THE PERFORMANCE OF A HYDRAULIC FLOW BOOSTER

by

VISHWAS K. SAWANT

A Thesis
presented to the University of Manitoba
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ABSTRACT

The Hillis pump is a recently invented hydraulic device which works on a principle similar to jet pumps. The main merits of the pump are reliable operation, the absence of moving parts, maintenance-free operation and the lack of sensitivity to the nature of the fluid being pumped. It is considered to be useful because of its simplicity and reliability in remote, occasionally unpleasant and dangerous environments.

The pressure head in the driving fluid is converted to velocity head through orifice tubes where the pressure is reduced. This reduction in pressure at the discharge end of the orifice tubes causes the driving fluid to mix with the main flow of the material to be moved. This thesis describes the equipment and procedures employed to obtain operating data for a 51 mm and a 100 mm diameter hydraulic flow booster conveying water. The data have been used to assess the performance of the hydraulic device, herein called a hydraulic flow booster, and to suggest design improvements to achieve satisfactory operation for the conveyance of manure and other materials containing a solid and a liquid phase.

The performance test results showed that, beyond a minimum injection pressure defined by the model size, the Hillis pump picks up water. Below this minimum pressure a portion of the injected flow rate is lost through the pickup end of the device. The pickup flow rate increases with an increase in the injection pressure up to a certain limit. This pickup capacity demonstrates the potential of the Hillis pump as a materials handling device. The 51-mm model removed manure having 12 percent total solids content from a storage pit. The same model successfully transported gravel stones having diameters up to 38 mm and a bulk density of 1847 kg/m^3. Further investigation is required to improve the design and efficiency of the hydraulic flow booster.

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Chapter I

INTRODUCTION

Hydraulic transport of solids is of considerable interest where low cost materials may be transported for long distances. Hydraulic transport is currently being used for conveying coal, mineral ores and salt mixtures in water. It may provide a clean and low cost method of handling organic waste materials in a slurry.

Agricultural production and processing generates organic by-products which are of significant economic and aesthetic importance. Livestock manure and associated waste water from large scale animal production systems, crop residues and discharge from processing plants constitutes the principal sources of agricultural by-products. Disposal or utilization of these agricultural by-products in the liquid state to achieve higher overall efficiency is desired. Liquid handling systems involved in livestock enterprises give rise to many serious materials handling problems on the farm. Flow characteristics and settling properties of slurries are largely responsible for their handling difficulties.

The characteristics of animal waste are influenced by food and water intake, composition of feed rations, species, age, sex of the animal and the environment. A mixed slurry acts as a non-Newtonian fluid. Many of the properties which influence pumping and flow characteristics of such liquids can not be determined from test data obtained for pumping equipment using water. The apparent viscosity of a slurry depends on the moisture content, total solids concentration, volatile solids, suspended solids, particle density, bulk density and particle size distribution.

Considerable variation has been observed to exist between the slurries from different animal species and also from animals on different feed rations. The solid particles may become attached to one another to form larger particles giving rise to different settling characteristics, and sediment properties when settled. It is known for example that the larger fibrous solids in pig manure slurries settle more quickly and are often responsible for blockage which occurs during pumping operations. Smaller particles with low specific gravity can float to the surface of the liquid eventually forming a crust. In storage tanks the situation can be reached where a slurry will stratify as shown diagrammatically in Figure 1 . Under these conditions it is impossible to withdraw homogeneous slurry without mechanical agitation.

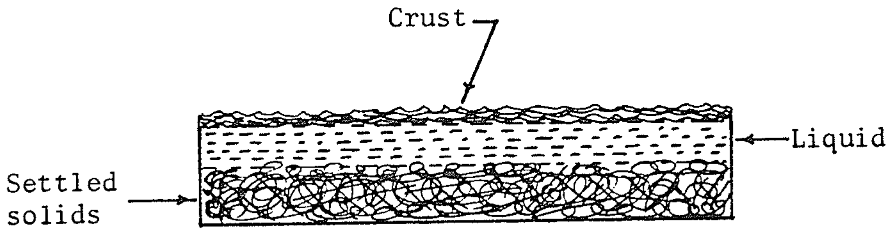


Figure 1: Settled slurry

There are a number of methods available for agitating the slurry in storage tanks. Conventional impeller as well as scroll and stator pumps and submersible pumps have been used to recirculate liquid in an attempt to create a turbulent condition sufficient to bring solids into suspension. Conventional pumps in general have proved unsuitable for this purpose because they are subject to blockage and excessive wear due to fibrous materials in the slurry. Various specialized pumps are now available for filling, emptying and recirculation of tank contents which include;

1. positive displacement

2. centrifugal
3. progressive cavity
4. diaphragm

Technical data available for existing sludge pumps does not specify performance characteristics for conveying manure which has a variable consistency range.

A hydraulic device invented by Frank Hillis, 2067 Cedar Hill cross road, Victoria, British Columbia has been recently used with marked success for rapidly and efficiently unloading fish from boats in the West Coast Fishing Industry. The outstanding performance reported for this application has attracted interest in its use for alternate materials handling and conveying requirements. One such additional application is the potential use of this pump for cleaning manure slurry pits which is an important task associated with modern livestock management systems. Generally loaded manure slurry pits produce gases, some of which, particularly hydrogen sulphide, are toxic. These gases are hazardous to the health of persons involved in cleaning the manure pits. Occasionally the hazard is extended to the risk of life. In such circumstances it is anticipated that the successful performance of the Hillis pump to remove manure from pits will eliminate dangerous risks from livestock enterprises.

A project was undertaken to evaluate the performance of the Hillis pump to move water, to move manure slurry from pits and to transport gravel. This thesis describes the pump and ancillary equipment acquired, the performance evaluation tests and contains the results obtained together with discussion.

