the flow in the form of a slug, the slug will fall to the bottom of the annulus. In this case, the sand slug spreads out across the entire area of the sump as it collides with it. Some of the sand will be carried by the flow into the tubing and removed from the system. Another part of the slug remains as the top sump sand layer. The rest of the sand invades the entrance of the tail joint. Distinct regions of purely glycerine flow and sand flow are not well defined. Sand is taken toward the pump outlet in what appears as streaks in the flow. These streaks have indistinct edges. They fill approximately 75% of the width of the tubing and are confined to its centre.

As time progresses, the glycerine flow drags the sand that had deposited on the top of the sump toward the centre of the tubing. A band of a dense glycerine/sand mixture slowly forms in the centre of the tubing. It begins to form distinct edges. This is the Wide Band Regime. This type of transition does not exhibit any regular waviness. It is depicted in Figure 4-5.

The time for this transition to occur, measuring from when the slug contacts the sand in the sump to when the Wide Band Regime is observed to be distinctly formed, is typically around 30 s. It has been found that this type of transition is more likely to be observed when the flow rate is small.

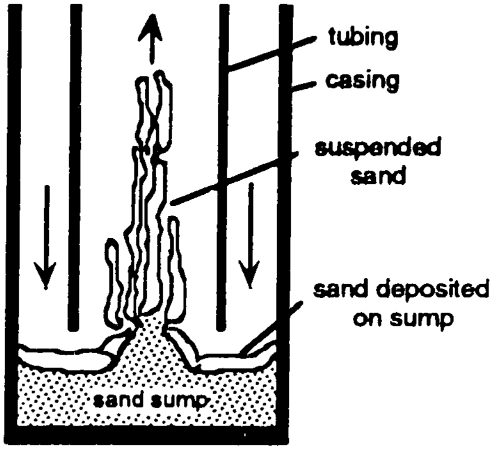


Figure 4-5: The Type 1 Transition from the Small Hole to the Wide Band Regime.

b. Type 2 - Oscillatory Waviness

In this transition, most of the slug added to the flow falls toward the centre of the tail joint entrance. It does not spread across the sump as in the Type 1 Transition. The slug is suspended by the upward flow in the area of the entrance to the tail joint. A wide band of sand forms in the centre of the tubing, but its edges are not well defined. Oscillatory waves appear. As more sand is slowly carried out of the tail joint by the flow, the Wide Band Regime begins to form. The oscillatory waves continue to be seen as the wide band regime becomes more defined. The small band forms at the wide band apex. The base of the small band moves laterally back and forth when the wide band oscillatory waviness predominates. Through the latter part of the transition, the oscillatory waves slowly dissipate. The wave action first stops in the bottom portion of the wide band, with the top of the wide band still exhibiting waviness. Slowly, the waviness dissipates in the top of the band as well. The time from when the slug strikes the top of the sump to when the oscillatory waviness appears to dissipate is approximately 1 min. This type of transition was found to be more prevalent at the higher flow rates.

c. Type 3 - Translational Waviness

In this transition, the first part of the sand slug (that has broken up during its descent in the well annulus) enters at the centre of the tail joint entrance. Here it remains as a dense mass in the centre of the sump. This portion of the slug forms the wide band. It protrudes into the entrance of the tail joint. The remaining part of the sand slug is pushed "up the back" of the newly formed wide band, travelling in the form of a wave, to the band apex. Here the combined slugs quickly form the Wide Band Regime. These travelling waves of slug material are called translational waves.

2. Transitions from the Wide Band to Small Hill Sand Removal Regime

No sand can be added to the flow during the process of these transitions if they are to occur.

a. Type 1 - No waviness, Total height band thinning

This transition from the Wide Band to the Small Hill Sand Removal Regime occurs relatively slowly. The width of the small band, which carries only upward flow and is located at the apex of the wide band, gradually becomes thicker. The width and height of the wide band gradually decrease. This is depicted in Figure 4-6. Only a small portion of the lowest section of the wide band does not thin. In that location, the wide band is not scoured by the flow entering the tail joint. This process continues until the Wide Band Regime becomes the Small Hill Regime. No regular waviness is readily observable. The time for this transition, measuring from when the Wide Band is considered to be a distinct regime to when the Small Hill Regime is formed, is typically about 2.5 min.

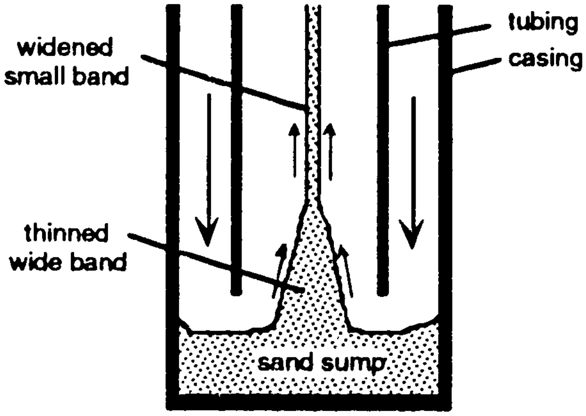
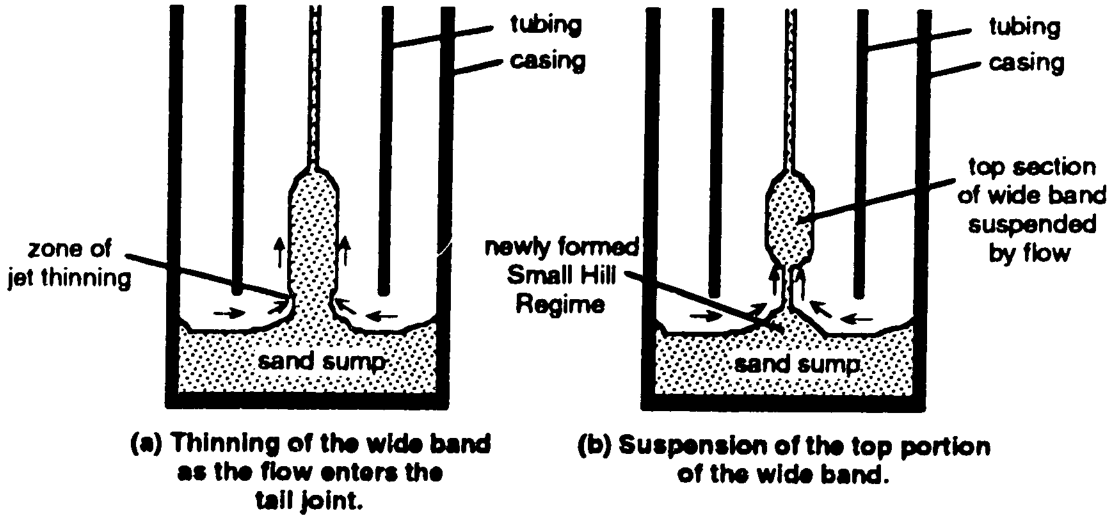


Figure 4-6: The shape of the wide band and small band typically seen in the Type 1 Transition from the Wide Band to Small Hill Sand Removal Regime.

b. Type 2 - Jet thinning

This process of thinning of the wide band, which occurs in the entrance area of the tail joint, causes the top section of the band to separate from its base. The downward flowing fluid in the annulus must follow a flow path that curves 180° as it enters the tail joint. The incoming jet scours the sides of the wide band at its base, slowly making that base of the band thinner than the band of sand above it. The top portion of the band becomes suspended by the flow when the base of the band has been sufficiently eroded. This allows for its removal by the flow. The base of the wide band quickly forms the Small Hill Regime. This transition is shown in Figure 4-7. It has been found that it is more this transition is more likely to occur at higher rates of flow through the tail joint.



(a) Thinning of the wide band as the flow enters the tail joint. **(b) Suspension of the top portion of the wide band.**

Figure 4-7: Physical processes of the Type 2 Transition from the Wide Band to Small Hill Sand Removal Regime.

C. Transitions within an Individual Primary Sand Removal Regime

1. Wide Band Sand Removal Regime

a. Processes to Decrease the Wide Band Sand Volume

(i) Sectional Thinning

This process is similar to the Type 2 Transition of Jet Thinning as the wide band is shortened by a breaking off of the top section of the wide band (and therefore also the small band). The "breaking off", in this case, occurs when a middle portion of the wide band simply thins at a faster rate than the rest of the band. This will be termed "sectional thinning" and is shown in Figure 4-8. When the thickness of the band in the area of the sectional thinning becomes sufficiently reduced, the upper part of the wide band becomes suspended by the flow. The suspended "body" of sand is slowly lifted to the pump outlet.

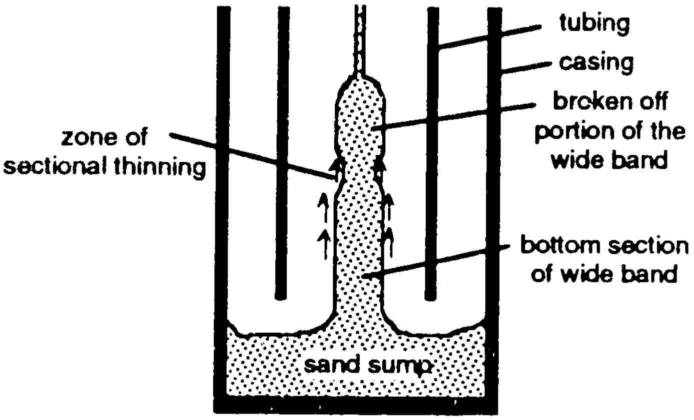


Figure 4-8: Sectional thinning of the wide band.

b. Processes to Increase the Wide Band Sand Volume

When a slug is added to the flow when the primary sand removal regime is already the Wide Band Regime, the additional sand is absorbed by the wide band in two main ways:

(i) Translational Wave

In this process, the slug is carried in a translational wave on the back of the wide band to the band apex. This wave appears as a bulge in the wide band when viewed through the front plexiglas sheet. The new sand at the top of the band may break apart and continue with the flow to the pump outlet or may quickly form into part of the wide band. The wide band, in the latter case, will rapidly increase in height.

(ii) Dense Band Base

Another process that may occur when a slug is added to an already formed wide band is that the slug will simply be absorbed at the base of the band. Thus, the bottom part of the wide band will be very dense. As the wide band grows in height, it will be found that the density of the band base will slowly decrease.

Any time a slug that is added it gets "stuck" in one side of the entrance, the wide band will shift to that side. The wide band on that side may even contact the wall of the tail joint. Typically the glycerine/sand mixture at the base of the band will be quite dense. Slowly, the flow will clear a space in the blocked area of the tail joint entrance. Once flow is allowed through this area, the band will shift back to the centre of the tubing. If circulation within the band exists, it is a single vortex with the direction of circulation determined by which side of the band is exposed to the upward glycerine flow.

2. The Small Hill Sand Removal Regime

The Small Hill Sand Removal Regime is rather uninteresting in that substantial changes in the flow pattern within this regime do not occur. As well, the time for these changes to occur is quite large. It is thought that after a long period the small hill will decrease in size (because sand is continually being carried out of the tail joint in the small band) until the regime changes to what is called the Tapered Regime. This regime is a primary sand removal regime for the small hole entrance. The reverse of this process was observed to occur when the flow in the well was initiated. The flow first formed the Tapered Regime, which slowly changed to the Small Hill Regime as the mound on the sump grew in size.

D. Effect of the Sand Slug Characteristics on the Flow Patterns

1. Background

To aid the discussion of this topic, some terms must be defined to better describe the type of sand slug that is added to the flow. This is because the flow patterns shown in the tail joint appear to depend on the properties of the slug.

A "flowable" sand slug is one that contains a higher percentage of glycerine. It flows easily under the application of a stress. The cohesion between the sand particles is not strong. The slug is completely saturated with glycerine. The concentration of sand in this slug is in the range of 35 to 45 % by volume.

A dense sand slug behaves more as a cohesive soil. It exhibits a strong cohesion and can be molded into a shape without losing its form (over a few minutes). The concentration of sand is in the range of 60 %. The slug may not be completely saturated with glycerine. It does not flow easily.

The different behavior of the slugs may be due to the amount of mixing that the slug can undergo. For the flowable slugs, the sand particles do not disperse, as for the sand slugs in water, within the carrier fluid. However, the slug is likely to be pulled apart as it travels down the well annulus due to its lack of cohesion. The fluid can mix with the slug and move the sand within the slug to create well defined flow patterns.

The dense slug will not mix with the surrounding fluid as it flows down the annulus. It remains in the shape into which it was molded, prior to the slug's addition to the flow, until it reaches the tail joint entrance. It is not stretched when it flows in the annulus. The flow cannot change the slug shape quickly. Also, the slug entrains fluid very slowly. Thus, the two types of slugs enter the tail joint in a different manner.

The description of the flow patterns in parts A, B, and C of this section primarily deal with flowable slugs in a more viscous glycerine. As testing proceeded, there was a tendency to use the dense slugs. As well, the glycerine viscosity deteriorated with time. The following gives the flow regimes for dense sand slugs added to a less viscous glycerine.

2. Description of Flow

For the dense slug tests, the flow shows only tendencies for certain patterns to form but there are no definite transitions and sometimes no definite regimes .

At the 7.5 m^3/day flow rate, the small (125 ml), dense sand slugs easily flow through the tail joint entrance and to the pump outlet. These slugs tend to stay in one piece as they move through the well. As the dense slugs become larger, they tend to become stuck in the annulus as well as just outside the tail joint entrance. When the slug blocks the tail joint entrance two things may happen. First, the slug may remain outside the entrance until another slug is added to interfere with the flow regime. Secondly, the slug may slowly move into the entrance. Here it blocks the flow into the tail joint. The difference in fluid level between the annulus and tubing will quickly increase when this occurs. When this head difference is large enough, a small jet meanders through the glycerine/sand mixture to open an area to flow. The head buildup in the annulus is eventually great enough for the fluid to push at least part of the slug out of the entrance. This part of the slug will likely be carried to the pump outlet. The other portion of the slug will remain clinging to one side of tail joint. The flow stretches the slug and moves it up the side of the tail joint. Here it forms what looks like a shifted wide band, but there is no circulation within the sand body. Plate 4-4 shows a shifted band created from a large, dense slug. With time, enough flow moves through the side of the entrance where the slug is located to move the band towards the centre of the tail joint. Downward circulation within this band was not observed. However, it is believed that over a long period (probably around 30 min) a very definite wide band regime would form. Plates 4-5, 4-6, and 4-7 show the transformation of the small slug into what is similar to the Wide Band Regime (however, there was no downward circulation within the wide band).

The dense slugs plug the entrance more easily than the flowable slugs. It is important to note that this plugging occurs from sand that is moving into the entrance from the annulus. It is also likely that a slug will block the flow through a portion of the entrance. When there is little sand in the entrance area, the Small Hill Regime tends to form.

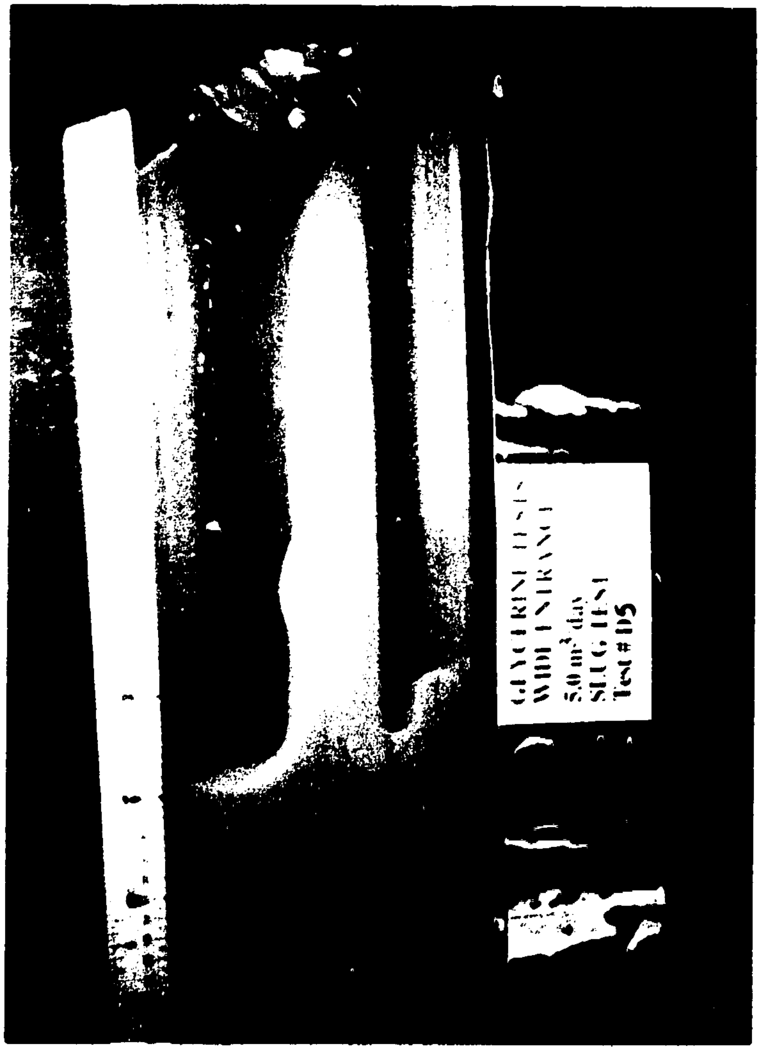


Plate 4-4: A shifted wide band formed from a large, dense sand slug.

Plate 4-5: A small, dense slug moves through the right hand side of the tail joint entrance.

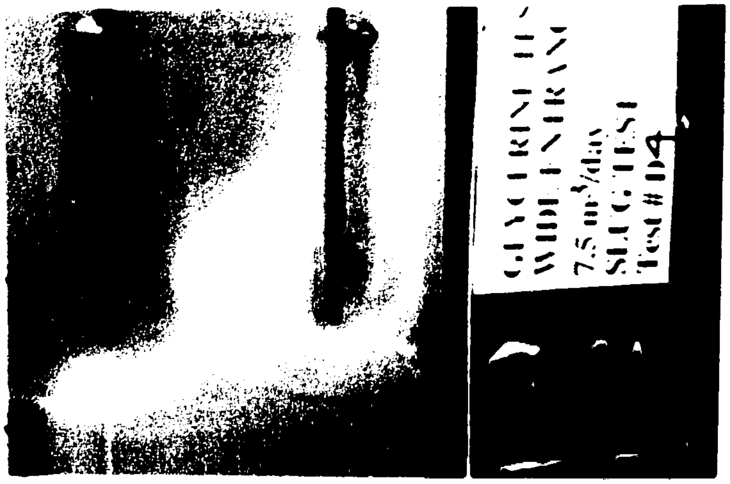


Plate 4-6: The slug forms what appears to be a shifted wide band.