Chapter II

DISCRIPTION OF THE HILLIS PUMP

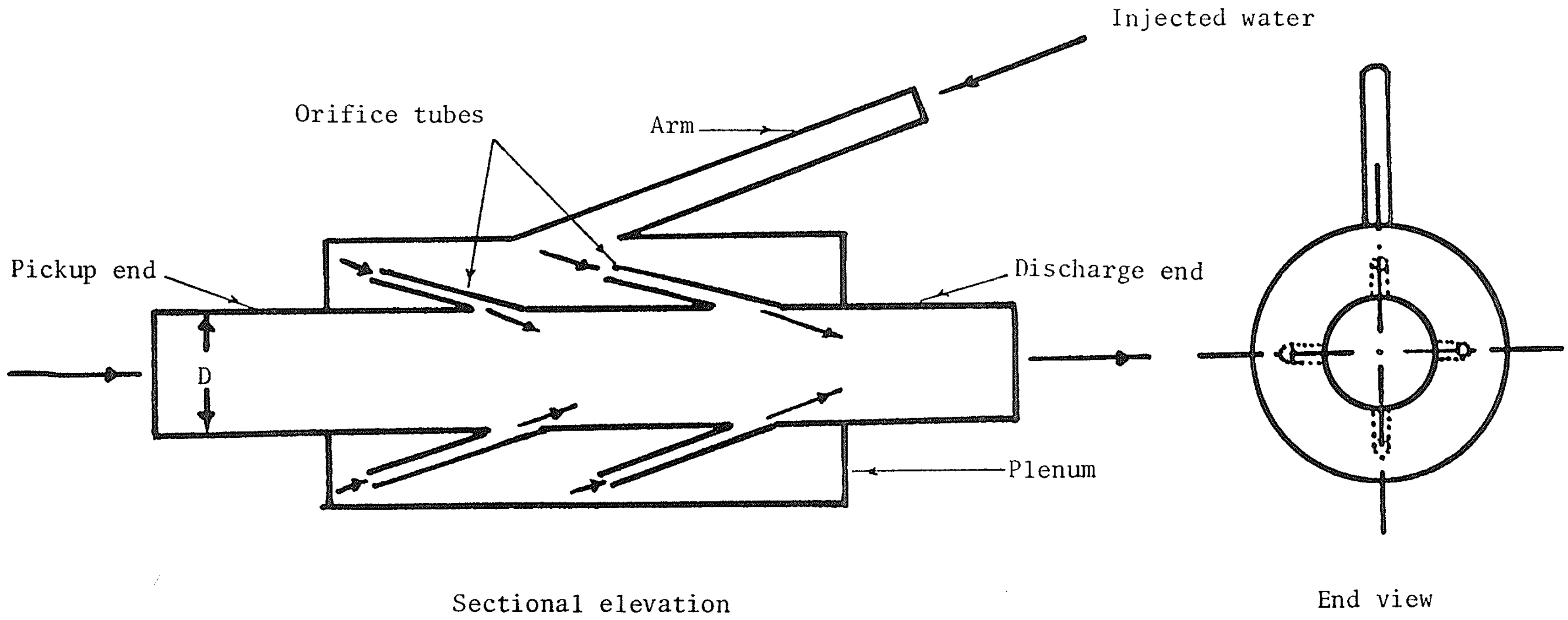
The Hillis pump was designed to operate with water and it is therefore basically a hydraulic device. Figure 2 shows construction details of the pump.

The pump which has no mechanically moving parts, consists of a straight-through pipe section enclosed by a larger concentric pipe water jacket. A pipe connection into the water jacket receives water under pressure from an external high pressure pump. A series of orifice tubes placed at various angles through the wall of the straight-through pipe section allows water to flow in jets from the jacket to the open cross section of the straight-through pipe. The flow pattern can not be observed but it is the jet action that creates a low-pressure region when placed into operation. Intake flow enters this low-pressure region to form the combined discharge from the pump. The orifice tubes do not protrude beyond the interior pipe wall to cause any restriction to the passage of material being moved.

Pumps have been fabricated in diameter sizes of 38, 51, 76, 100, 130, 150, 200 and 254 mm. The size rating refers to the diameter of the straight-through pipe section of the pump. A 51-mm and a 100-mm model were used in this performance evaluation program.

The number of orifice tubes connecting the plenum with the straight-through pipe in existing models range from 8 to 24 depending on the size of the pump. The 51-mm and 100-mm pump used in this study both contained 8 orifice tubes with their diameter being 4.5 mm and 9.5 mm respectively. These tubes were located in the form of two circular rings inside the plenum chamber on the wall of the straight-through pipe. Water at pressures of 1370 kPa and above was recommended by Hillis to provide good pumping performance. Tube angles with the straight-through pipe wall were variable and ranged from 22 degrees at the pickup end down to 8 degrees near the discharge end. It can be observed from Figure 2 that flow in the pump jacket is turned through a variable angle in excess of 270 degrees as the water discharges, forming the jets.

A unique feature to this pump is that a non-obstructed passage is provided over the full interior cross sectional area of the selected pump size for the flow of the material being moved. The application of the pump is such that it may be more properly considered to be a flow booster since the device is used in conjunction with a pump rather than being in itself a pump. However the unit has been patented as the Hillis pump and this designation will be used throughout this thesis.



D = Diameter of Hillis pump (size of the model)