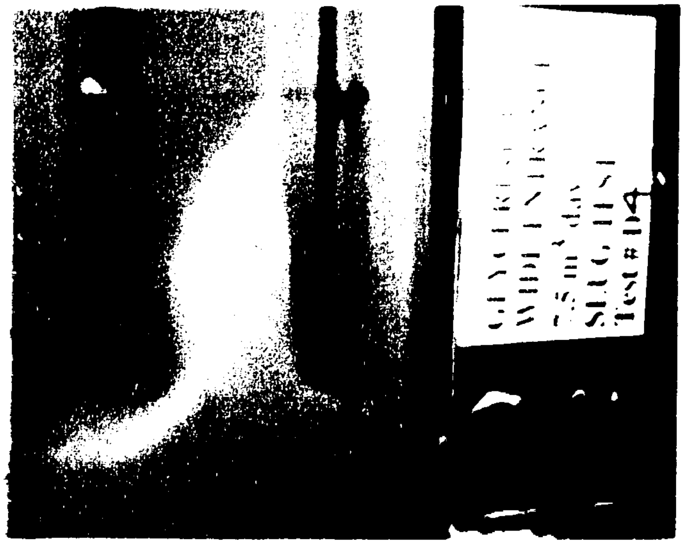


Plate 4-7: The flow shifts the wide band toward the centre of the tubing.

If a large slug becomes suspended in the tail joint at the 7.5 m³/day flow rate, it will likely break apart as it is carried to the pump outlet. It is stretched by the force of its own weight and the opposite shearing force caused by the upward flow. Again, part of this slug will likely be carried out of the tail joint. The other portions of the slug will fall to the side of the tail joint to become a wall deposit. Figure 4-9 gives the appearance of a typical wall deposit. The deposit will slowly be eroded by the flow. As well, it will slowly move up or down the tail joint wall. Circulation may be seen within one of these deposits as the sand mixture becomes less dense.

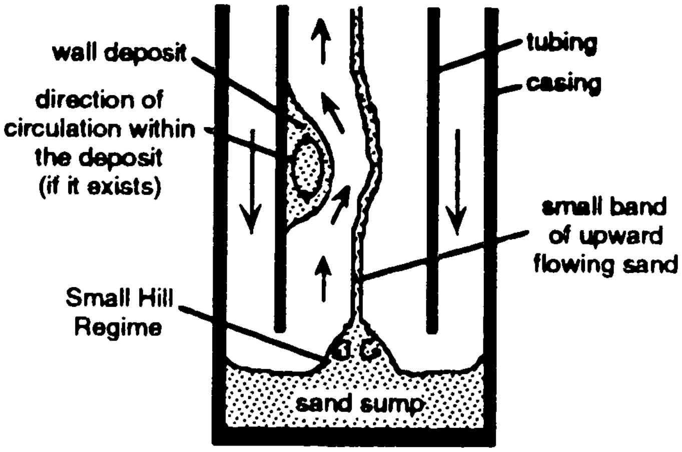


Figure 4-9: Wall deposit of a glycerine/sand slug.

For the 5.0 m³/day flow rate, the behavior of the flow was very similar to that seen for the 7.5 m³/day test. The dense slugs tend to block the entrance and are pushed into the tail joint when the head difference between the annulus and tubing becomes sufficient. Once it is within the tail joint, the slug will stretch and break up. Some of the slug is carried away by the flow. The other part deposits along the side of the tail joint or within the entrance. Again the entrance is often partially filled with slug sand, with one side of the entrance open to flow. When this occurs, what looks like a shifted wide band will tend to form. Eventually, this band moves to the centre of the tubing as the regime stabilizes as a radial flow through the entrance.

During the 5.0 m³/day test, a flowable slug was added to find the difference in flow behavior between the two types of slugs. One side of the tail joint was blocked by a previously added, dense slug. The flowable slug moved through the entrance to the side of the tail joint where the flow was blocked. A shifted wide band, with circulation, formed. This wide band contained smaller pieces of the dense slug. These pieces did not mix with the sand from the flowable slug and did not circulate within the band. The Wide Band Regime was destroyed when one of the dense slug pieces was pulled out of the wide band by the flow and lifted to the pump outlet.

For the 2.5 m³/day test, the same flow regimes were seen as for the higher flow rates. The sand slugs often plug the entrance. The Wide Band Regime, complete with circulation in the wide band, formed during this test.

III. SMALL HOLE ENTRANCE

A. Fluid Flow through the Small Hole Entrance

To enable a better appreciation of the two phase, fluid/solid flow mechanics through this tail joint, the "fluid only" flow must be described. The streamlines for this flow are sketched in Figure 4-10. The contraction of the small hole provides for an acceleration of the fluid through it. Also note the vortices formed in the corners at the intersection of the tubing with the bottom plexiglas piece (from which the 32 mm diameter, semi-circular small hole is cut). The viscous flow fills the tail joint within a few centimetres of the small hole entrance.

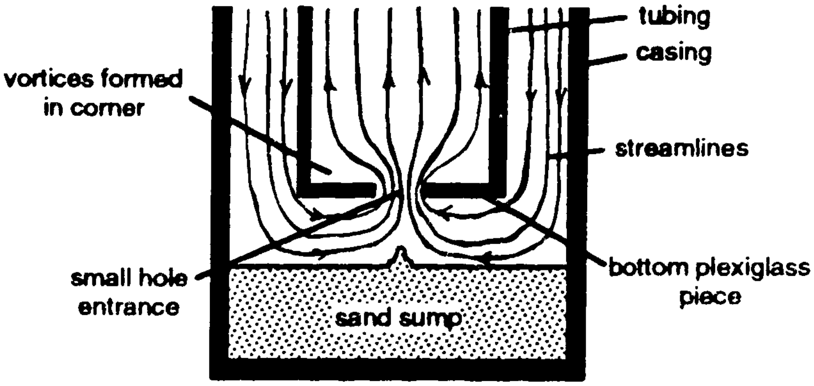


Figure 4-10: Streamlines for the glycerine flow through the small hole entrance.

B. Primary Sand Removal Regimes

1. Tapered Sand Removal Regime

The main flow pattern observed for this tail joint design is the Tapered Regime. It is characterized by a half-cone shaped mound of sand in the centre of the sump which is pushed against the front plexiglas. A small band of upward flowing sand exists at the apex of this tapered mound. Circulation within the mound has not been observed. Sand particles are displaced from the sump surface and move radially inward to the small mound of sand. The displaced particles proceed up the side of the mound and are carried to the pump outlet in the small band. The Tapered Regime is sketched in Figure 4-11 and is pictured in Plate 4-8.

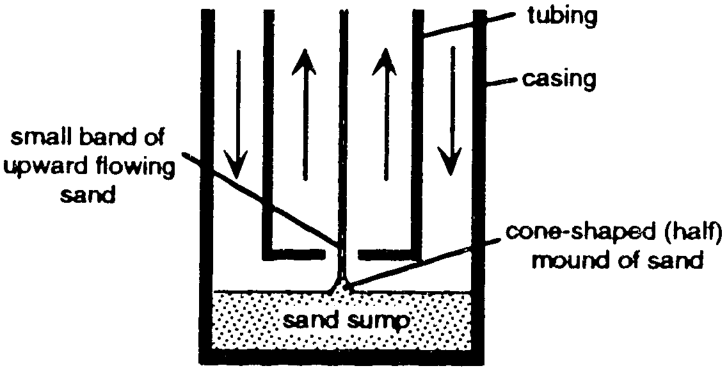


Figure 4-11: The Tapered Sand Removal Regime.

Plate 4-8: The Tapered Sand Removal Regime.

The width of the small band is approximately constant from its base to the pump outlet, except for a contraction of the band width within the entrance. The small band width is typically 3 mm. This is roughly 18 times the average sand grain diameter of 0.17 mm. As well, a bulge in the small band sometimes forms as sand accumulates just above the entrance. This bulge is also shown in Plate 4-8. It has been observed to form at the 2.5 m^3/day flow rate, but not at the 5.0 and 7.5 m^3/day flow rates.

2. Suspended Band Sand Removal Regime

The Suspended Band Sand Removal Regime is characterized by a cylindrically shaped, wide band of a glycerine/sand mixture that forms in the centre of the tubing that is suspended above the entrance. This regime is shown in Figure 4-12 and in Plate 4-9. The lower portion of the regime from the sump to the base of the "suspended band" is equivalent to the Tapered Regime. The suspended band is much like the wide band in the Wide Band Regime. A distinct downward circulation exists in the centre of the band. The sides (or outer radius) of the band move upwards with the surrounding flow. Sand particles moving towards the pump outlet flow in the small band that is located at the apex of the suspended band. There is no downward component to sand particle flow in the small band.

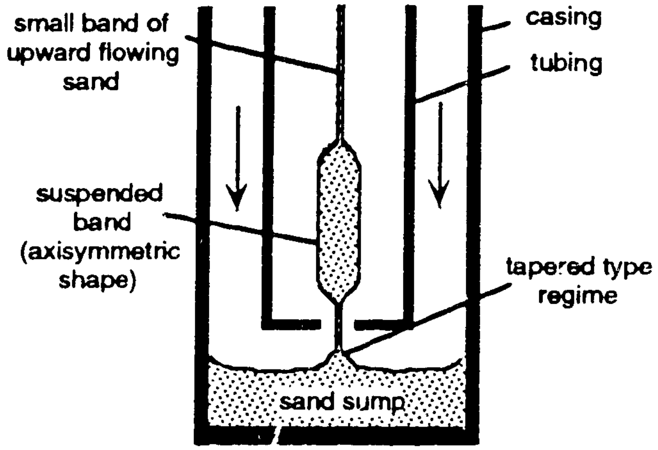


Figure 4-12: The Suspended Band Sand Removal Regime.

The width of the suspended band is typically around 35 mm. The width of the small band, both above and below the suspended band, is 3 to 4 mm.

Oscillatory waviness of the suspended band has not been observed. This is true even for the fast video playback speeds. When instabilities in the flow do occur, the suspended band falls towards the tail joint wall and breaks into two or three parts. These parts of the band will either be carried to the pump outlet or form deposits on the tail joint wall. These deposits may be similar to the type of wall deposit described for the wide entrance or may form a "continuous wall deposit", where the sand spreads through the entire circumference of the tail joint wall as a thin sheet. Plate 4-8 shows a short, continuous wall deposit above the bottom plexiglas piece of the tail joint.

It has been observed before that just before the suspended band falls towards the tail joint wall, the small band beneath the suspended band will move slightly to one side of the band. The small band from the Tapered Regime seems to separate from the upward circulation of the sides of the suspended band. The suspended band quickly becomes unstable after this occurs. Therefore, it is suggested that the suspended band exists in two forms. The first is

Plate 4-9: The Suspended Band Sand Removal Regime.

a "band bulge", where the suspended band is combined with the Tapered Regime that has formed on the sump. In this case, there are no flow instabilities and the band would be observed to slowly move upward to the pump outlet. The second type of band is the "suspended body", where the suspended band does not combine with the Tapered Regime. In this case the flow instabilities cause the formation of wall deposits. It also is thought that it is possible that instabilities in the flow could change the behavior of the suspended band from the band bulge to the suspended body.

The shape of the suspended band tends to change the longer it is suspended by the flow. Initially, the shape of the band is axisymmetric with a constant width. Later, the base of the band will often grow in width while the top of the band is thinned, changing the band to a more streamlined shape. Figure 4-13 shows the new band shape as compared with the band in Figure 4-12. Often this change occurs just before the flow pushes the band to the pump outlet. However, the change in band shape is not a prerequisite for this to happen, as an axisymmetric band was observed to move to the pump outlet.

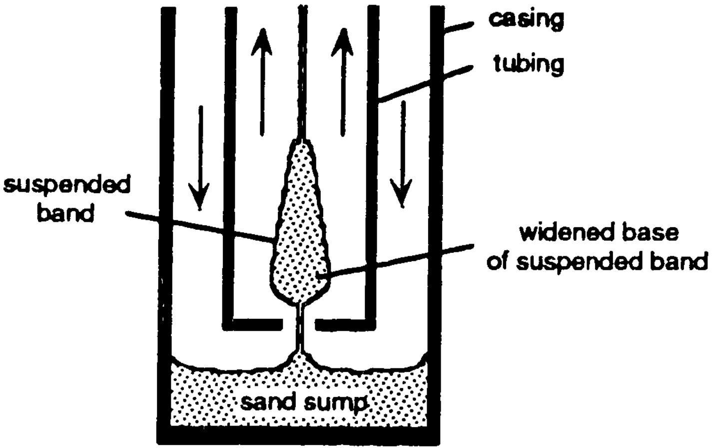


Figure 4-13: The widened base of the suspended band.

Another characteristic of the Suspended Band Regime is that it is possible to have more than one suspended band. This was observed when the one of the bands was a remnant from a previous slug. In this case, the smaller top band was moved more quickly to the pump outlet than the larger, bottom suspended band.

C. Flow Transitions due to Sand Slug Addition

As for the wide entrance, the flow patterns observed for the small hole entrance depend on the type of slug added. The flowable slugs were used when the glycerine was more viscous. The dense slugs were used when the glycerine viscosity was degrading.

1. Flowable Sand Slugs

When a small slug (approximately 125 ml) of a flowable, glycerine/sand mixture is added to the flow, it falls through the well annulus to deposit on the sump. The fluid flowing nearest to the sump picks up the sand particles from the slug and easily carries it through the contraction of the small hole entrance. As it passes through the entrance, the flow expands and therefore decelerates. The sand from the slug becomes suspended above the entrance. This is shown in Figure 4-14. This suspension becomes unstable and begins to stretch in the direction of the flow. It exhibits an irregular waviness. A suspended band is forming. When the edges of the band become more clearly defined, the waviness of the suspension diminishes. The Suspended Band Regime forms. For the small slug, it is likely that the suspended band is stable. The base of the band will be seen to expand just before the flow pushes the suspended band to the pump outlet.

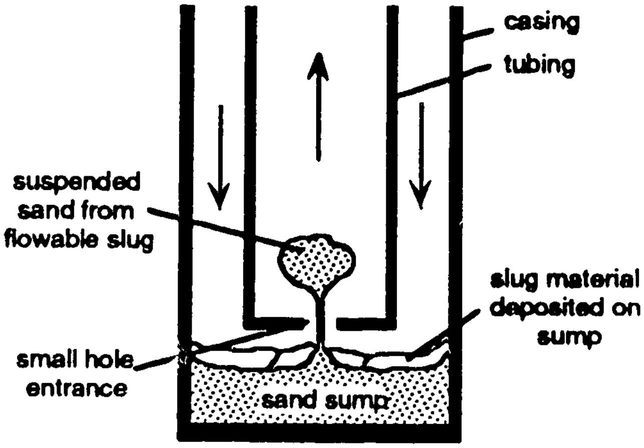


Figure 4-14: Sand suspended above the small hole entrance just after the addition of a slug.

The larger flowable slugs will also easily flow through the entrance. However, as the volume of sand suspended above the entrance becomes large, the instability of the suspension increases. The flow will try to allow the suspended band to form. However, it will break into pieces before the Suspended Band Regime develops. A part of the sand slug will flow to the pump outlet and another part will form a wall deposit.

If the flowable slug is very large, it may briefly block the glycerine flow through the small hole as it moves through the entrance. An increase in the head difference between the level of fluid in the well annulus and the tubing will push the slug out of the small hole. The slug becomes suspended by the flow above the entrance. It is likely that this suspension will be unstable and will create deposits on the tail joint wall.

When a slug is added to the well when the flow is exhibiting the Suspended Band Regime, three types of changes to the flow pattern were observed. First, when the base of the suspended band was near the mid-height of the tail joint, the incoming slug flows around the band. The suspended band breaks up so that part of the slug moves to the pump outlet. The remaining sand from the band and the slug combine to form suspension above the small hole entrance from which a new Suspended Band Regime emerges. When the base of the suspended band is near the pump outlet, the slug will move into the tail joint and stretch upwards. The suspended band moves downwards in the tail joint to combine with the new suspended band from the slug. The combined band becomes very wavy. The top part of the combined band will tend to break from the bottom section of the band and move to the pump outlet. The bottom portion of the combined band will form the Suspended Band Regime. If the base of the suspended band is close to the entrance, the slug will move through the entrance to collide with the band. Some of the slug will spread across the width of the tail joint. Another part of it will move upwards to surround the suspended band. This part of the slug will carry much of the old band with it as it travels to the pump outlet. With the remaining sand in the tail joint, the Suspended Band Regime forms.

2. Dense Sand Slugs

The behavior of the flow using the dense slugs was very similar to that seen for the wide entrance, dense slug tests. The two flow rates tested using the dense slugs were 2.5 and 7.5 m^3/day. Unlike the wide entrance tests, the flow regime was dependent on the flow rate. Again the dense slugs tended to become stuck in the well annulus and just outside the tail joint entrance.

For the 2.5 m^3/day test, the flow pattern developed in essentially the same manner for every slug. Initially, the first part of the slug blocks one side of the small hole entrance as it enters the tail joint. As the rest of the slug moves through the same hole, it completely blocks the glycerine flow. As the head difference between the fluid in the annulus and the tubing increases, a jet will push the slug through a small portion of one side of the entrance. The incoming flow pushes the sand to the opposite side of the tail joint. This is much like the initial formation of the shifted wide band for the wide entrance. Slowly, fluid creeps through the part of the slug still blocking the entrance to allow for radial flow through the small hole. The slug sand becomes suspended within the tail joint. However, this regime is very unstable and the suspended sand, which is still fairly cohesive, falls to the tail joint wall. Here the slug forms the type of wall deposit shown in Figure 4-9. This is also is unstable. It will stretch and fall down the tail joint wall to form a continuous wall deposit. This deposit considerably reduces the area open to flow. A typical continuous wall deposit that formed in this test is shown in Plate 4-10. As shown in this photograph, the area for flow in the tail joint is not much larger than the area of the small hole. Also shown is the meandering behavior of the channel formed by the continuous wall deposit. The primary regime for this state of flow is the Tapered Regime. The small band tends to remain in the centre of this channel.

Addition of another slug will clean the continuous deposit from the tail joint wall. The slug may accomplish this through contact with the deposit as it travels through the tail joint. A slug may also clean the tail joint when it blocks the entrance to flow, as any sand suspended within the tail joint will quickly fall towards the sump. The previously described process of continuous wall deposit formation will then occur. When a slug is not added, the flow will slowly erode the deposit. The sand in the upper region of the continuous deposit tends to settle into the sand in the lower region. The sand on the inner radius of the deposit comes together to form a separate suspension in the shape of a ball. This ball of sand tends to fall into the flow in the channel formed from the deposit. It will be carried upwards by the flow to be either removed from the tail joint or spread more thinly across the tail joint wall.

For the 7.5 m^3/day test, the dense slugs block the entrance. However, the flow is able to quickly carry the slug out of the tail joint once enough head has developed in the well annulus to push the slug through the small hole. The flow then returns to the Tapered Regime. The formation of continuous wall deposits did not occur during this test.

Plate 4-10: A continuous wall deposit with channelization of the flow.

IV. SLOTTED TAIL JOINT

A. Fluid Flow through the Slotted Tail Joint

Dye visualization tests for the fluid only flow through this tail joint have found that almost the entire volume of flow moves through the back slot to the pump outlet. There is a small amount of flow through the side slots and no flow through the bottom opening. The addition of the back slot appears to create a dead zone for flow anywhere beneath a few centimetres below the bottom of the back slot. The location of the upper level of the dead zone was observed to depend on the properties of the fluid flowing through the well, the flow rate, and the properties of the fluid already filling the annulus and tubing beneath the pump outlet. The typical location for the top of the dead zone is shown in Figure 4-15.

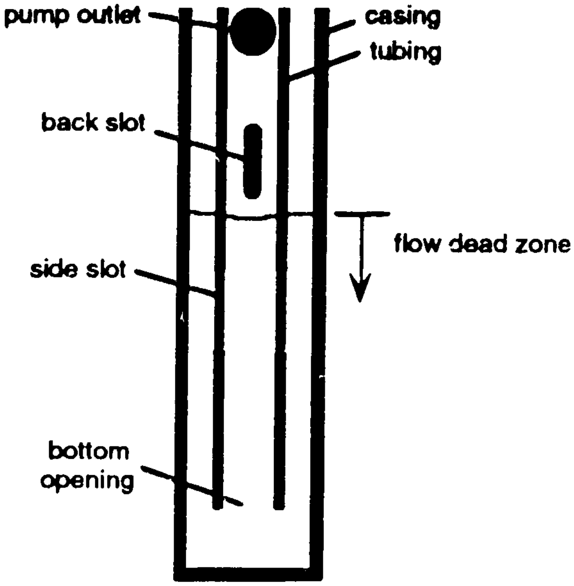


Figure 4-15: The location of the dead zone for flow in the slotted tail joint.

B. Slot Jet Sand Removal Regime

The steady state sand removal regime for this tail joint is the Slot Jet Regime. It forms after the level of sand in the annulus and tail joint reaches a level within top portion of the back slot. A powerful jet forms in the region of the back slot that remains open to flow, as all the flow is directed through this area. There is no flow through the side slots or bottom opening as they have been plugged with sand.

C. Slug Sand Addition

There was little difference in flow behavior for the flowable and dense slugs. Tests began with a clean sump. The first slugs added to the well fell directly into the annulus area beneath the side slots. As the level of sand reached the side slots, the sand began to spill into the tubing area beneath the slots. As more slugs are added, the side slots become plugged with sand. Eventually, the slug sand in the annulus rises to the level of the back slot. At this point, the slugs would be pulled through the back slot into the tail joint. These slugs fill the inside of the tail joint, until only a small portion of the back slot remains free of sand. How much of the slug falls into the tail joint, rather than carried by the jet to the pump outlet, depends on the flowability of the slug. The dense slugs tend to fall into the sump; the flowable slugs tend to be carried away by the flow. With the addition of enough sand, the flow will form Slot Jet Regime.

Once the flow is in the Slot Jet Regime, the flowable slugs will move easily through the back slot to the pump outlet. The dense slugs will tend to plug the back slot as it moves through it. The head difference between the fluid in the annulus and in the tubing increases. The extra pressure pushes the slug through the slot and to the pump outlet. If the slug is large, the extra pressure that has developed in the annulus may cause smaller jets to move through the sand blocking the side slots. Flow through the side slots exists only for a short time, as flow through the back slot quickly resumes once some of the sand has been cleared from the upper part of the tail joint. After this occurs, sand will settle from within the tail joint to block the area in the side slots that was open to flow.

PART 2: VISCOUS, LAMINAR FLOW - CONTINUOUS SAND FEED

I. BACKGROUND

The continuous sand feed tests typically lasted 30 min. The duration of the test was shorter if there was a breakdown of the mixing section of the apparatus. If the time into the test was less than about 10 min when the breakdown occurred, the test was repeated.

The flow in these tests enters the well as a two phase, homogeneous slurry of sand and glycerine.

II. WIDE ENTRANCE

For this entrance, the slurry essentially behaves the same as a single phase fluid flowing through the well. The flow fills the entire width of the tail joint. As well, there is no significant deposition of sand on the sump if the sump level is close to the tail joint entrance. As before, "close to the entrance" is defined as within about 3 cm. If the sump level is not near the tail joint entrance, the slurry will fill the open area between the sump and the entrance. The slurry is stagnant from the original sump level to the level of 3 cm below the entrance. Here, the sand slowly settles out of the slurry to deposit on the sump. Tests were not of sufficient duration for the sump to rise to a level near the entrance. From observation, the time for the sand to completely settle out of the glycerine/sand slurry is in the order of 24 h. The following discussion gives the flow patterns for the case where the sump level is near the tail joint entrance.

Flow patterns similar to that of the Small Hill and Wide Band Regimes appear in every continuous sand feed test using this tail joint design. Typically, the widths of the components of each regime (i.e. the wide band, small band, and small hill) are wider than their counterparts in the slug tests.

For the flow pattern that is similar to the Small Hill Regime, the small hill has more of a tapered shape than the rounded mound seen in the slug tests. Circulation within this small hill has been observed. The small band contains upward flowing sand particles whose velocity is less than the sand particles flowing in the surrounding fluid. The width of the small band varies from about 3 to 8 mm.

The top of the small hill appears to open up and stretch when the transition from the Small Hill Regime to the Wide Band Regime occurs. It is suspected that this change is due to heterogeneity in the slurry. The sand sometimes is not thoroughly mixed with the glycerine and balls of sand form in the flow. The presence of these miniature slugs (which are about 1 cm in diameter) may force the transition to the Wide Band Regime much the same way as a larger slug forces this transition in the slug tests.

For the flow pattern that is similar to the Wide Band Regime, downward circulation within the wide band has been observed. The transition from the Wide Band Regime to the Small Hill Regime most often occurs by an overall thinning of the wide band width. This is similar to the "Total Height Band Thinning" in the slug tests. During some of the tests, there was no movement of the sand particles within the wide band. Therefore, it is considered that the formations seen in this group of tests may be due to the presence of the front plexiglas sheet. It is difficult to prove this hypothesis, as the depth of the formations into the tail joint cannot be observed due to the presence of the sand particles in the surrounding flow.

It is also thought that the sump shape affects which regime forms at the beginning of the tests. Each test began with clean glycerine in the well. After the slurry enters the tail joint, one of the regimes will form. It was found that if the sump shape is approaching a flat sump, then the Small Hill Regime tends to form. If the sump shape is similar to that given in Figure 4-16, the Wide Band Regime tends to form. The upraised portion of the sump, shown in this figure, is in the centre of the sump and is bisected by the front plexiglas.

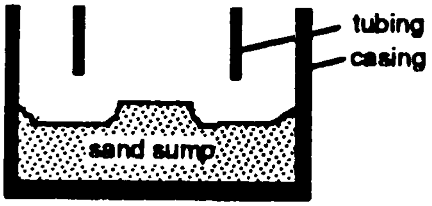


Figure 4-16: The sump shape that may initiate the formation of the Wide Band Regime.

No waviness was observed for the flow rates and sand concentrations in these continuous feed tests.

III. SMALL HOLE ENTRANCE

For the small hole entrance, all tests began with a sump level that was near the tail joint entrance. Again, there was very little sand deposited on the sump. The sump level typically rose 2 mm by the end of 30 min of testing. No waviness was observed.

The initial condition for the tests was that the fluid already in the well was clean of sand and the fluid that was moving through the well consisted only of glycerine. This flow caused the Tapered Regime to form. As in the slug tests at the 2.5 m^3/day flow rate, there exists a bulge in the small band a few centimetres above the tail joint entrance. This bulge did not form at the higher flow rates. At all flow rates, the Tapered Regime (or what looked like the Tapered Regime) continued to be present as the sand slurry was fed into the well.

For the 2.5 m^3/day flow rate at the low sand concentration of 10%, the bulge in the small band continued to be seen throughout the duration of the test. The first "bulge" in the small band moved upward in the tail joint by a few centimetres before another suspension began to form. The first bulge was slowly taken out of the tail joint as the second bulge formed. The second bulge was stretched by the flow to form a small band of greater width.

For the sand concentrations tested at the 2.5 m^3/day flow rate that were higher than 10%, the bulge that had formed in the small band prior to the addition of the sand slurry to the well was carried out of the tail joint when the slurry flow was initiated. This bulge did not reform during these tests.

The Tapered Regime was eliminated by the slurry flow during the 40% sand concentration test at the 2.5 m^3/day flow rate and the 20% sand concentration test at the 5.0 m^3/day flow rate. This occurs by a slow erosion of the tapered mound of sand on the sump and the small band. During the later test, it was observed that there was no upward flow of sand particles in the small band just prior to this occurring.

The components of the Tapered Regime for the continuous feed tests were observed to be wider than their counterparts in the slug tests for the 10 and 20 % sand concentration at the 2.5 m^3/day flow rate. The width of the small band measured as much as 1 cm.

For the 2.5 and 5.0 m^3/day flow rates, the slurry flow fills the entire tail joint width within 10 s from the beginning of the slurry flow through the tail joint. For the 7.5 m^3/day flow rate, the slurry initially flows only through the centre of the tail joint. The slurry flow slowly spreads across the tail joint width and completely fills the tail joint after 1 min.

IV. SLOTTED TAIL JOINT

Almost all of these tests with the slotted tail joint began with a sump level at least 1 cm below the lowest potion of the tail joint. Glycerine flows in the well with essentially all flow directed through the upper potion of the back slot. The well was clean of sand except for the sand in the sump. When the sand slurry flow into the well is initiated, part of the slurry stream flows down through the annulus to the sump. Another part is pulled through the back slot. This flow divides into one stream that moves toward the pump outlet and another that falls through the tail joint to the sump. A higher proportion of this stream moves to the pump outlet as the flow rate increases. Some of the latter sand stream flows through the side slots into the annulus as it passes them. The other portion sand moves through the inside of the tail joint to spread across the sump when it collides with it. Some of this stream may move upward from the sump into the annulus. Thus, the incoming sand quickly fills the volume of the annulus and tubing beneath the pump outlet. After this occurs, almost all of the flow is directed through the back slot to the pump outlet.

For the 2.5 m^3/day flow rate, all of the flow moves through the back slot. This flow spreads across the width of the tail joint before reaching the pump outlet. The boundary of moving slurry from the still fluid is depicted in Figure 4-17.

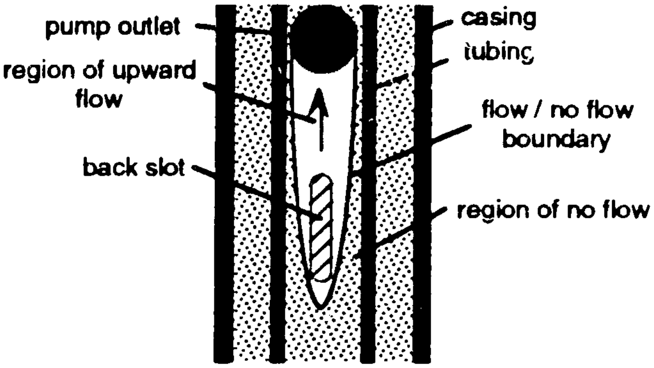


Figure 4-17: Shape of flow/no flow boundary for flow through the back slot to the pump outlet.

During the 5.0 m^3/day and 7.5 m^3/day tests, a curious pattern of flow formed in the upper half of the tail joint after the sand slurry had dispersed in the well beneath the pump outlet. Two lines appeared in the slurry flow to etch a shape similar to that of a wine glass. The bottom of this shape touch the lowest portion of the side slots. Its upper edges approach the tail joint wall asymptotically near the pump outlet. The lines are sketched in Figure 4-18.

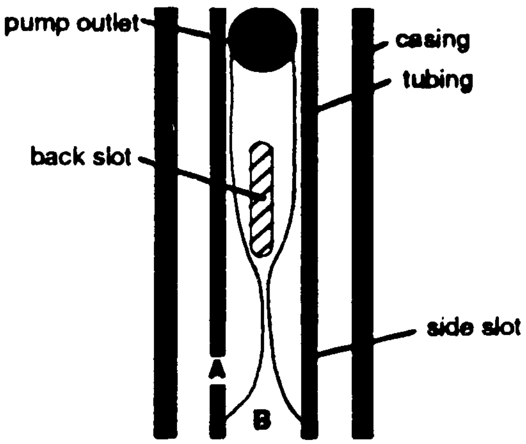


Figure 4-18: Wine glass shape formed by the boundary lines of two flows - one flow through the side slot and one through the centre of the tail joint.

In coincidence with the above observation is a slow flow through the entire length of the side slots. Also seen is a slow upward flow in the area shown as region B in Figure 4-18. However, it is not firmly decided whether the upward flow in this area is actually the movement of sand particles or a movement due to buoyancy of air bubbles which are trapped in the slurry during the mixing process. It is thought that the flow through the side slots must actually occur because the bubbles are seen to move horizontally from the annulus to the tubing and then upward to the pump outlet. This movement of the bubbles could not be due to their buoyancy because the bubbles would rise within the annulus, instead of within the tail joint.

When the sand feed is stopped and the glycerine again moves through the well as a single-phase fluid, the annulus clears of sand to the level of the top portion of the back slot. The typical shape of the flow/no flow boundary soon after stopping the sand feed into the flow is depicted in Figure 4-19.

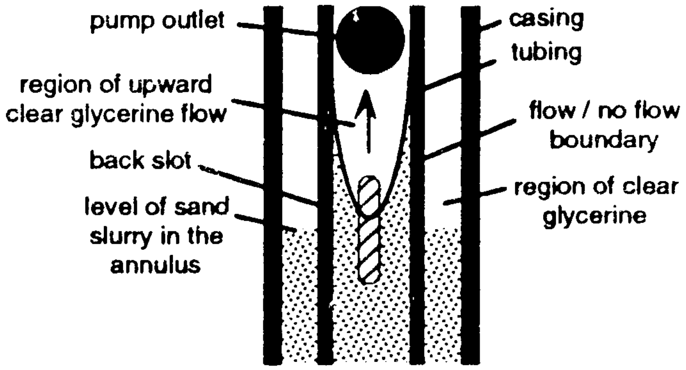


Figure 4-19: Typical shape of the flow/no flow boundary soon after a single-phase glycerine flow moves through a well filled with glycerine/sand slurry.

PART 3 - TURBULENT WATER FLOW - SAND SLUG ADDITION

I. BACKGROUND

With the addition of sand either in the form of a slug or as a continuous feed into the flow, the sand will fill the well sump until the sump level reaches within a few millimeters of the tail joint entrance. This is similar to the viscous flow, where the pump has an influence below the tail joint entrance of only a few centimetres. The sand added to the flow was water wet for the slug tests (the voids in the sand matrix were filled with water). The sand was dry for the continuous feed tests.

Investigation of the effect of the length of the tail joint on the formation of the different flow regimes showed that it was negligible. The tail joint length will affect the structure of the turbulence within the tail joint i.e. the vortex patterns. It may also be significant during a period of cessation of flow through the entrance, such as sanding in of the tail joint. There is potentially more sand to settle out of the flow within the tail joint into the entrance. However, it is not the intention of the model to accurately portray this phenomenon.

II. WIDE ENTRANCE

A. Primary Flow Regimes

1. Single Jet Flow Regime

A jet entering the tail joint only at one side of the entrance characterizes the Single Jet Regime. This jet has a varying area available to flow; the depth of flow beneath the tail joint entrance and width of the jet along the tail joint circumference change with the amount of sand present in the flow, the flow rate, and time. The jet was observed to always form against the front plexiglas sheet on either side of the tail joint. Sand deposits within the well on the side of the tail joint and in the annular area opposite the jet. The Single Jet Regime is a partial radial flow through only one section of the tail joint entrance. The appearance of the single jet in a front view of the model well is depicted in Figure 4-20. The jet enters the tail joint at what is defined as the "jet angle". This is the angle that the entering jet makes with the horizontal. The jet in Figure 4-20 has a jet angle of 90° . Plate 4-11 also gives the typical appearance of the Single Jet Regime when it is considered to have a high jet angle. Plate 4-12 gives the Single Jet with a low jet angle of about 45°.

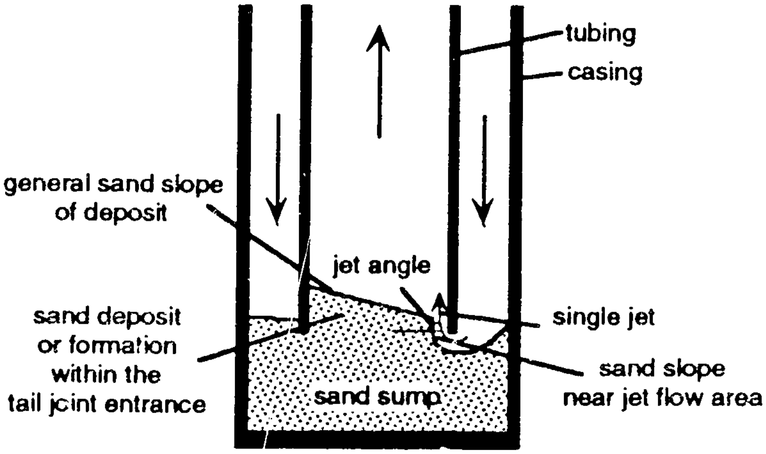


Figure 4-20: The front view typical of the Single Jet Flow Regime.