Figure 2: Hillis pump construction details

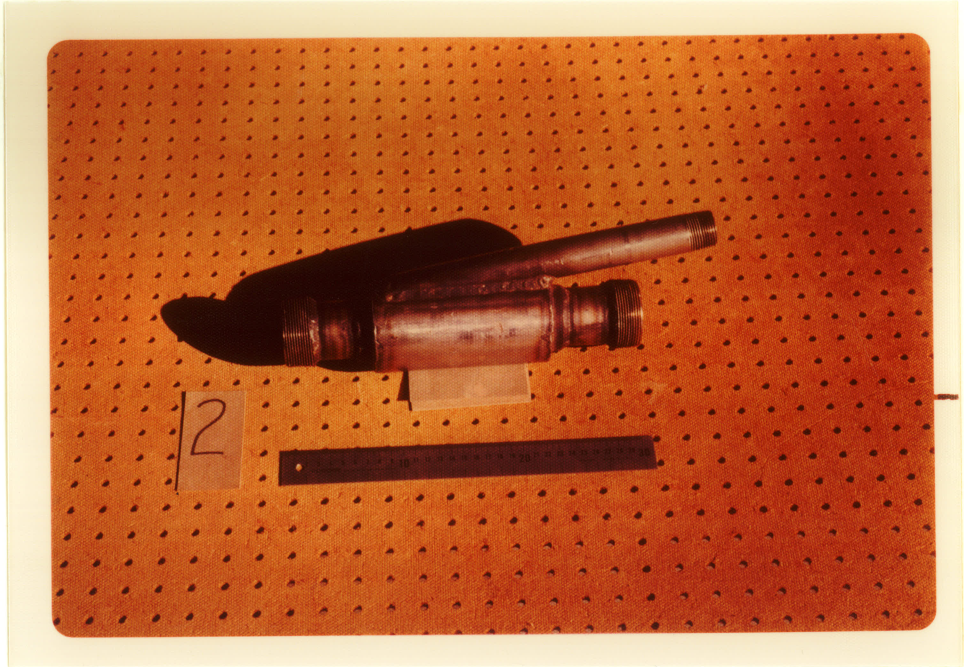


Figure 3: Hillis pump (51-mm model)

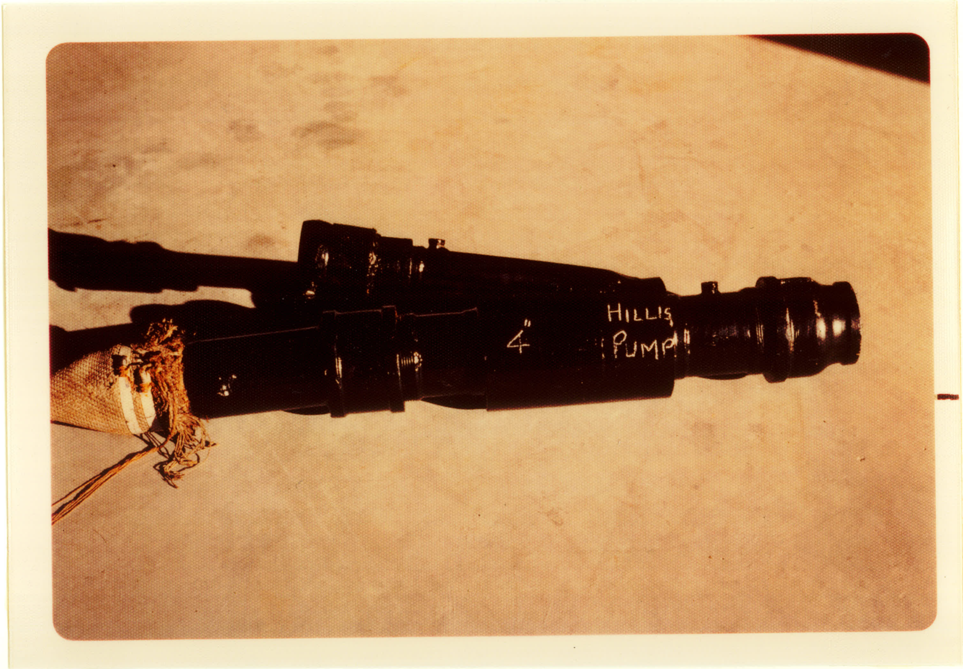


Figure 4: Hillis pump (100-mm model)

Chapter III

EQUIPMENT AND TEST APPARATUS

3.1 EQUIPMENT

The equipment used in this study included the following:

1. Perkins Diesel engine.
2. Ingersoll Rand centrifugal pump.
3. Tachometer.
4. Flowmeters.
5. U-tube manometers.
6. Pressure gages.
7. Vacuum-pressure gage.
8. Pipes or hoses.

Appendix A contains specification details of all above equipment.

A 53 kW Diesel engine and a centrifugal pump were mounted on a rectangular C-beam steel frame to form an integral base mounted unit (see Figure 5). Power was transmitted from the engine to the pump through a belt and pulley drive. A hand lever operated over-centre clutch was provided to engage and disengage the transmission of power from the engine to the pump.

A wooden dock and raft were also built. The dock provided an access to the raft which provided convenience for adjustments such as lowering, raising and positioning of the Hillis pump (see Figure 6). The raft also provided a platform for the stationing of instruments (see Figure 7).

3.2 LAYOUT OF EQUIPMENT

Figure 8 indicates the arrangement of equipment for testing the Hillis pump operation with water.

The test site chosen was on the left bank of the Red River at the Universty of Manitoba Campus. The engine and centrifugal pump unit was safely placed on the bank as close to the water as possible. An 8.5 m length of 76 mm diameter pvc hose was connected to the suction side of the centrifugal pump to serve as a suction line. A foot valve was installed on the other end which was placed in the water. A 90-degree expanding (38-76 mm) elbow was installed on the delivery side of the centrifugal pump (see Figure 5). An orifice plate, 61 mm in diameter, was placed in the delivery line close to the centrifugal pump to serve as an upstream orifice meter with a U-tube manometer

Figure 5: Diesel engine and centrifugal pump, trailer mounted to form an integral portable unit