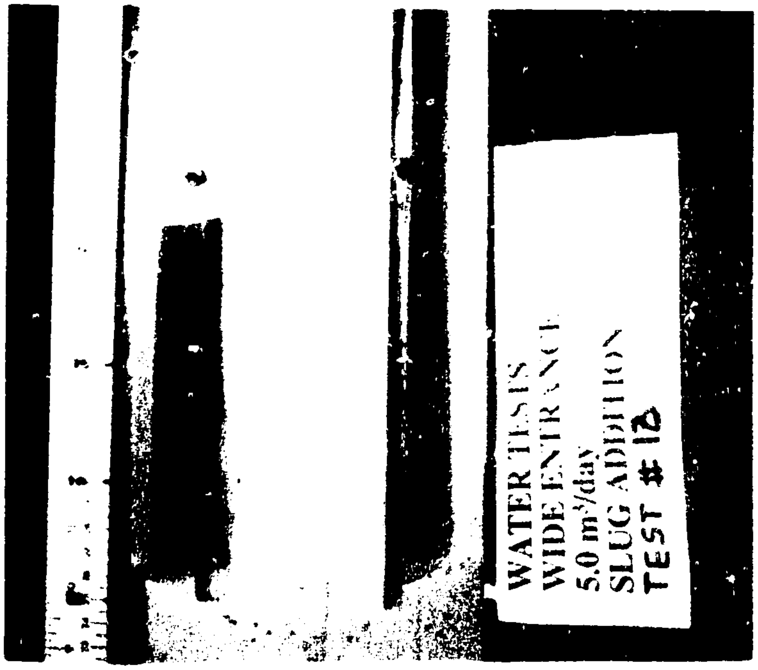


Plate 4-11: The Single Jet Regime with a high jet angle in the wide entrance.

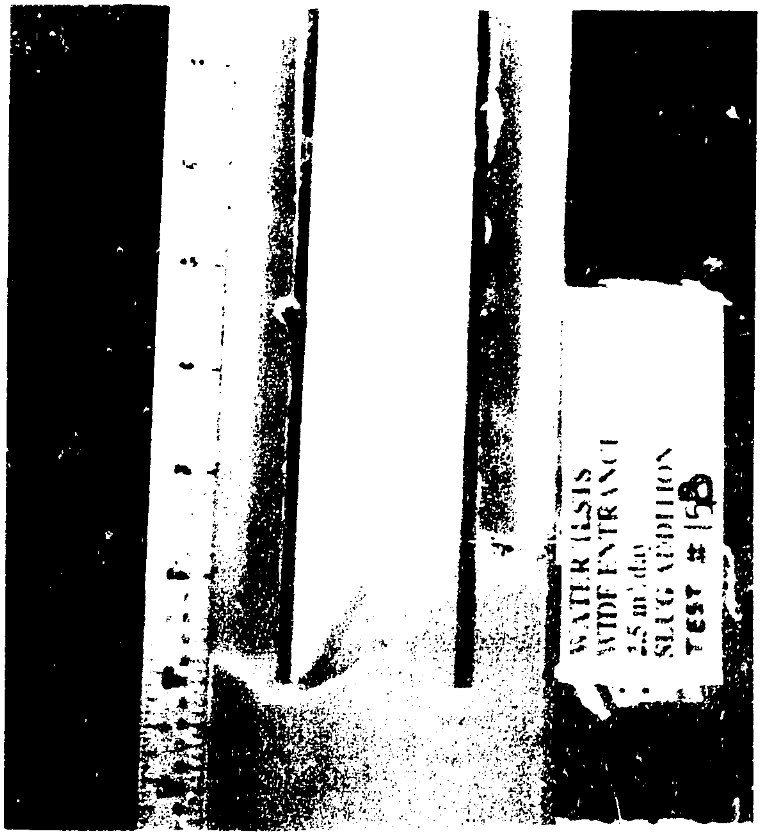


Plate 4-12: The Single Jet Regime with a low jet angle in the wide entrance

The jet continually scours at the sand deposit in the entrance. Downward flow on the side of the tail joint opposite a single jet of high jet angle continually deposits sand particles on the general slope formed by the sand. The volume of this sand formation can remain fairly constant if the rate of scour by the jet is about the same as the rate of deposition from the vortex. The higher the flow rate, the more likely the scour is greater than the deposition. As the flow rate decreases, the deposition of sand particles becomes greater than the sand erosion by the jet. It has been observed that as the amount of sand that has deposited in the entrance increases, the jet angle will fluctuated and/or decrease. It is thought that the flow tries to reach an equilibrium between the momentum of the jet and the stability of the sand slope near the entrance. This slope frequently fails and sand moves into the area open to jet flow. The jet, now with a restricted area of flow, increases in velocity and therefore its capacity to carry sand. It erodes at the slope and the flow area increases. Deposition on the slope causes it to grow and eventually become unstable. This cyclical process occurs until enough sand is carried away from the entrance for the slope to be stable in proportion to the jet.

Jet angle will depend on the flow rate and the amount of sand deposited in the tail joint entrance if the hypothesis that the jet and the sand slope try to reach equilibrium of their corresponding forces is correct. The momentum of the jet increases with flow rate and therefore the force on the slope that the jet can provide. The amount of sand deposited in the tail joint influences the slope's stability. Observations show that jet angle may be dependent on flow rate as the jet is typically fairly steady at 90° at the 5.0 m^3/day flow rate, but at the 7.5 m^3/day flow rate the jet angle tends to be lower at about 80°. Secondly, the jet angle tends to fluctuate at the 2.5 m^3/day flow. A fluctuating jet angle was observed to correspond to a fluctuating head difference between the fluid in the well annulus and in the tubing (the fluid level in the annulus being greater). As well, if the flow rate is increased while the flow is in the Single Jet Regime, the jet angle tends to decrease.

There is a structure to the turbulence within the tail joint. This structure varies with the flow rate, the concentration of suspended sand, and the jet angle. As the flow rate increases, the flow in the tail joint becomes violently turbulent. An example of this "structure" is that at the 5.0 m^3/day flow rate, with a moderate suspended sand concentration, and while flow exhibits the Single Jet Regime with a jet angle approaching 90°, there are typically three large zones of circulation that form along the height of the tail joint (for the length of tail joint used for these tests). For the lower portion of the tail joint, the jet will flow along tail joint wall similar to a wall jet. Vortices are shed from the jet with counter-clockwise circulation if the jet enters at the right hand side of the tail joint and clockwise circulation if the jet enters at the left hand side. These vortices exist in the centre portion of the tail joint width. Along the wall of the opposite side of the tail joint is a predominantly downward flow. This downward flow deposits sand in the entrance. The bottom zone of circulation exists for a flow length of about 14 cm from the entrance. In the mid portion of the tail joint, the jet may continue its flow along the wall. A large vortex will form with its circulation in the same direction as the smaller vortices shed from the jet in the lower part of the tail joint. This vortex fills most of the tail joint width and is approximately 10 cm high. It is elliptical in shape. The jet also frequently shoots across to the opposite tail joint wall as it reaches this mid-zone of the tail joint. The large vortex changes its direction of circulation when this occurs. In the upper zone, there is a large vortex of approximately the same size of the vortex below, and with a circulation opposite in direction. The circulation pattern is shown in Figure 4-21. Many smaller vortices exist within the framework of the main circulation pattern. Large suspended sand concentrations within the tail joint will quiet the turbulence, especially in its upper regions. It will also see the bottom zone of circulation shortened in length.

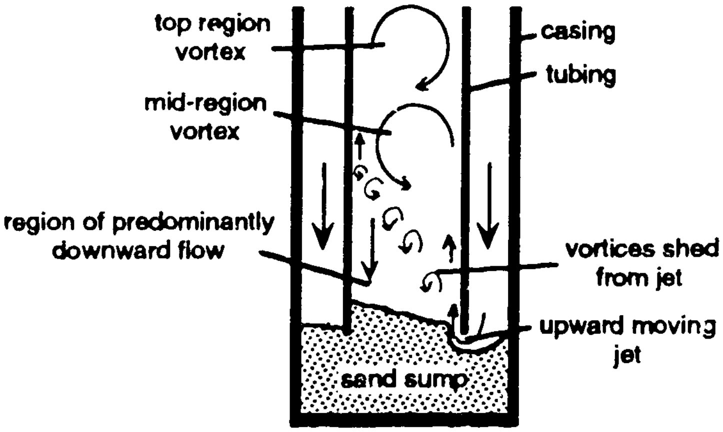


Figure 4-21: Circulation pattern along the height of the wide entrance tail joint at the 5.0 m^3/day flow rate and a Single Jet Regime with a jet angle approaching 90°.

At the 2.5 m^3/day flow rate, the sand suspension is not violently turbulent as it is at the higher flow rates. However, it appears that there is more of a total circulation within the tail joint as there is a dominant upward flow on the side of the jet and a dominant downward flow on the side opposite the jet. For a jet with a high jet angle, the length of flow for the jet before its energy seems to be dissipated is only about 6 cm. The width of flow of the jet along the circumference of the tail joint is very small at about 1 cm. The jet angle continuously fluctuates as the sand that has deposited as a "slope" in entrance rushes in the flow area every few seconds. The entrance may even become sanded in when this occurs. Sanding of the entrance is described further in the section on slug sand addition.

Steady circulation patterns caused by the incoming jet are not easily observable at the 7.5 m^3/day flow rate as the sand slug is carried out of the well quickly and there is only a small time for its suspension in the tail joint.

2. Radial Jet Flow Regime

The Radial Jet Flow Regime is a radial flow along the wall of the tail joint. The jet flows along the entire tail joint radius. The top of the sump within the entrance forms a half-cone shape. The typical appearance of this regime through the front of the model is given in Figure 4-22 and in Plate 4-13. The width of flow of the jet from the inside edge of the tail joint to the outside edge of the raised portion of the sump is typically about 5 mm.

When the flow is in this regime, there are no large vortices along the tail joint height as described for the Single Jet Regime. The Radial Jet Regime creates a less organized and less violently turbulent flow within the tail joint than the Single Jet Regime of high jet angle for the same flow rate.

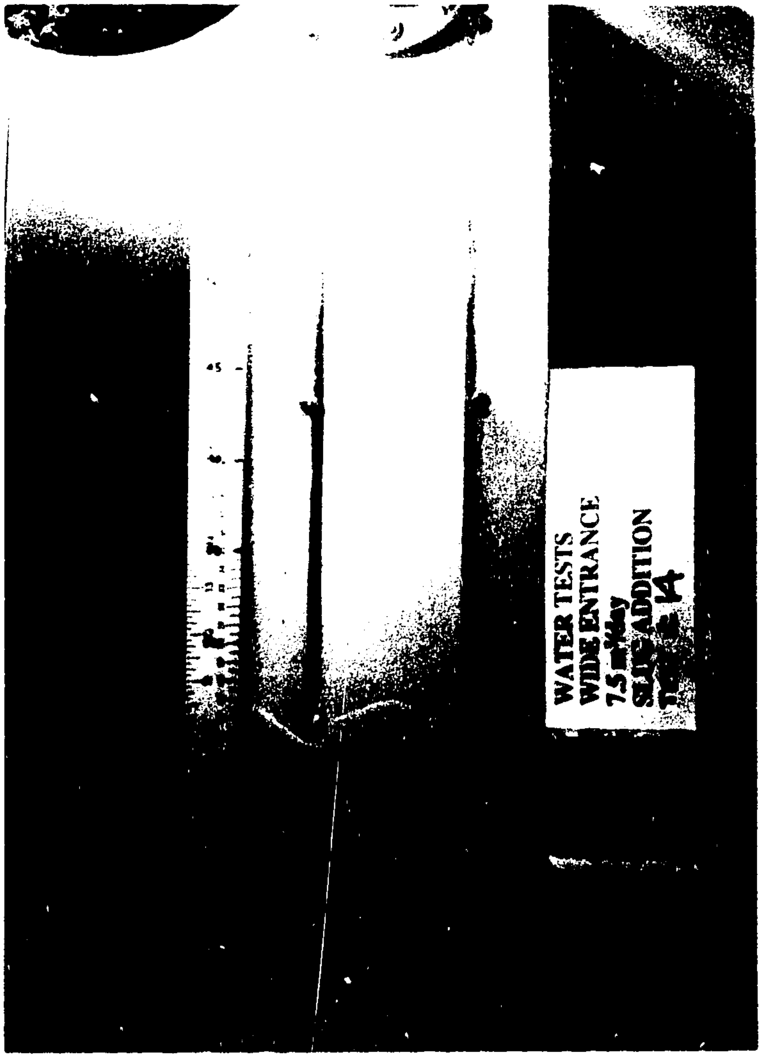


Plate 4-13: The Radial Jet Flow Regime.

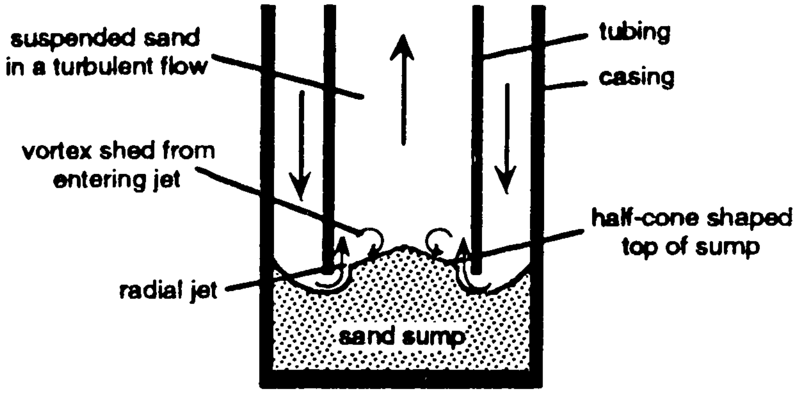


Figure 4-22: The Radial Jet Flow Regime.

B. Sand Slug Addition

1. General

Sand blockage or "sanding in" of the tail joint entrance does not occur from the outside of the entrance (sand moving from the annulus to the tail joint) as in the glycerine tests. Sand blocks the entrance from within the tail joint. It occurs only when the flow is in the Single Jet Regime. The sand slope, which develops within the entrance in the sump area opposite the jet, fails. Immediately, the cessation of flow through the tail joint causes the suspended sand to quickly settle and pile in the entrance. As this occurs, the head difference between the fluid in the annulus and tubing increases. When this head difference is great enough, piping occurs in the sand bed formed in the bottom of the tail joint. A jet forms in the liquefied area of the bed. The piping will usually occur in the location in the entrance which was open to flow just prior to the sanding in. Plates 4-14 to 4-17 show the progression through the entrance of a slug that is large enough to cause sanding in of the tail joint.

Considered as the important factors to allow sanding in of the entrance are the flow rate, the volume of sand deposited within the entrance, and the concentration of suspended sand in the entrance area. The flow rate increases the ability of the water to carry the sand and the momentum of the jet. The volume of sand deposited within the entrance influence the stability of the formation within the entrance. More sand within the entrance gives the formation a greater tendency to move into the area of flow. Finally, the concentration of suspended sand in the entrance area influences the amount of sand that can be deposited in the entrance under varying negative flow conditions such as the sudden cessation of flow when sanding in occurs.

2. 5.0 m^3/day Flow Rate

For the 5.0 m^3/day flow rate, slug sand becomes suspended in a violently turbulent flow and is eventually carried out of the tail joint after a long period. The time for removal of the sand from tail joint is not known as during testing another slug was always added before this could occur. Time between addition of the slugs was 4 min.

When a slug is added when the flow is in the Radial Jet Regime, the depositing sand raises the level of the sump unevenly, until one side of the entrance is blocked. Flow is now directed to one open area only and the Single Jet Regime becomes stable. It is unlikely that the Radial Jet Regime will reform after this occurs at this flow rate. From observation, it is

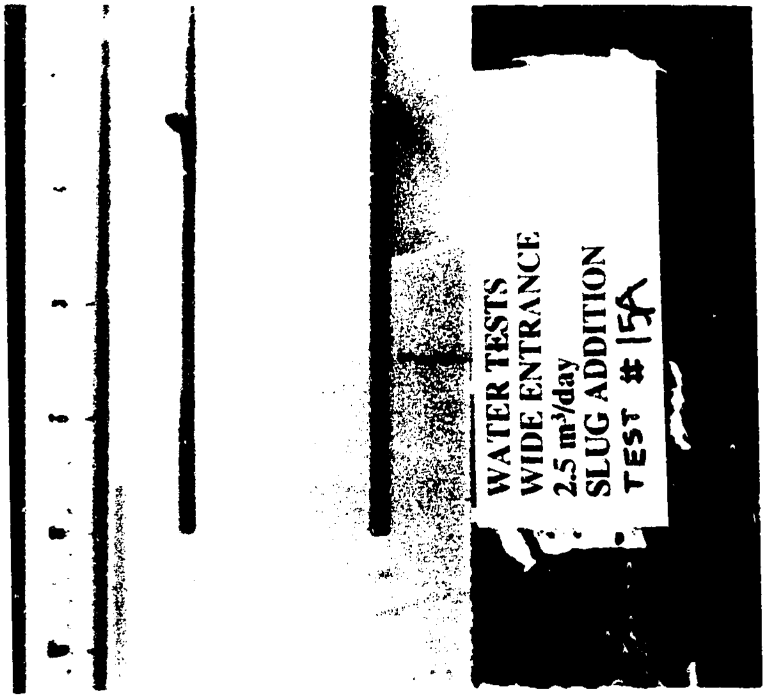


Plate 4-14: A large slug has blocked flow through the entrance and sand piles in the well annulus.

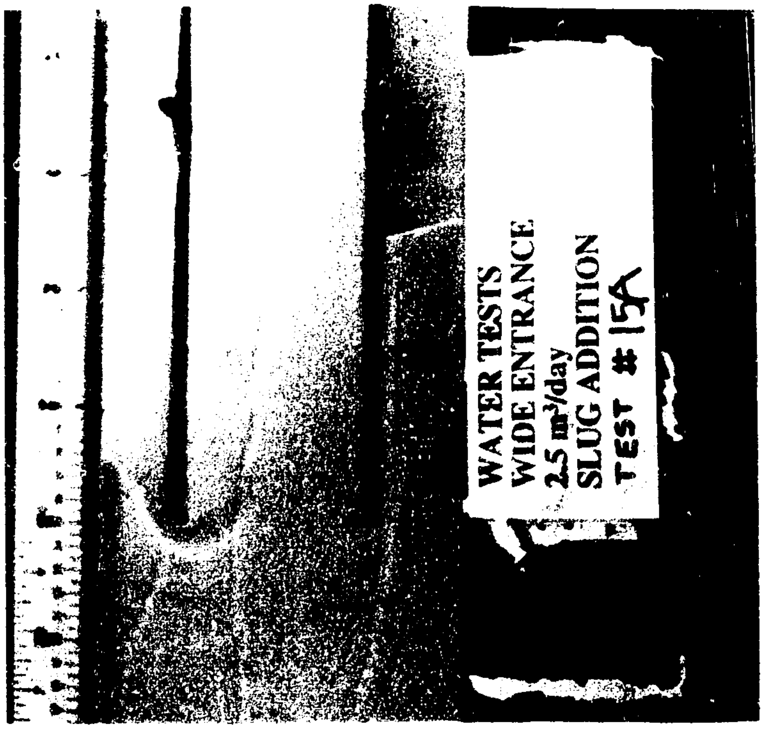


Plate 4-15: The jet is making its way through the sand plugging the entrance.