Figure 6: Wooden dock and raft to work with the Hillis pump

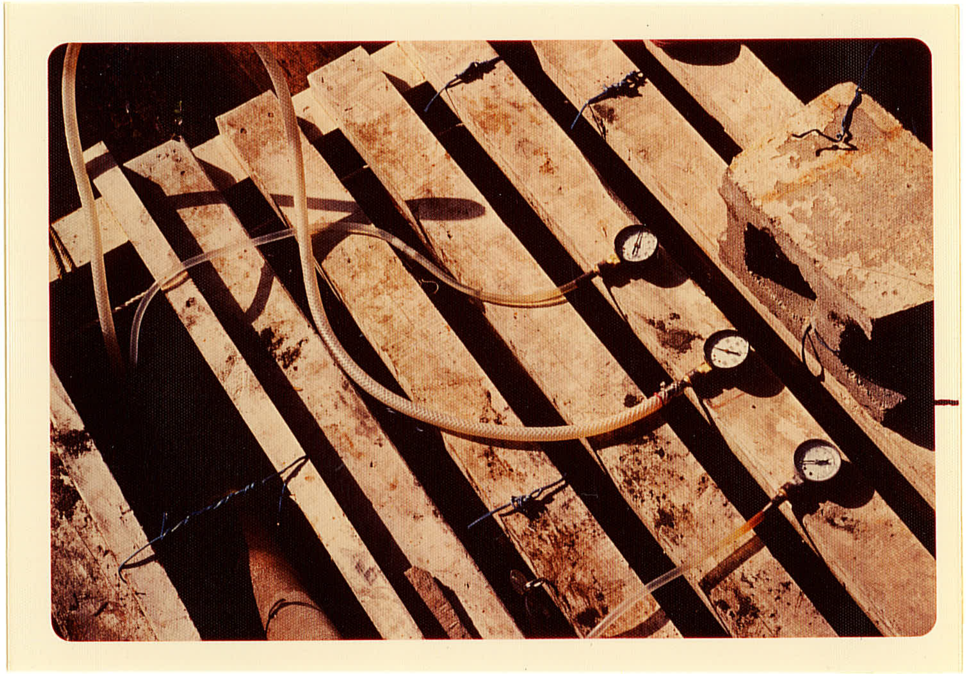


Figure 7: Vacuum-pressure gage, high-pressure gage and low-pressure gage connected to the Hillis pump during test

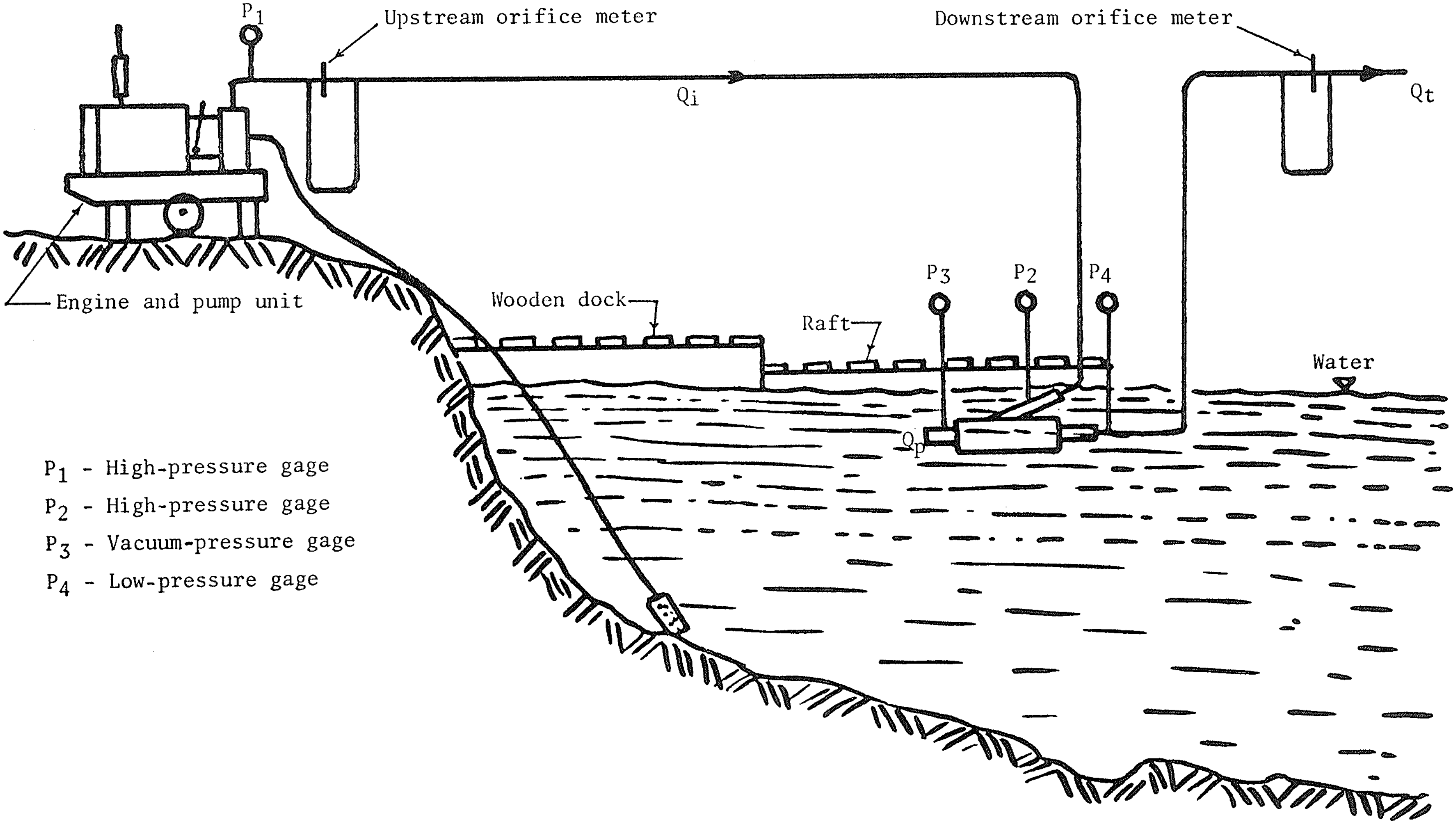


Figure 8: Schematic diagram of the experimental set up

connected to its pressure taps (see Figure 9). This orifice meter and the Hillis pump were connected by a 8.5 m length of 64 mm diameter fire hose.