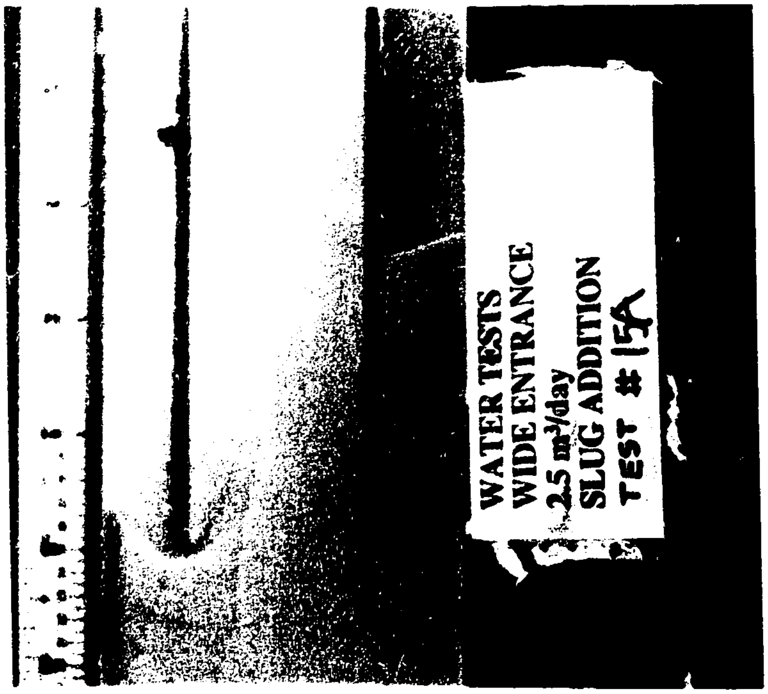


Plate 4-16: A weak, single jet forms.

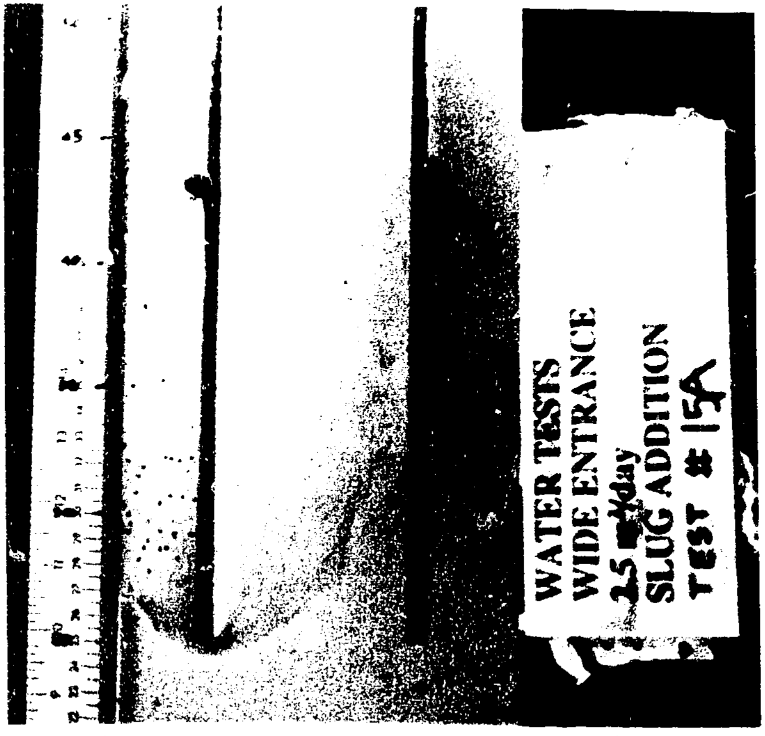


Plate 4-17: The last of the slug moves into the tail joint as signified by the movement of the poppy seeds through the entrance.

believed that the only way a Radial Jet Regime can form at the 5.0 m^3/day flow rate is if the slug sand raises the sump level just to the level of the tail joint entrance. Addition of significant amounts of sand when the sump level was already near the tail joint entrance would allow the Radial Jet Regime to form only as a transitional state lasting for only a few seconds before a stable Single Jet Regime forms.

If a slug of sand is added to the flow when the flow regime is the Single Jet of jet angle approaching 90°, this angle will decrease to about 45° (a low jet angle). Little turbulence is seen in the tail joint except for the motion of the jet. The jet, which is fed by a water/sand mixture, shoots across the tail joint width to hit the opposite wall of the tail joint. The flow width along the circumference of the tail joint also decreases. After all of the slug moves through the entrance, turbulence in the tail joint slowly increases. The single jet will also slowly return to a high jet angle.

3. 2.5 m^3/day Flow Rate

For the 2.5 m^3/day flow rate, slug sand is removed from the tail joint very slowly. In one test, it was observed that after the movement of the slug through the entrance, the difference in level for the fluid in the annulus and in the tubing remained constant for several minutes. This may be an indication that the sand is not being removed from the tail joint. If the tail joint was clearing of sand, the difference in these fluid levels would decrease.

When a slug is added to the well, it will tend to block off one side of the entrance so that the Single Jet Regime forms. The excess sand moves through the entrance as a single jet with a high jet angle if the tail joint is initially free of sand. For a tail joint already filled with suspended sand from a previous slug, the jet angle will decrease and remain at 45° until all of the slug has passed through the entrance. The newly suspended sand forms what looks like a fluidized bed in the lower portion of the tail joint. There is a definite interface between a sand suspension in the lower part of the tail joint and the clear fluid (or less concentrated sand suspended from a previous slug) in the upper part of the tail joint. This interface is shown in Plate 4-18. The gradient of the sand concentration with height along the tail joint becomes uniform gradually with time. After all of the slug has passed through the entrance, the jet angle fluctuates. The time scale for this change can be in the order of a few seconds. The sand formation in the entrance may alternately fail to move into the area of jet flow and is eroded by the jet. The flow area is may not be completely blocked by the sand when this "slope failure" occurs. Sanding in of the entrance did occur for some slugs as they moved through the entrance. However, sanding in of the entrance may occur spontaneously without a recent slug addition.

For one test at 5.0 m^3/day with a large suspended sand concentration within the tail joint, the flow rate was slowly decreased. The initial regime was the Single Jet with a 90° jet angle. As the flow rate is lowered, the violent turbulence in the tail joint diminishes. The jet's influence (the region which it disturbs) across the tail joint width decreases. The jet angle does not change. The raised portion of the sump in the entrance grows in height. The sand in the formation often slides into the area open to flow. This blockage of the flow area occurs only briefly (approximately 1 s) before the Single Jet Regime reforms. As the flow rate is further decreased to 1.54 m^3/day, the suspended sand behaves more as a fluidized bed; a definite interface forms between the top of the sand suspension and a clear water. The jet's effect on the fluid across the width and height of the tail joint again diminishes. It remains at a jet angle of 90°. The fluidized bed level decreases slowly and the sump level within the entrance grows rapidly. The sand deposit in the entrance fails

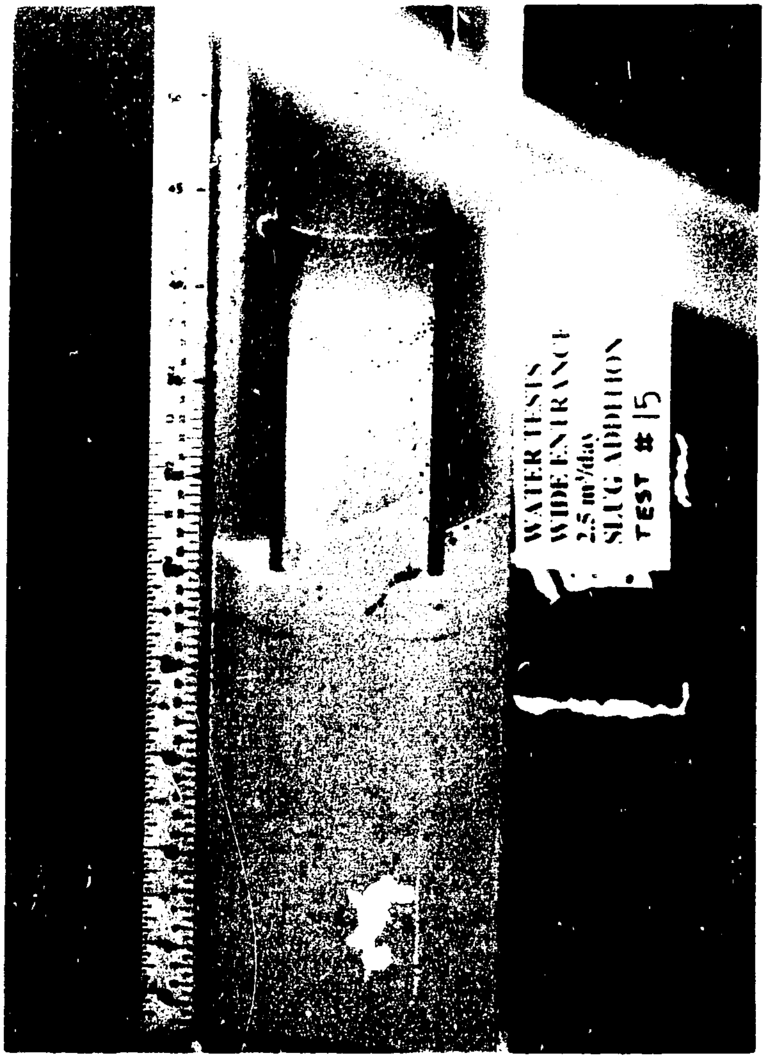


Plate 4-18: Interface between the suspended slug sand and the clear water in the tail joint.

with more frequency (about every 10 s) and blocks the entrance for a longer period (now about 5 s). Overall, the fluidized bed level is decreasing; but is lifted upwards when piping occurs in the area formerly open to the jet flow. The process of filling the flow area with sand and its cleaning it out by piping occurs repeatedly. When the flow rate is slowed to 1.15 m^3/day, the entrance is blocked longer and the time for piping and jet flow is shorter. This cyclical process is continuing to occur when the test is ended.

4. 7.5 m^3/day Flow Rate

For the 7.5 m^3/day flow rate, slug sand is brought into and carried out of the tail joint very quickly. Very little sand stays suspended in the turbulent flow in the tail joint. Even a very large slug, 5.30 kg or 2.75 L of a water wet sand, was taken out of the tail joint within 1.75 min. Typically slugs are taken out of the entrance within 1.5 min from the time the first part of the slug reaches the tail joint entrance to when the concentration of sand suspended in the tail joint is judged to be minimal.

When the slug added is small (less than about 0.55 L of water wet sand) and the initial regime is the Radial Jet, it is likely that the flow will remain in the Radial Jet Regime as it passes through the entrance. One side of the radial jet tends to dominate over the other. The location of the more powerful part of the jet alternates. The raised portion of the sump in the centre of the tail joint slowly erodes to be shorter and flat, after the slug has passed through the entrance.

Addition of larger slugs sees the formation of a Single Jet Regime. Typically, the tail joint entrance has very little sand deposited within it as the sand is carried away very effectively at this flow rate. When the slug is added, the sand deposit within the entrance increases in height and the jet angle goes to approximately 80°. When all of the slug has passed through the entrance, the entrance is very quickly cleaned of sand.

III. SMALL HOLE ENTRANCE

A. Primary Flow Regimes

1. Single Jet Flow Regime

A jet entering the tail joint through only one portion of the small hole characterizes the Single Jet Regime for the small hole entrance. This regime has very similar characteristics to the Single Jet Regime for the wide entrance. However, for this tail joint, the jet was observed to form in locations in the small hole other than against the front plexiglas. Sand deposits within the entrance and annulus on the side opposite the jet. The jet angle for this regime can vary from about 30° to 90°. Plate 4-19 shows the Single Jet Regime with a high jet angle. Plate 4-20 shows this regime with a low jet angle.

Often associated with a single jet is a strong vortex with a vertical axis of rotation. This vortex is named the "vertical vortex". It has formed at all flow rates tested. The axis of rotation is usually located near the centre of the small hole when there is a large amount of sand in the entrance area. The vortex makes the sump that raised in the entrance appear to be swirling. Compare Plate 4-21, which shows a Single Jet Regime with this vortex, to that in Plate 4-20, which does not exhibit this phenomenon. The flow rate is 2.5 m^3/day.

The vertical vortex may lower to sump level. It is then very effective in cleaning the sand from underneath the bottom piece of this entrance. This was observed to occur when the single jet with vertical vortex had cleaned most of the sand from the entrance. This vortex is shown in Plate 4-22.

2. Radial Jet Flow Regime

The Radial Jet Flow Regime is a fully radial flow through the small hole. The jet flows along the entire small hole circumference and enters the tail joint flowing vertically. The appearance of this regime through the front plexiglas is given in Figure 4-23. It is also shown in Plates 4-23 and 4-24. Plate 4-25 shows that the raised portion of the sump in the entrance is not affecting the flow. There is a radial flow, with a depth of only a few millimetres, underneath the bottom piece of the tail joint.

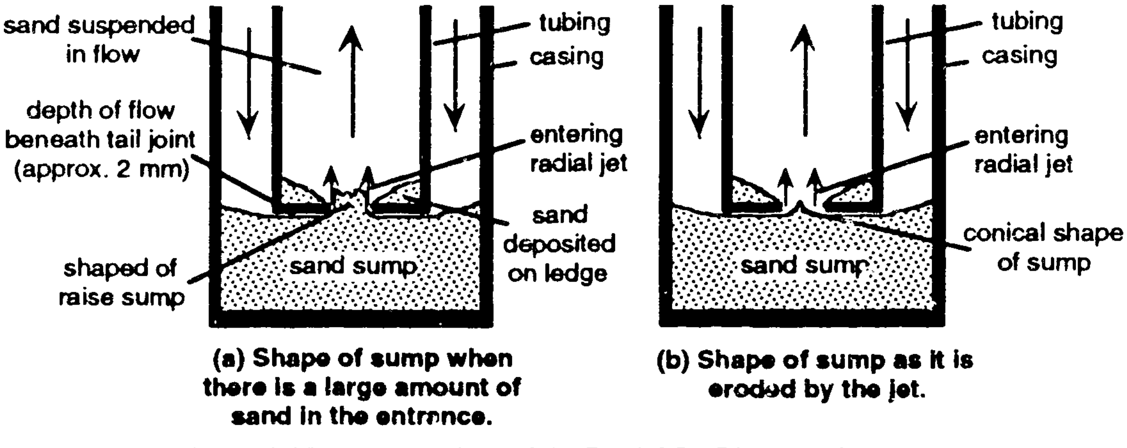


Figure 4-23: A front view of the Radial Jet Flow Regime.

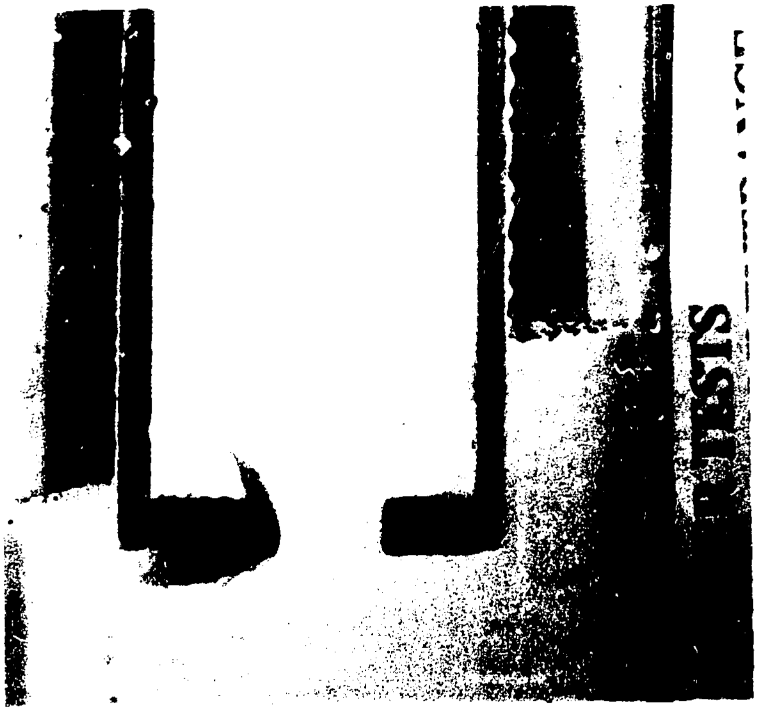


Plate 4-19: The Single Jet Regime of high jet angle for the small hole entrance.

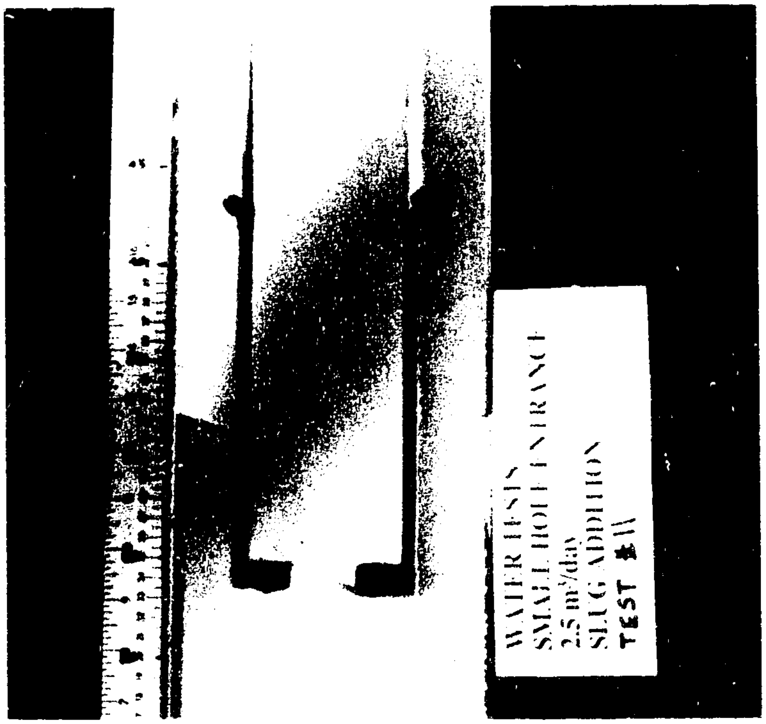


Plate 4-20: The Single Jet Regime of low jet angle for the small hole entrance.