When the 51-mm model of the Hillis pump was studied, the discharge was conveyed through a 12.5 m length of 64 mm diameter fire hose that discharged water back to river. A second 61 mm diameter orifice plate was installed in this discharge line just prior to its discharge into the river. A U-tube manometer was connected to its pressure taps and the unit functioned as a downstream orifice meter to measure total flow rate. When the 100-mm model of the Hillis pump was studied a 6.7 m length of 100 mm diameter fire hose was used as a discharge line. An 81 mm diameter orifice plate was installed in this discharge line. This downstream orifice meter together with a U-tube manometer connected to its pressure taps was used to measure the total flow rate (see Figure 10).

A vacuum-pressure gage was connected through plastic tubing to a pressure tap on the pickup end of the Hillis pump. A high-pressure gage was connected through plastic tubing to a pressure tap on the arm of the Hillis pump that receives water under high pressure from the external centrifugal pump. A low-pressure gage was connected through plastic tubing to a pressure tap on the discharge end of the Hillis pump. An additional high-pressure gage was mounted

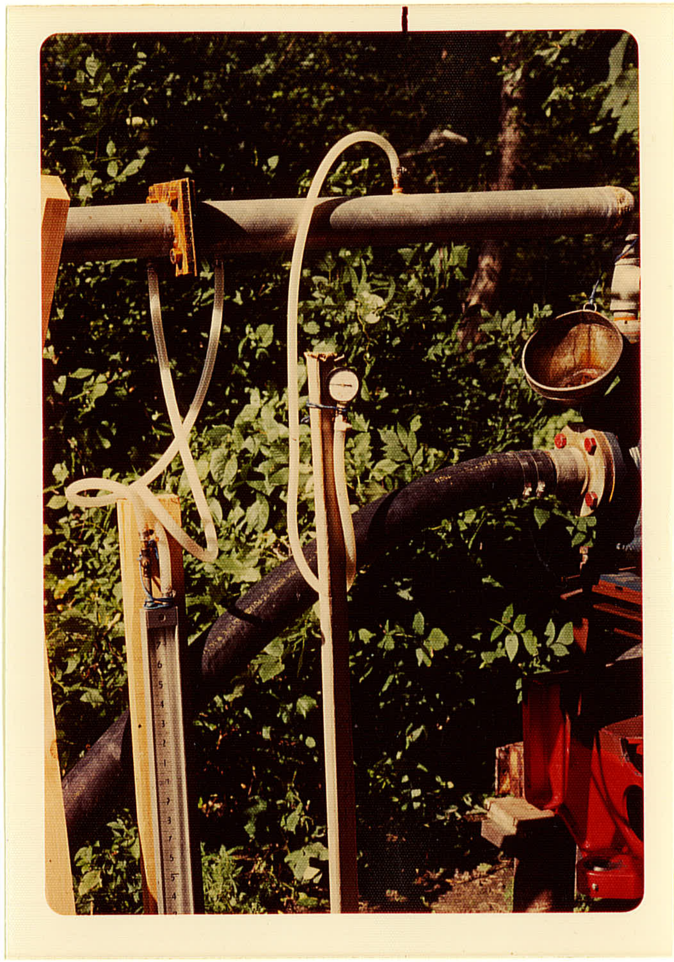


Figure 9: Upstream orifice meter and a high-pressure gage to indicate centrifugal pump delivery pressure

Figure 10: Downstream orifice meter and total flow rate from the Hillis pump

on the upstream end of the upstream orifice meter next to the 90-degree expanding elbow. The Hillis pump was then lowered and submerged in the water about 150 mm below the water surface in a horizontal position.

Chapter IV

TEST PROCEDURE

4.1 PERFORMANCE OF A 51-MM AND 100-MM MODEL OF THE HILLIS PUMP IN MOVING WATER

Calibration of instruments was completed before the beginning of a series of tests with both models.

4.1.1 Calibration of the gages

A static calibration of all pressure gages used was completed in the laboratory prior to field use. The relationship between the applied pressure and the indicated gage pressure was determined for applied pressures in the range of 100 to 1380 kPa. Calibration of the vacuum-pressure gage was achieved with the aid of a U-tube mercury manometer and a vacuum pump. The relationship was obtained between applied vacuum and indicated gage vacuum for applied vacuum in the range of 250 mm Hg to 680 mm Hg (see appendix C).

4.1.2 Calibration of the flowmeters

Orifice meter design parameters used were from standard data and relationships available in the literature. Then the equation for discharge through an orifice was applied. Actual laboratory calibration was not undertaken because test apparatus was not available and also because of time limitations. However, the use of orifice meters to measure water flow is well established and the author is confident that reliable flow rate measurements were obtained. Particular care was exercised to insure that criteria for the design of orifice meters and recommendations for their use were followed.

4.1.3 Parameters recorded

Parameters recorded during the performance evaluation included :

1. Engine speed when it was operating the centrifugal pump (n).
2. Delivery pressure of the centrifugal pump (P_1).
3. Differential pressure head indicated by the upstream orifice meter manometer (ΔH_1).
4. Injection pressure at which water delivered by the centrifugal pump entered the plenum chamber of the Hillis pump (P_2).
5. Discharge pressure at the discharge end of the Hillis pump (P_4).
6. Pressure developed at the pickup end of the Hillis pump (P_3). The pickup end of the Hillis pump was closed tightly by using a circular rubber disc.

The reading of the pressure developed was taken with the disc in place.

7. Differential pressure head indicated by the downstream orifice meter manometer (ΔH_2).

All above readings were taken at 11 different operating speeds of the external centrifugal pump for both models of the Hillis pump. A set of all above seven readings for 11 different engine and pump speeds completed one test. Five such tests were completed for the 51-mm model and ten for 100-mm model. The mean of the data of all tests for respective models was calculated and used in the recorded results (see appendix F). Originally all data was recorded in FPS units and later converted to SI units.

4.1.4 Precautions

Equipment and instrumentation concerns complied with in preparation for performance tests using water included :

1. Tubes connecting high pressure taps from the centrifugal pump delivery line to pressure gages required strength adequate to withstand the high pressure water in the line.

2. The upstream orifice meter U-tube manometer and tubes connecting the manometer to the orifice meter needed to withstand high pressure water in the line.

3. Care was exercised to ensure that no air bubbles occured between the manometer fluid and fluid flowing through orifice meter while taking manometer readings.

4. Care was also taken to insure that no air bubbles were allowed to accumulate in the lines between any pressure tap and pressure gage.

5. Manometers were located below the orifice meters and when this was not possible care was taken to insure that tubes connecting the orifice meter taps to the manometer ran a little down below the orifice meter level and then rose to the manometer connections so that air bubbles, if present, were removed.

6. The Hillis pump was installed so that the pickup end of the pump was always submerged in the water during a test.

7. Constant engine speed was established prior to taking any particular set of test readings.

4.2 PERFORMANCE OF THE 51-MM MODEL OF THE HILLIS PUMP IN MOVING MANURE SLURRY AND GRAVEL

4.2.1 Moving manure slurry

A qualitative test was completed at the Glenlea Research Station to assess the capability of the Hillis pump for removing thick manure sludge from a manure storage pit. Figure 11 is a schematic illustration of the set up for this test. Samples of slurry near the pickup end were taken to determine their total solids content. These determinations were completed by drying 100 mL samples at 103 °C for 25 hours in an electric oven in the laboratory.

4.2.2 Moving gravel

The equipment layout for this test was similar to that used for moving manure slurry and was located on the same site at the Glenlea Research Station. A sieve analysis was completed in the laboratory to determine aggregate size and composition characteristics for the gravel transported by the 51-mm model.

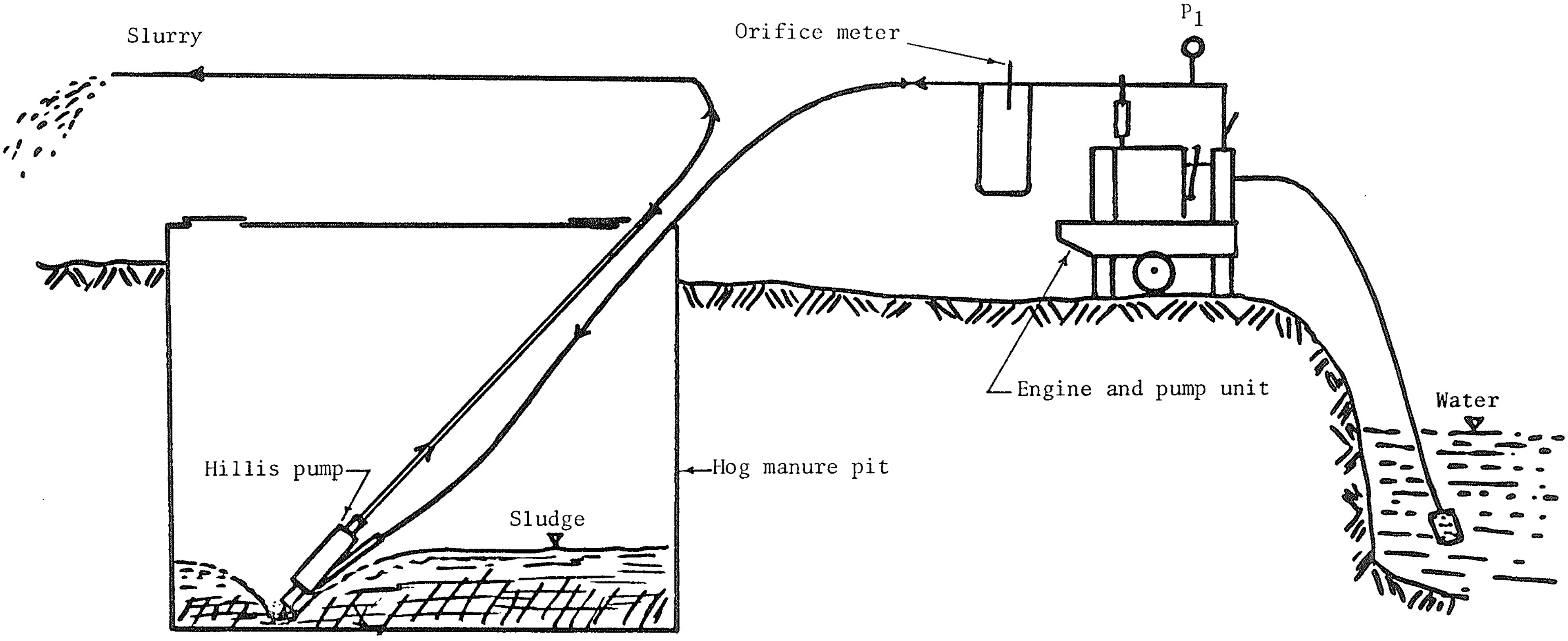


Figure 11: Schematic diagram of the set up for pumping hog manure slurry from a manure pit with the 51-mm model

Chapter V

RESULTS AND DISCUSSION

5.1 PERFORMANCE WITH WATER

Results of the performance tests for a 51-mm and a 100-mm Hillis pump moving water were obtained by calculations from test data and are shown in the form of various plots from Figure 12 to 17 .

The various plots are:

1. Centrifugal pump speed versus injection pressure (see Figure 12). Injection pressure was measured by a pressure gage located on the arm of the Hillis pump plenum chamber.

2. Injection pressure versus pressure developed at the pickup end of the Hillis pump (see Figure 13).

3. Injection pressure versus flow rate injected into the Hillis pump (Q_i), flow rate picked up by the Hillis pump (Q_p), and total flow rate from the Hillis pump (Q_t) (see Figure 14).

4. Injection pressure versus pickup ratio (R). Pickup ratio is the ratio of flow rate picked up (Q_p)

to the flow rate injected (Q_i) passing through the Hillis pump (see Figure 15).

5. Injection pressure versus discharge head from the Hillis pump (see Figure 16). Discharge head is the pressure at the discharge end in metres of water.

6. Injection pressure versus pressure drop across the Hillis pump (see Figure 17). Pressure drop across the Hillis pump is the difference between injection pressure and the pressure at the discharge end of the Hillis pump.