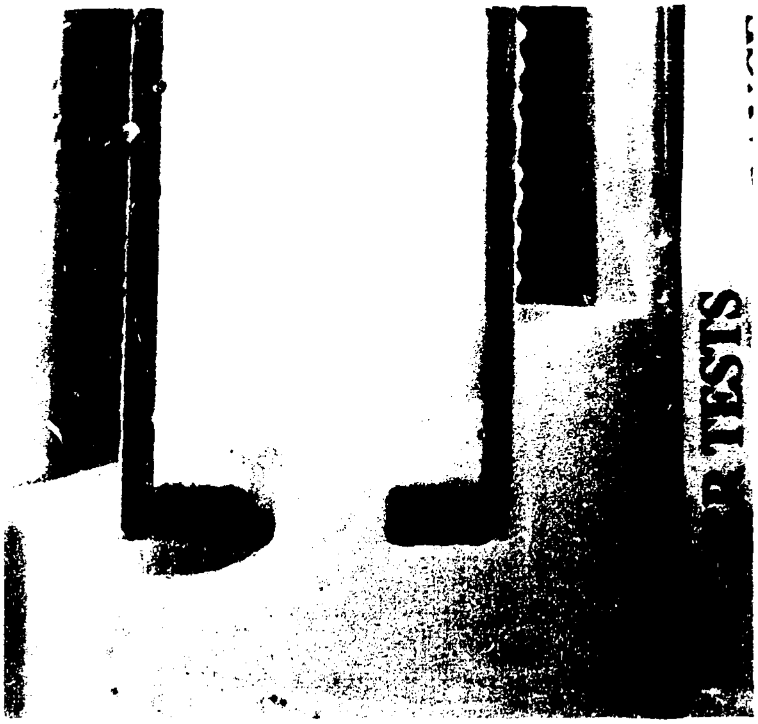


Plate 4-21: The Single Jet Regime with a vertical vortex.

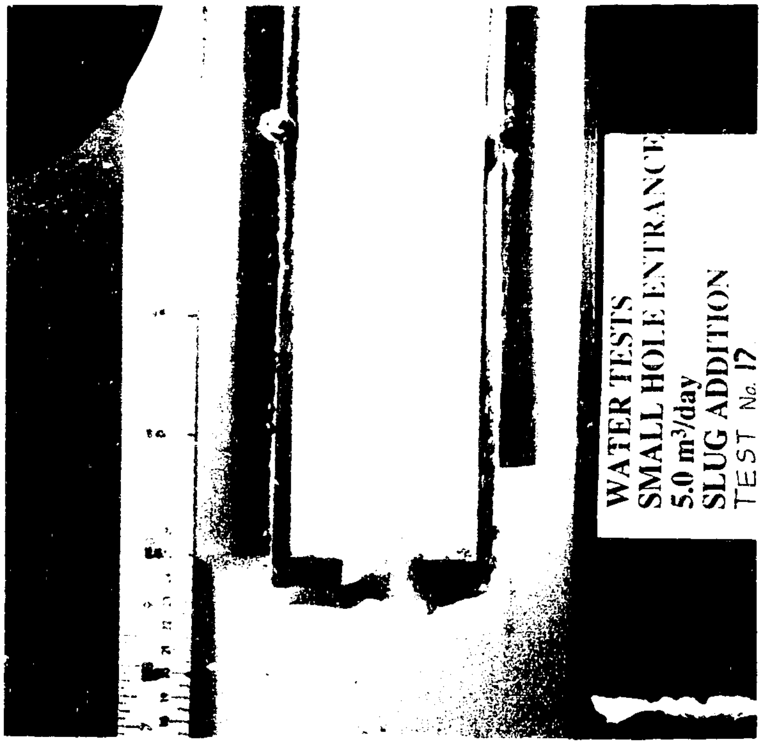


Plate 4-22: A vertical vortex at sump level.

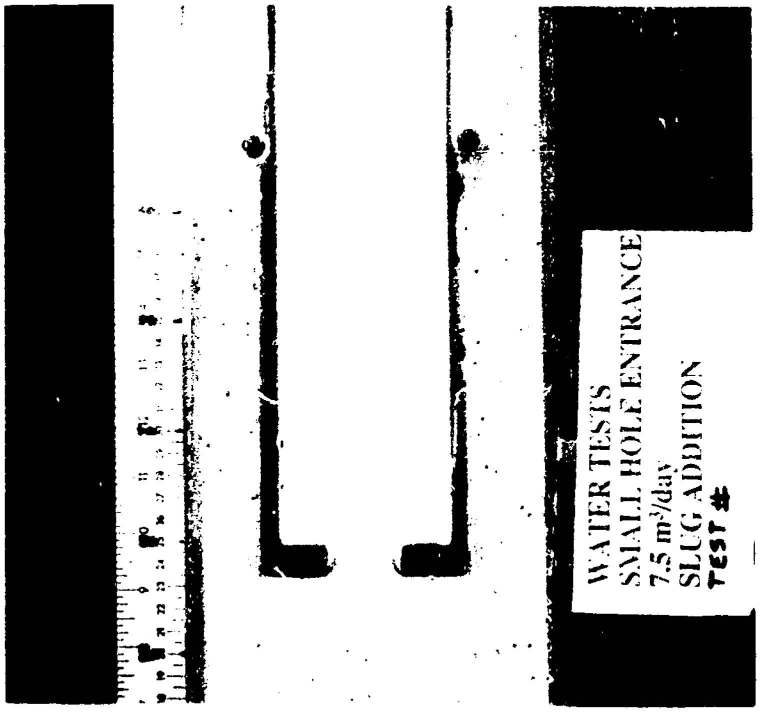


Plate 4-23: The Radial Jet Flow Regime when there is a large amount of sand in the entrance.

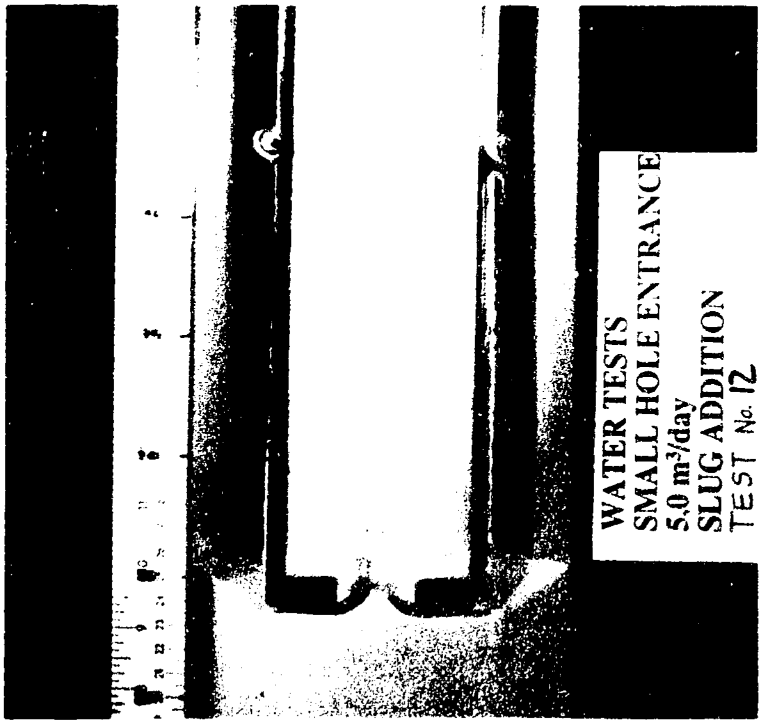


Plate 4-24: The Radial Jet Flow Regime as the entrance is cleaned of sand.

Plate 4-25: A more representative view of the Radial Jet Flow Regime.

Always associated with the Radial Jet Regime is a vertical vortex. The axis of rotation for this vortex is located at the centre of the equivalent fully radial flow. As for the Single Jet Regime, this vortex makes the sand in the raised portion of the sump within the small hole appear to be swirling.

B. Slug Sand Addition

1. General

Sanding in of the small hole entrance occurs in the same manner as the wide entrance. The reader is referred to the corresponding section for the wide entrance for its description.

2. 5.0 m^3/day

At 5.0 m^3/day, the flow cleans out the sand around the tail joint entrance very quickly. The entrance area is cleaned within the 4 min time interval between slug additions. At this flow rate, the dominant flow pattern the Single Jet Regime.

For the small slugs (about 250 ml of water saturated sand) and a flow regime that is initially the Radial Jet Regime, as the just added slug reaches the entrance, the Radial Jet Regime remains stable. The sump level rises to within about 2 mm from the bottom of the tail joint. A vertical vortex forms in the centre of the small hole. Sand slowly builds in the centre of the small hole until the sump shape looks like that in Figure 4-23 (a). The vertical vortex continues to exist. As the sand slug finishes passes through the entrance, the depth of flow of the jet beneath the bottom piece increases. The Radial Jet Regime returns to that in Figure 4-23 (b).

When the slug is large enough, the Single Jet forms from the Radial Jet Regime. The process is similar to that described above. As the first part of the slug reaches the entrance, the Radial Jet remains stable. The sump level rises to within a few millimetres of the tail joint. A strong vertical vortex forms in the centre of the small hole. The sand then blocks one side of the entrance. The Single Jet with a vertical vortex flow pattern forms. The jet angle is close to 90° and the axis of the vortex is near the edge of the small hole opposite the jet. The vortex fills with slug sand. A more definite Single Jet Regime is present and the vortex motion decreases. As the end of the slug passes through the entrance, the vortex motion becomes very strong. After cleaning the sand out of the entrance, the vertical vortex moves to sump level to clean the sand from beneath the side of the tail joint blocked with sand.

When a slug is added when the flow is the Single Jet Regime, what occurs in the entrance area is similar to that described in the preceding paragraph. Since one side of the entrance is already blocked with sand, the incoming slug further increases the sand level within that side of the tail joint and annulus. The single jet will likely be associated with a vertical vortex as the first part of the slug passes through the entrance. If there is a large amount of sand in the entrance, the vortex will not be seen , and the jet angle will be 90°. As the end of the slug passes through the entrance, the vortex forms again. It helps to clean the sand out of the entrance. The flow tends to form a Single Jet with a vertical vortex on the sump level after this occurs, as in Plate 4-22.

3. 2.5 m^3/day Flow Rate

For the 2.5 m^3/day flow rate, the sand is not taken out of the tail joint within the 4 min time interval between slug additions. The Single Jet Regime is the dominant flow pattern at this flow rate.

If a slug is added when there is not much sand in the entrance area of the tail joint, the Single Jet Regime with a vertical vortex tends to form. After the slug has passed through the entrance, this vortex cleans the entrance area and moves to the main sump level to form a weak vortex (compared to the vortices formed at the other flow rates) just beneath the entrance. This vortex is shown is Plate 4-22.

If there is a large amount of sand in the entrance area, the Single Jet forms with a vertical vortex. Sand fills the entrance on the side opposite the jet. As the slug passes through the entrance, the jet angle is about 80°. When clear water flow into the tail joint resumes, the jet angle decreases to 30°. At this angle, the jet crosses the small hole to enter the tail joint just above the ledge on the side opposite the jet's entry. This is shown in Plate 4-26. The Single Jet Regime at this jet angle remains fairly stable. The jet angle will fluctuate moderately when some of the sand that has piled up on the ledge, created by the extra bottom piece for this tail joint, falls into the entrance. The jet angle also decreases, to see a very small, weak vertical vortex form on the sump form for a few seconds. If a slug is added while the flow regime is in this pattern of the Single Jet with 30° jet angle, the jet angle increases to about 80°. It decreases back to 30° when the slug flow through the entrance ends. There is no vertical vortex formation.

4. 7.5 m^3/day Flow Rate

At the 7.5 m^3/day flow rate, the slugs are cleaned out of the well within about 1.5 min from the time they reach the tail joint entrance to when the tail joint is considered to be free of sand. The Radial Jet Regime is the dominant flow pattern at this flow rate.

The flow description is very similar to that at the 5.0 m^3/day flow rate for slug addition. However, the flow remains in the Radial Jet Regime until the slug volume reaches above about 1 L of water saturated sand. The depth of flow beneath the tail joint as the slug flows through the entrance is 2 to 3 mm. A steady state depth of flow for the jet under the tail joint is about 1.5 cm. As well, the flow tends to return to the Radial Jet Regime very quickly.

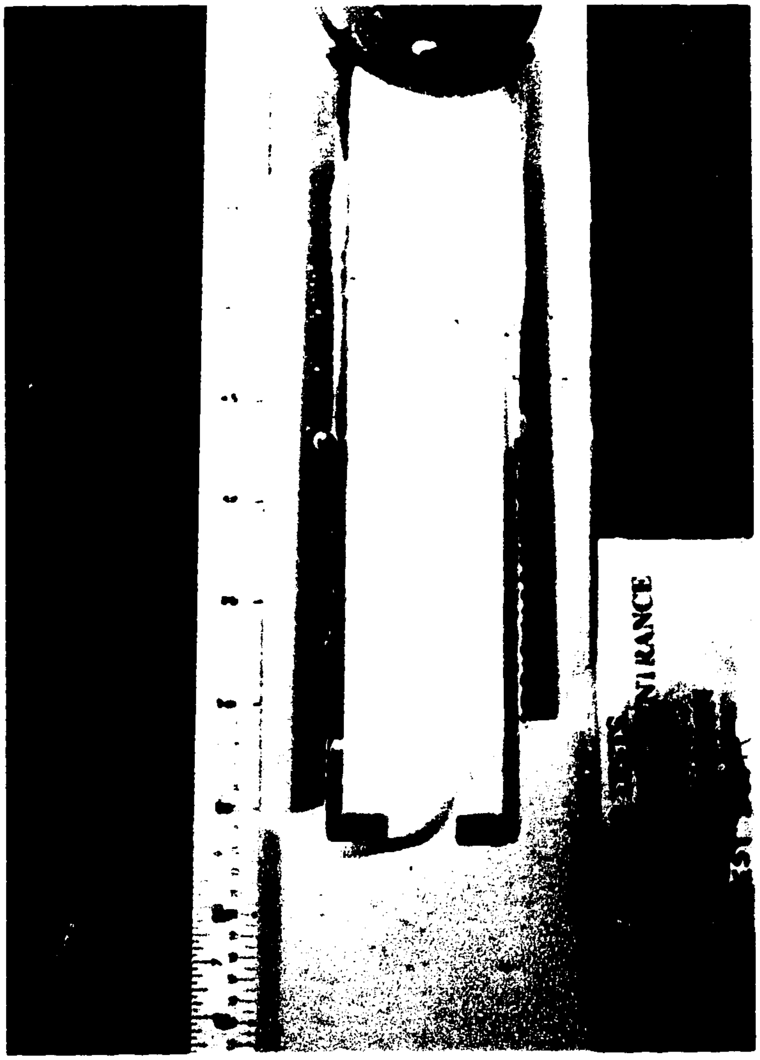


Plate 4-26: The Single Jet Regime at a 30° jet angle.

IV. SLOTTED TAIL JOINT

A. Slot Jet Flow Regime

As for the glycerine tests, the steady state flow regime for the slotted tail joint is the Slot Jet Regime. It forms after the sand level in the tubing and annulus reaches within the top portion of the back slot. A powerful jet forms in the region of this slot that remains open to flow. All flow is directed this area. There is no flow through the side slots or bottom opening as they have been plugged with sand. Plate 4-27 gives the front view of this regime. The black horizontal lines across the sand sump are poppy seeds. They mark the end of each sand slug. Plate 4-28 is a view from the back of the well. It shows that the back slot almost completely fills with sand.

Two "column vortices", long vortices with a vertical axis of rotation, sometimes appear within the tail joint is most of the back slot is free of sand. Sand particles allows the visualization of these vortices in Plate 4-29.

B. Sand Addition

Tests began with a sump level lower than the bottom of the tail joint. Sand slugs added to the flow fill the sump in the annulus and tubing fairly evenly. Only a small portion of the slug is carried to the pump out of the tail joint until the sump level rises to within the back slot. The Slot Jet Regime forms when this occurs.

For the Slot Jet Regime, slugs are carried out of the well very effectively. The jet carries the sand out of the back slot to the pump outlet quickly. Plate 4-30 shows the jet in this process. The sump level does not change significantly once this regime forms. The tail joint cannot be cleaned of sand. Increasing the flow rate and/or allowing a long period of no sand addition will at best clean the sump to a few centimetres below the back slot.

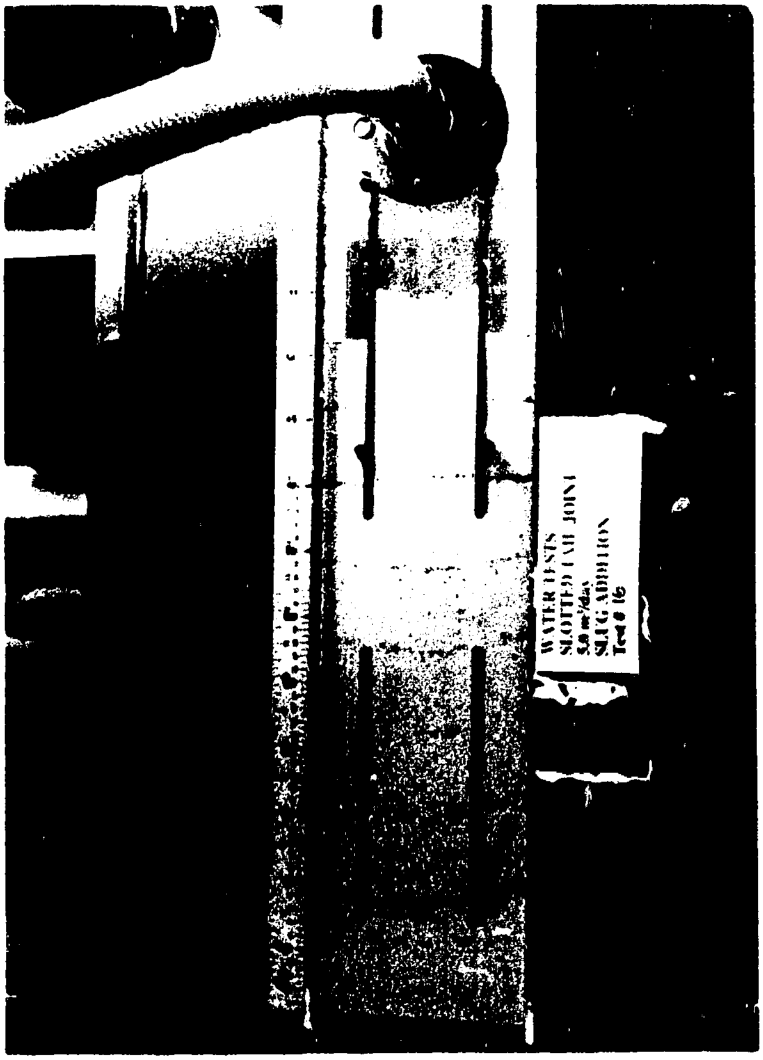


Plate 4-27: The front view of the Slot Jet Regime in a water flow.