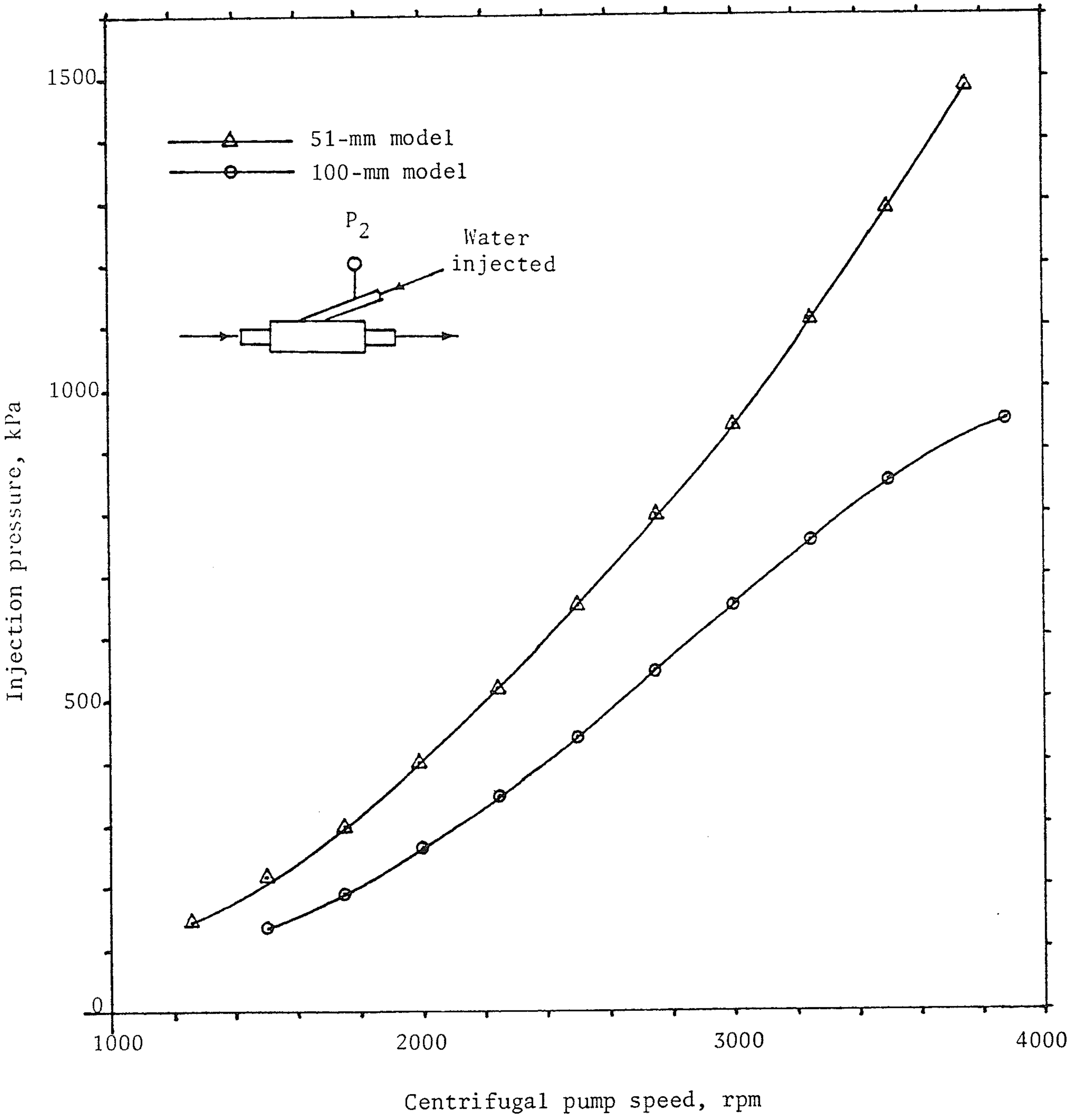
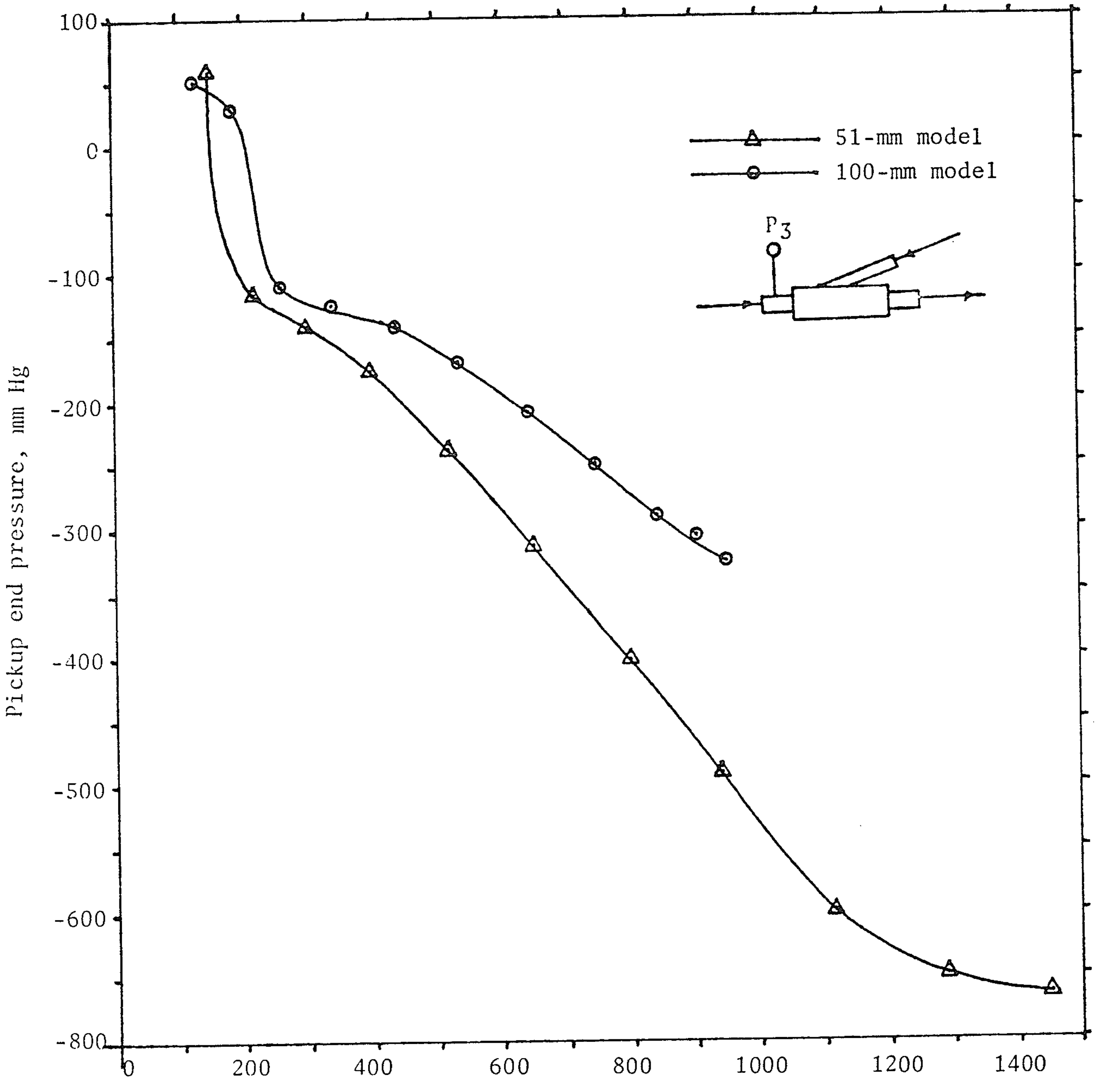