Plate 4-28: A view of the back slot from the back of the model.

Plate 4-29: The two column vortices formed just above the level of the sump.

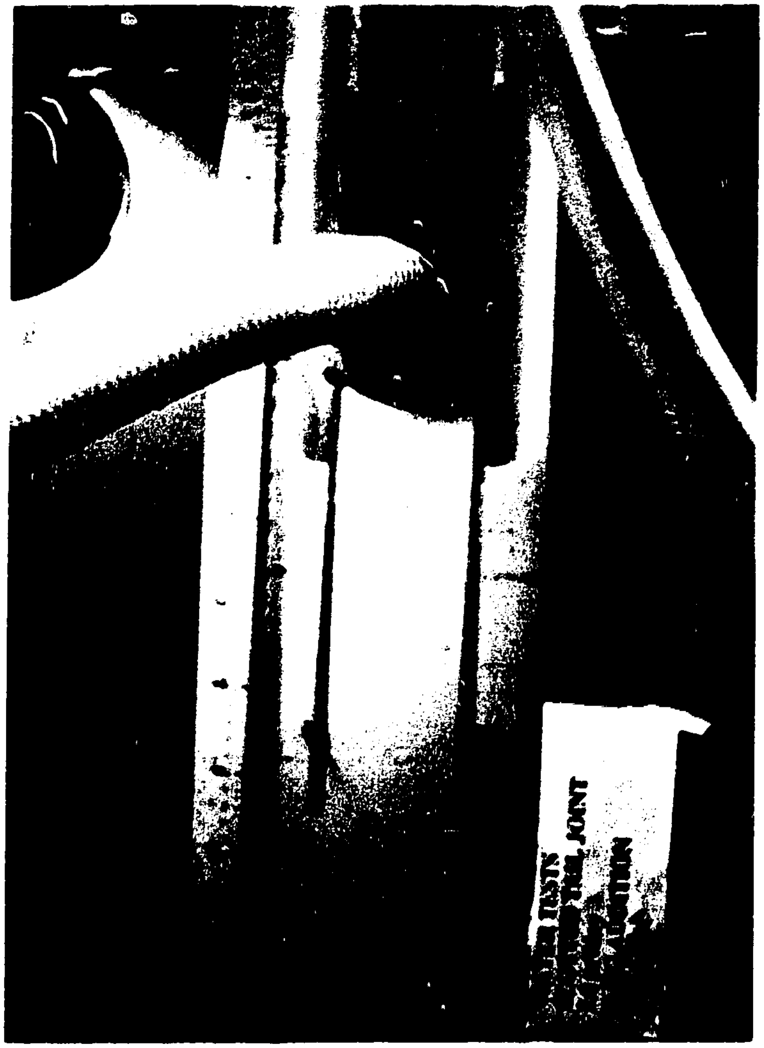


Plate 4-30: The jet of the Slot Jet Regime carries sand through the back slot to the pump outlet.

PART 4: TURBULENT WATER FLOW - CONTINUOUS SAND FEED

I. BACKGROUND

As described in the chapter discussing experimental setup and procedure, sand was fed continuously into the well for what is called the continuous sand feed tests. Fluid flow rates were adjusted to account for the solids flux into the well to ensure a constant mixture flow rate through the tail joint.

The apparatus was monitored closely during these tests, as a buildup of sand in the tube connecting the pump outlet to the removal pump (see Figure 2-3), tends to cause a sudden influx of sand into the first cavity of the pump. The pump to becomes clogged with sand and it fails to operate. This problem is especially serious at the 2.5 m^3/day flow rate. Due to this, some of these tests may have ended prematurely.

Three tests were conducted for each tail joint: one at a sand concentration (by volume) of 10 % for a 2.5 m^3/day mixture flow rate; another at 30 % sand at 2.5 m^3/day; and finally, a test at 10 % sand concentration for the 7.5 m^3/day flow rate.

As with the slugs tests, the different flow regimes will not form until the sump level has reached within a few millimetres of the tail joint entrance for the wide entrance and small hole entrance tail joints.

I. WIDE ENTRANCE

For the 2.5 m^3/day, 10 % sand feed test, the first regime to form as the sand moved into the entrance was the Single Jet at a jet angle of 90°. The interface between the newly suspended sand in the tail joint and the clear water slowly moved toward the pump outlet. The jet angle then decreased to about 80° and the flow pattern remained steady for about 1 min. At this time, the cyclical process of sanding in of the entrance and then piping to allow a Single Jet flow (at a jet angle of 60°) began. Within a minute, the Single Jet Regime became steady. It was stable for 7 min when the test was stopped.

For the 2.5 m^3/day, 30 % sand test, the same Single Jet Regime with a 90° jet angle forms initially. This lasted for 30 s before the jet angle decreased to 60°. Sanding in of the entrance, followed by the reinitiation of jet flow starts after two minutes in the previous regime. The period of fluctuation between the sanded in and jet flow states is only a few seconds. After 3 min of alternating between these two states, the tail joint sanded in and the tests was stopped.

For the 7.5 m^3/day, 10 % sand feed test, the Single Jet formed initially again at the jet angle of 90°. The jet angle decreased to 60° soon after. This regime was steady until the test was ended after 9.5 min.

From these observations, it appears that the steady state regime for a continuous sand feed into the flow through the wide entrance is the Single Jet Regime of a 60° jet angle. If too much sand is present in the tail joint, the same sanding mechanism occurs as in the previously described slug tests. The tail joint sands in because of sand suspended within the tail joint, not from a buildup of sand in the annulus that plugs flow into the entrance that might intuitively be expected.

III. SMALL HOLE ENTRANCE

For the 2.5 m^3/day, 10 % sand test, the first regime to form was the Single Jet at a 90° jet angle. A vertical vortex forms within 2 min of the initiation of this regime. The alternating states of sanded in and jet flow (with a vertical vortex) occurs for a few seconds. The single jet with vertical vortex is steady for 3 min when the tail joint becomes sanded in permanently. The test ended.

For the 2.5 m^3/day, 30 % sand feed test, the Single Jet Regime with a vertical vortex first formed. Within 1.5 min of the Single Jet formation, the entrance became plugged with sand and the test ended.

For the 7.5 m^3/day, 10 % sand feed test, The Radial Jet Regime forms with a vertical vortex. The depth of flow for the jet under the tail joint is about 2 mm. This regime is very steady and after 10.5 min, the test is ended.

The above continuous feed tests confirmed the results of the slug tests. The Single Jet is the dominant primary flow regime at the low flow rates tested. As the flow rate increases, the Radial Jet Regime becomes dominant.

IV. SLOTTED TAIL JOINT

For all of the three continuous feed tests for the slotted tail joint, the Slot Jet Regime formed after the sand filled the annulus and tubing to a level near the top of the back slot. Almost all sand added to the well falls into the sump volume beneath the back slot until this occurs. The Slot Jet Regime is very efficient at carrying sand out of the well. The Slot Jet Regime was stable for about 5 min for each test before the test was ended. Sanding in of the tail joint did not occur.

CHAPTER 5: SUMMARY & DISCUSSION

I. FLOW PATTERNS

A. Background

For both the wide entrance and small hole entrance tail joints, the level of sand in the sump rises to very near the tail joint entrance before any significant amount of sand is removed from the well. This is true for the viscous, glycerine flow with slug sand addition; the water flow with slug sand addition; and the water flow with a continuous sand feed. For the viscous, glycerine flow, the sump level rises to within about 2 to 4 cm of the tail joint entrance. For the water tests, the sump level rises to within a few millimetres of the tail joint entrance. The distance from the tail joint entrance to the sand level in the sump increases with increasing flow rate. The flow patterns described below do not form until the sump level is "near" the tail joint entrance. The most prominent flow regimes observed during testing are summarized below.

B. Regimes of Flow

1. Wide Entrance

The Small Hill Regime consists of a small mound of a glycerine/sand mixture in the centre of the tail joint, which protrudes a few centimetres into the tail joint entrance. It is close to semi-cylindrical in shape, with its flat side pushed against the front plexiglas. There is circulation of the sand particles within this mound. It is caused by the shear of the passing flow. In three dimensions, this circulation is equivalent to a vortex ring. Sand is carried to the pump outlet in a small band of upward flowing sand particles at the apex of this mound. The Small Hill Sand Removal Regime was observed in the viscous flow tests with the slug sand addition.

The Wide Band Regime is characterized by a wide band of glycerine/sand mixture that forms in the centre of the tail joint. It is a tall, semi-cylindrical column of sand, with its flat side located against the front plexiglas. The width of the band is approximately 40 mm, while its depth into the flow is about 35 mm. The centre of this band circulates downwards with a velocity greater than the observed settling velocity of the particles in a quiescent glycerine. Most of the sand particles in the upward moving portion of this column recirculate within the band as they reach its apex. However some of the sand particles on the outside of the wide band are not trapped in the downward circulation, but are carried into a small band and move to the pump outlet. The base of the small band forms at the apex of the wide band. There is no circulation within the small band. The Wide Band Sand Removal Regime was observed to occur in the viscous flow tests with the slug sand addition.

The Single Jet Regime is characterized by a small jet that forms against the plexiglas at either side of the tail joint. Sand deposits within the well and annulus opposite the jet. It is a partial radial flow through only one section of the entrance. The Single Jet Flow Regime was observed to occur in the water tests for both the slug sand addition and continuous sand feed.

The Radial Jet Regime is a radial flow along the wall of the tail joint. The jet flows along the entire tail joint circumference. The sand level in the sump rises within the centre portion of the tail joint. The top of this raised portion of the sump is often (half) conical in shape. The jet width is typically about 5 mm. This width is the depth of jet into the tail joint from the tail joint wall at the entrance of the tail joint. The Radial Jet Flow Regime was observed to occur in the water tests for both the slug sand addition and the continuous sand feed.

2. Small Hole Entrance

The Tapered Regime is characterized by a half-cone shaped mound of sand in the centre of the sump which is pushed against the front plexiglas. A small band of upward flowing sand particles exists at the apex of this mound. There is no circulation within either the conical mound or the small band. Sand particles are displaced from the sump surface and move radially inward to the small mound of sand. These particles then proceed up the side of the mound and are carried to the pump outlet in the small band. The Tapered Sand Removal Regime was observed in the viscous flow tests with the slug sand addition.

The Suspended Band Regime is characterized by a cylindrically shaped, wide band of a glycerine/sand mixture that forms in the centre of the tail joint and is suspended above the entrance. It is a combination of the Tapered Regime and the Wide Band Regime. The Tapered Regime exists beneath the suspended band. The suspended band, about 35 mm in width, has a downward circulation in its centre (as in the Wide Band Regime). Sand particles move toward the pump outlet in a small band, about 3 mm in width, located at the apex of the suspended band. The Suspended Band Sand Removal Regime was observed to occur in the viscous flow tests with the sand slug addition.

The Single Jet Regime for the small hole entrance has similar characteristics to the Single Jet Regime for the wide entrance. However, the jet was observed to form at locations other than against the front plexiglas. As well, often associated with a single jet is a strong vortex with a vertical axis of rotation. This axis is usually located near the centre of the small hole when there is a large amount of sand within the entrance. When the vortex lowers to the sump level, it becomes very effective in cleaning the sand from underneath the bottom piece of this entrance. This occurs when there is not a lot of sand within the tail joint entrance. The Single Jet Flow Regime was observed to occur in the water tests for both the slug sand addition and continuous sand feed.

The Radial Jet Regime is a fully radial flow through the small hole. The jet flows along the entire small hole circumference and enters the tail joint flowing vertically. There is also a radial flow, with a depth of only a few millimetres, under the bottom piece of this tail joint. Always associated with this regime is a vortex with a vertical axis of rotation. The vortex axis in located very close to the centre of the small hole. The Radial Jet Flow Regime was observed to occur in the water tests for both the slug sand addition and continuous sand feed.

3. Slotted Tail Joint

The Slot Jet Flow Regime was the only steady state flow pattern observed for the slotted tail joint. It forms after the level of sand in the well annulus and tail joint reaches within the top portion of the back slot. A powerful jet forms in the region remaining open to flow, as all the flow is directed through this area. This regime was observed to form for the glycerine tests with slug sand addition; the water tests with slug sand addition; and the water tests with a continuous sand feed.

II. DISCUSSION OF RESULTS

A. Wide Entrance

1. Viscous Flow - Slug Sand Addition

It was found that for the viscous flow in the wide entrance, the flow regimes depend more on the slug characteristics than then flow rate for the range of flow rates tested. The "dense" sand slug is a strongly cohesive mass of glycerine wet sand. It can be molded into a shape which will not lose its form for several minutes. It does not flow and, once added to the well, does not quickly mix with the surrounding fluid. It has a higher percentage of sand than a flowable slug. A "flowable" sand slug flows easily and will mix with the surrounding fluid when added to the well. The cohesion between the sand particles is not strong.

For the "flowable" sand slug addition tests, the two dominant flow patterns were the Small Hill and Wide Band Sand Removal Regimes. The Small Hill Regime is a steady state regime formed when there is little sand available in the area around the tail joint entrance. When a sand slug is added, the flow will form the Wide Band Regime. If no sand is added while the flow is in this regime, the Wide Band will eventually revert to the Small Hill Regime through a variety of transitions. It is believed that the Wide Band Regime is essentially simply a "taller" version of the Small Hill Regime. If a slug is not added for a very long period, it is thought that the Small Hill Regime will eventually form into the Tapered Regime, although this was never observed. For even longer periods of no sand addition, eventually the flow should clean the sump so that it can no longer pick up sand particles. Sand is cleaned out of the tail joint very slowly when the flow is in either of the two main regimes. Sand is cleaned out of the tail joint quickly only during times of transition between the regimes. The same type of flow patterns were seen for all flow rates tested; however, the transitions between the regimes tend to depend on the rate of flow. The flowable slugs did not tend to block flow through the tail joint entrance.

For the "dense" sand slug tests, the flow shows only tendencies for certain patterns, but there are no definite transitions and sometimes no definite regimes. With little excess sand in the area of the tail joint entrance, the Small Hill Regime tends to form. With the addition of a small sand slug, the slug moves easily through the tail joint entrance without changing its form or breaking apart. The larger slugs frequently tend to lodge in the annulus, especially just outside the tail joint entrance or within it. When sand remains in the entrance, a shifted wide band forms. If a slug becomes suspended within the tail joint, it is likely that instabilities in the flow will cause it to fall against the tail joint wall to form a wall deposit. The same type of flow patterns were seen for all flow rates tested.

Sand removal efficiency is therefore also not greatly dependent on flow rate, but on slug characteristics and the pressure available to push the slug through the tail joint entrance. Sanding of the tail joint is more likely to occur the less flowable the sand slug. It should be noted that the blockage of flow occurs as a dense, high viscosity slug moves from the annulus into the entrance. It is essentially a problem of a highly viscous "fluid" moving through an orifice. The larger the orifice and/or the less viscous the flow, the less pressure (head) required to push the slug through the entrance.

The different behavior of the slugs may be also partly due to the amount of mixing that the slugs can undergo with the surrounding carrier fluid. The flowable sand slugs remain in a loose form and are likely to be pulled apart as they travel down the well annulus. This type of slug can entrain fluid. The dense slug will not mix with the surrounding fluid as it flows down the annulus. It remains in the shape into which it was molded, prior to the slug's addition to the flow, until it reaches the tail joint entrance. It does not stretch when it flows in the annulus. The flow cannot change the slug shape quickly. As well, the slug entrains fluid very slowly. Thus, flow must essentially carry a solid body. When the dense sand slug begins to entrain fluid and become more flowable, more predictable flow regimes are observed (e.g. the wide band regime).

2. Viscous Flow - Continuous Sand Feed

The homogeneous glycerine/sand slurry essentially behaves as a single phase flow through this tail joint. No definite flow patterns were observed. However, there were some formations against the front plexiglas. It is thought that these formations have negligible depths into the flow. However, because the sand slurry blocked view of these formation from any angle other than through the front plexiglas, this depth could not be observed. No sanding of the tail joint occurred, even at very high sand concentrations (40 % sand by volume) for the lowest flow rate tested of 2.5 m^3/day. The slurry fills the volume of the well available as a sump as soon as flow through the well is initiated. Like the single phase glycerine flow, the slurry was stagnant at a depth beneath the tail joint entrance of only a few centimetres (about 3 cm). Thus, as the sand settles of the slurry, the sump will fill with sand until the sump level reaches within a few centimetres of the tail joint entrance.

The ratio of the mean velocity of flow through the tubing at 2.5 m^3/day to the settling velocity a single sand particle of the average grain size of 0.17 mm is 320. This is much larger than the value for the ratio of 2, recommended by Govier and Aziz (1972) for the operating conditions to avoid choking or plugging of the pipe in a vertical flow.

3. Water Flow - Slug Sand Addition

For the water tests, sand slug characteristics did not vary with the slurry produced with the continuous sand feed; the sand slug was essentially an intermittent version of the continuous feed. Slug sand dispersed throughout the well annulus. There was no cohesiveness to the slug as in the glycerine tests.

The flow tends to "arrange" the sand particles within the tail joint in such a way as to create a high velocity jet in the tail joint entrance. This allows for a higher velocity of flow through the entrance and a more turbulent flow in the tail joint. A large sand slug (about 5.5 L of water saturated sand in a period of 100 s) can be added to the flow without sanding of the tail joint.

The main flow patterns observed were the Single Jet and Radial Jet Regimes. At the 2.5 m^3/day flow rate, the Radial Jet Regime appeared only briefly when sand was added to the well. It acted as a transition regime between the state of a low sump level (the sump level was not high enough for any flow regime to form) and the Single Jet Regime. At the 7.5 m^3/day, the Radial Jet Regime was much more stable, and the flow seemed to "prefer" this state. For small volume sand slug additions, the Radial Jet Regime remains stable at the higher flow rates. For the larger slugs, the Single Jet Regime forms, but only briefly before the flow returns to the completely radial flow. For the intermediate flow rate of 5.0 m^3/day, the Radial Jet Regime is a transitional state in the formation of the Single Jet Regime.

Sand blockage or "sanding in" of the tail joint does not occur from the outside of the entrance (sand moving from the annulus to the tail joint) as in the glycerine tests. Sand blocks the entrance from within the tail joint. It occurs only when the flow is in the

Single Jet Regime. The sand slope, which develops within the entrance in the sump area opposite the jet fails. Immediately, the cessation of flow through the tail joint causes the suspended sand to quickly settle and pile in the entrance. As this occurs, the head difference between the fluid in the annulus and tubing increases. When the head difference is great enough, piping occurs in the sand bed formed in the bottom of the tail joint. A jet forms in the liquefied area of the bed. The piping usually occurs in the location within the entrance which was open to flow just prior to sanding. The process of blocking the entrance, piping, and a return to jet flow, was often observed to occur several times during a test.

Considered as important factors to sanding are the flow rate, the volume of sand deposited in the entrance, and the concentration of sand suspended in the entrance area. The flow rate increases the ability of the water to carry the sand away from the entrance. It also increases the momentum of the jet, which may balance the forces to cause the sand deposited in the tail joint entrance opposite the jet to flow into the area open to flow. The volume of sand deposited within the entrance, influences the stability of the formation within the entrance. More sand within the entrance gives the formation a greater tendency to move into the area of flow. Finally, the concentration of suspended sand in the entrance area influences the amount of sand that can be deposited in the entrance under varying negative flow conditions such as the sudden cessation of flow. It also influences the amount of sand that can be carried away from the entrance area.

Efficiency of sand removal depends greatly on flow rate (for the range of flow rates tested). At the low flow rate of 2.5 m^3/day, any sand that is fed into the well essentially stays suspended within the tail joint. There is little sand removal from the well. Brief periods of sanding of the entrance occur frequently. There is also a high probably of a permanently sanded in condition at this flow rate (i.e. the test had to be stopped). At the higher flow rate of 7.5 m^3/day, sand removal is very efficient. It is carried out of the tail joint by the flow very effectively and quickly. The 5.0 m^3/day was intermediary between these two sand removal efficiencies, as the sand was removed from the tail joint but at a slow rate.

The ratio of the mean velocity of a water flow through the tubing to the settling velocity for a single, average sized particle for the 2.5, 5.0, and 7.5 m^3/day flow rates is 0.32, 0.64, and 0.96. This is just less than the suggested operating condition of Govier and Aziz (1972) that the mean velocity of flow should be twice the mean settling velocity. The flow rates suggested for use in the model are apparently within a range (compared with the settling velocity of the sand particles) where an increase in flow rate is very important to the successful operation, in relation to sanding, of the well. The 2.5 m^3/day flow is a poor operating rate for the well. The 7.5 m^3/day flow represents a comparatively safe operating rate for the model well.

4. Water Tests - Continuous Sand Feed

Only three tests were performed for the continuous sand feed tests: a 10 % sand concentration for a 2.5 m^3/day flow; 30 % sand at 2.5 m^3/day; and 10 % sand at 2.5 m^3/day. The Single Jet Regime formed as the stable regime in all instances. Only for the 2.5 m^3/day test at 30 % sand concentration the test was stopped because the tail joint had sanded in (permanently). The mechanisms of sanding were the same as for the slug sand addition tests. It is felt, however, that the tests where the tail joint did not sand in (with about a 10 min test duration) were not operated for a sufficient time to allow for a buildup of sand concentration within the tail joint. This would affect the possibility of sanding.

Therefore, it is felt that those particular tests are inconclusive. This applies for all tail joints tested.

B. Small Hole Entrance

1. Viscous Flow - Slug Sand Addition

The flow patterns formed for this viscous flow in the small hole entrance depend on the "flowability" of the sand slugs , as for the same flow in the wide entrance tail joint.

For the flowable sand slugs, the small size slugs (about 250 mL of glycerine saturated sand) of move easily through the tail joint entrance. Once inside the tail joint, the sand becomes suspended just above the entrance to form the Suspended Band Regime. For larger sand slugs, the slug is able to move through the entrance and the Suspended Band Regime will begin to form. However, the suspension of sand above the entrance is often unstable; it will break apart, with some of the slug removed from the tail joint from the flow, and the rest of the sand falling towards the tail joint wall to become a wall deposit. Sanding of the tail joint entrance is unlikely for the flowable sand slugs. Sand is not removed from the tail joint quickly unless the flow regime undergoes a transition to another state.

Unlike the wide entrance, the flow regimes for the dense sand addition for the small hole entrance appeared to be dependent on flow rate. The dense slugs again tend to become lodged in the well annulus and just outside the tail joint entrance. At the 2.5 m^3/day flow rate, if a sand slug blocks flow through the entrance often only part of the slug is removed from the entrance when the flow through the entrance is reinitiated. Slowly, a radial flow forms in the entrance and the slug sand becomes suspended. The suspension of the dense slug sand above the entrance is unstable and this will eventually result in the formation of a continuous wall deposit. At the 7.5 m^3/day flow rate, the dense slugs again tend to block flow through the entrance. At this rate of flow, the slug sand that moves through the entrance is quickly carried out of the tail joint.

Sand removal efficiency is dependent on the sand slug characteristics and the pressure available to push the slug through the entrance Flow rate does not appear to be an important factor for the removal of the flowable slugs from the tail joint, but becomes significant for the removal of the dense sand slugs. This entrance plugs easily with the addition of dense slugs. It is believe that this is because the size of the orifice is small. It requires greater pressures to pushes the slug through the entrance than for an equivalent slug flow through the wide entrance.

2. Viscous Flow - Continuous Sand Feed

As with the wide entrance, the slurry fills the sump and is stagnant (and the suspended sand settles) anywhere beneath about 3 cm below the tail joint entrance. There was no significant formation of flow patterns. Almost all sand was added to the well was removed by the flow. The flow behaved similar to a single phase laminar flow through the tail joint. The slurry flow fills the entire width of the tail joint.

3. Water Flow - Slug Sand Addition

As with the wide entrance, the flow tends to arrange the sand particles within the tail joint entrance in such a way to create a relatively high velocity jet. For the water flow in the small hole entrance, the two main flow patterns are the Single Jet and the Radial Jet Flow Regimes. At the 2.5 and 5.0 m^3/day flow rates, the Single Jet Regime is the dominant flow pattern. It is often associated with a vortex with a vertical axis of rotation. This vortex helps to clean sand from the entrance area. At the 7.5 m^3/day flow rate, the dominant flow pattern is the Radial Jet Regime. It also often is associated with a vortex with a vertical axis of rotation. Sanding for the small hole entrance occurs in the same manner as for the wide entrance.

Efficiency of sand removal again greatly depends on flow rate. At 2.5 m^3/day, most of the sand stays suspended within the tail joint. There is a great potential for sanding of the entrance. At 7.5 m^3/day, the flow removes sand from the tail joint very quickly and effectively. The 5.0 m^3/day, the flow patterns observed were intermediary between the patterns observed at the higher and lower flow rates.

4. Water Flow - Continuous Sand Feed

As for the other tail joint, only three tests were performed: a 10 % sand concentration for a 2.5 m^3/day flow; 30 % sand at 2.5 m^3/day; and 10 % sand at 2.5 m^3/day. The Single Jet Regime formed for the two tests at 2.5 m^3/day. The tail joint sanded in for both these tests. For 7.5 m^3/day, a stable Radial Jet Regime formed.

C. Slotted Tail Joint

For a single phase glycerine flow through the slotted tail joint, almost the entire flow moves through the back slot. There is a small amount of flow through the side slots, and no flow through the bottom opening. The use of the back slot appears to create a dead zone for flow anywhere underneath this slot.

For the viscous flow with slug sand addition and both types of sand addition in the water flow, the sand level in the sump rises to within the upper potion of the back slot. In all cases, the Slot Jet Regime forms. This regime is characterized by a jet in the small area of the back slot left open to flow. After this regime is established, the sand level remains within the top portion of the tail joint indefinitely. Increasing the flow rate and/or decreasing the sand concentration in the well fluids will at best clean the tail joint of sand to just beneath the back slot.

For the viscous flow with slug sand addition, there is little difference in behavior for the flowable and dense slugs. The added sand fills the well until the formation of the Slot Jet Regime. Once the flow is in this regime, the flowable slugs move easily through the back slot to the pump outlet. The dense slugs tend to plug the slot. However, once within the tail joint the slug will move to the pump outlet. The back slot would easily and frequently become plugged by slug sand. It is thought that this is because of the small size of orifice left open to flow.

The flow of the viscous homogeneous slurry in the slotted tail joint behaves somewhat differently. At the 2.5 m^3/day flow rate, all of the viscous slurry moves through the back slot to the pump outlet. Beneath the level of the back slot, the well is filled with a stagnant slurry. At 5.0 and 7.5 m^3/day, there is also a slow flow through the side slots, although still most of the flow is through the back slot. Problems occurred when the flow was stopped for long periods (hours). The sand settles out of the slurry and the entrance becomes sanded in. Since a single phase flow can only clean this tail joint from the back slot to the pump outlet, the rest of the tail joint remains filled with the viscous slurry. The sand eventually settles out of suspension and the tail joint becomes filled with sand to the level of the back slot.

For the water flow, once the tail joint was in the Slot Jet Regime very large slug sizes could be added with little deposition in the tail joint.

For all the tests with a continuous sand feed into a water flow, no sanding of the entrance occurred. The Slot Jet Regime is a very stable flow pattern and is very efficient in removing sand from the well.

After running test with the viscous, homogeneous slurry, single phase glycerine was fed into the well in hopes of cleaning the tail joint and well of sand. The well annulus cleared of sand to the level of the top portion of the back slot. Within the tail joint, a jet of glycerine forms in the top portion of the back slot. In similar situation occurred while trying to clean the well of a single phase glycerine that filled the well using a water flow. The water could only clean the glycerine in the annulus and tail joint again only to a level within the top of the back slot. Increasing the water flow rate, did not aid in cleaning the tail joint. Thus, it appears that the Slot Jet Regime is a result of flow stratification.

III. COMPARISON OF THE TAIL JOINT DESIGNS

For viscous flow with cohesive, non-flowing sand slugs it is best to provide a large area for flow. The wide entrance performed best of the three tail joints for handling (not becoming plugged with sand) for this type of flow. However, this does not mean that sand is effectively removed from the well. It was found that most of the sand added to the well in this form is not removed from the well quickly once the flow is in regime. Sand removal does appear to depend on the flow rate (for the range of flow rates tested). The small hole entrance and slotted tail joint performed not as well for sanding as the wide entrance because of their smaller openings for flow.

For a homogeneous, viscous slurry, it is not expected that sand deposition to cause a blockage of flow to the pump would occur while flow continues through the well. This holds for all three tail joints tested. However, the slotted tail joint fills with sand to the level of the back slot, as the slurry is stagnant anywhere beneath this region. For both the small hole and wide entrance tail joints, the stagnant region exists a few centimetres beneath the entrance.

For the water flow, the small orifice and short length of flow to the pump decreases the susceptibility of the tail joint to sanding. The slotted tail joint performed well in terms of sand removal from the tail joint if one is not concerned with the level of sand in the well rising within the back slot. The tendency for sanding in a water flow increases with decreasing flow rate within the range of flow rates tested.

Unfortunately, each of the three type of designs for the tail joint perform better in different types of slurry flow. The wide entrance appears to be the best design for to handle a viscous, cohesive slug. However, it seemed to have the weakest performance in the waters tests. The slotted tail joint performed best for sand removal in a water flow (once the flow was in the Slot Jet Regime), but poorly for handling a viscous, cohesive slug. The small hole entrance performed moderately well in all types of slurry flow.

IV. FIELD APPLICATIONS

One of the most useful findings of this research is that the addition of the slots in the slotted tail joint essentially creates a dead zone for flow anywhere underneath the back slot. In discussions with the oil company personnel contributing to the main CFER study, it was understood the main use of the tail joint was to extend the influence of the pump. The example was given that if a smaller diameter well was drilled to extend from an existing well, the tail joint would be used as an extension to the pump. If a slotted tail joint is used for this purpose, it is very likely that the sand will fill the annulus and tail joint to the level of the very top slot in the tail joint. In this case, the smaller diameter well would fill with sand.

It is considered very likely that a oil well sump will fill with sand until the sand level in the well is near (probably only a few centimetres) the tail joint entrance or the pump entrance in the case of a slotted tail joint or barefoot pump. Potential use of a sump (or rathole) for any other purpose other than storage of sand is unlikely. There is a level within the well where the pump will no longer after the flow. Sand will deposit in the well anywhere beneath this level.

The problem of very viscous sand slugs blocking flow through the tail joint entrance, increasing the flow rate does not appear to help remove sand. It is the pressure difference across the tail joint entrance that will aid the slug into the tail joint into the pump. The practice of loading wells (adding fluid to the well annulus) might be considered if this is thought to be occurring.

Another useful finding is the great dependence of sand removal from the well on flow rate for the tests using water. This assuming that the sand in the well fluids is dispersed and is not a viscous, cohesive mass. It appears the range of flow rates used in testing gives a critical range of velocity for removal of sand from the well. An increase in flow rate can be very important to improve sand removal. There was very poor removal of sand at the 2.5 m^3/day flow rate and fairly good removal at the 7.5 m^3/day flow. These flow rates correspond to 5.0 m^3/day and 15 m^3/day in the prototype well. The dependence of sand removal on flow rate is likely due to the fact that the mean velocity of flow in the tail joint is of the same order (of magnitude) as the terminal settling velocity of the sand particles in the flow.

The relation suggested by Govier and Aziz (1972), to use of the ratio of the mean velocity of flow to the terminal velocity of the largest particle in the slurry to determine good operation conditions for a vertical slurry flow, may also be a good relation to predict sanding tendencies in the well. They suggest that the mean velocity should be at least two times the terminal velocity of the particle. Calculation of this relation gives ratios of 0.7, 1.1, and 1.5 for the 2.5, 5.0, and 7.5 m^3/day flow rates respectively. These values are very close to the desired value quoted by Govier and Aziz, again suggesting that these flow rates are in a critical range, where a relatively small increase in flow may greatly improve sanding. It is suggested, that this type of calculation be used in the field to determine a desirable pumping rate for the well. This is especially true when it is felt that the wells are sanding due to a large influx of water into the well. Tests suggest that the use of the flow rate given a value of ratio at least two, could very well prevent sanding from occurring.

Tail joint length may be significant during a cessation of flow through the tail joint for a water/sand slurry flow, such as sanding in (or blockage of flow). There is potentially more sand within the entrance to settle out of the flow into the entrance. A greater pressure would then be required to reinitiate jet flow through the entrance. This statement specifically applies to the wide entrance and small hole entrance tail joint designs. Sanding of the entrance for the slotted tail joint for the water tests was not observed.

V. CONCLUSIONS

The conclusions are summarized as follows:

- No tail joint performed best in all sanding conditions.
- For all tests, the well sump filled with sand to a level within a few centimetres within the tail joint entrance. It is likely that this will also occur in the prototype well.
- The slotted tail joint fills with sand to a level within the top slot. This is true for all types of slurry conditions.
- For a viscous, homogeneous slurry sand deposition does not occur if the sand level in the well in "near" the tail joint entrance and flow continues through the well.
- For the viscous flow tests with slug sand addition, the tendency of the tail joint to become plugged with sand, depend not on flow rate, but the viscosity of the slug moving into the tail joint. The more viscous the sand slug, the more likely it is to plug the tail joint.
- For a viscous flow, it is best to provide a large opening for flow if very viscous sand slugs are expected. As well, fluid level in the annulus becomes important, as it provides the pressure to push the slug through the tail joint.
- For the water flow, the sand removal is very sensitive to flow rate. A small increase in flow rate, in this range of flow, greatly improves sand removal from the well. In this case, the sand is dispersed throughout the carrier fluid.
- The mechanisms for sanding of the tail joint for the water flow occur because an increase in the concentration of sand in suspension within the tail joint and buildup of sand in the tail joint entrance area. Tail joint length becomes important (shorter is better) because of the increased volume of sand available to deposit in the tail joint entrance (for the same suspended sand concentration) when there cessation of flow through the tail joint.
- For the water flow, it is best to increase the flow rate if problems with sanding of the well occur if the sand is dispersed throughout the fluid.

VI. FUTURE RESEARCH

As this project is a preliminary investigation into the mechanics of flow in the area around a progressive cavity pump within a heavy oil well experiencing an influx of sand, there is much work can be done in the future.

The effect of a multiphase flow on the flow mechanisms and sanding behavior of a well must be investigated. This thesis work ignored the effect of gas component in the well fluids. It may also be desired to test more viscous fluids or emulsions.

An interesting study would further investigate the effect of the properties of a viscous slug on the sanding behavior of the well. This could include a study of the behavior of a viscous, cohesive, sand slug in a water flow. It may also be interesting to further study a sand slug that cannot mix with its surroundings i.e. a sand slug wet with oil in a glycerine or water flow. It might be determined if, for example, the wide band in the Wide Band Regime is entraining fluid or if it would even form in this instance. A plastic bag or balloon could be filled with fluid to also gain this effect. It is important to investigate the non-mixing, cohesive sand slug behaves in a water flow so that a comparison of the results of the glycerine tests with this type of flow can be made. It is suggested that the viscosity of the carrier of fluid might not be as important to the formation of the wide band regime as the characteristic of the slug. However, turbulence may have an effect on the flow pattern formation.

It is also necessary to compare the results presented in this thesis to those found for a fully radial flow. It may also be necessary to more closely model the closed tail joint system of the prototype (see the section on "Mechanisms of Flow in the Well" in chapter 3). The present model does not accurately portray the flow in the prototype when the tail joint becomes blocked with sand. It may also be desired that the model be capable of pressures greater than those used in the described model. It is also suggested that a greater range of flow rates be used.

Another possibility for further work is to investigate the "barefoot" pump design. There may be three possibilities for the position of the rotor within the stator. First, the end of the rotor may be within the stator, so that the flow is within the pump before it is within a cavity created by the rotor movement within the stator. The second is that the end of the rotor may be flush with the pump entrance. It is suggested that the eccentricity of the rotor movement be taken into account as it may effect the flow stability or stir up the fluid in the vicinity of the pump entrance. Thirdly, the rotor may protrude out of the stator. This may cause a beneficial mixing of the fluids in the wellbore in the pump entrance region.

It was found that different conditions of flow show different features. In future, these regimes might be correlated using dimensional arguments. Important flow parameters will be the Reynolds number and the Densiometric Froude number.

It is also recommended that if it is desired to understand and solve problems that are associated with the fluid mechanics of the operation of an oil well, the properties and behavior of the well fluids should be more monitored. The composition, properties, and behavior of the bulk fluid produced may give important clues to operate a well effectively.

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