Figure 12: Centrifugal pump speed versus injection pressure



Injection pressure, kPa

Figure 13: Injection pressure versus pressure developed at the pickup end

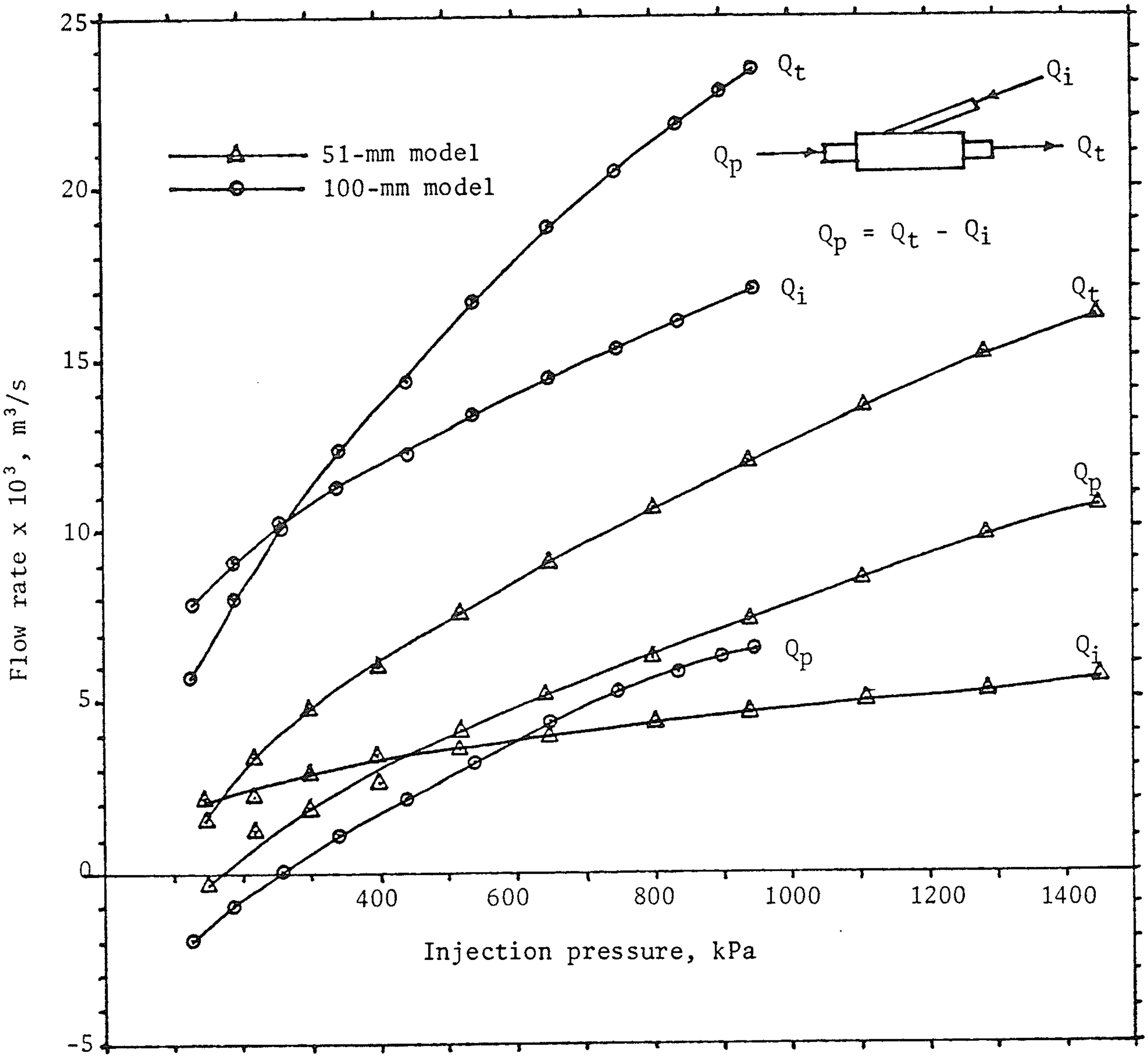


Figure 14: Injection pressure versus various flow rates

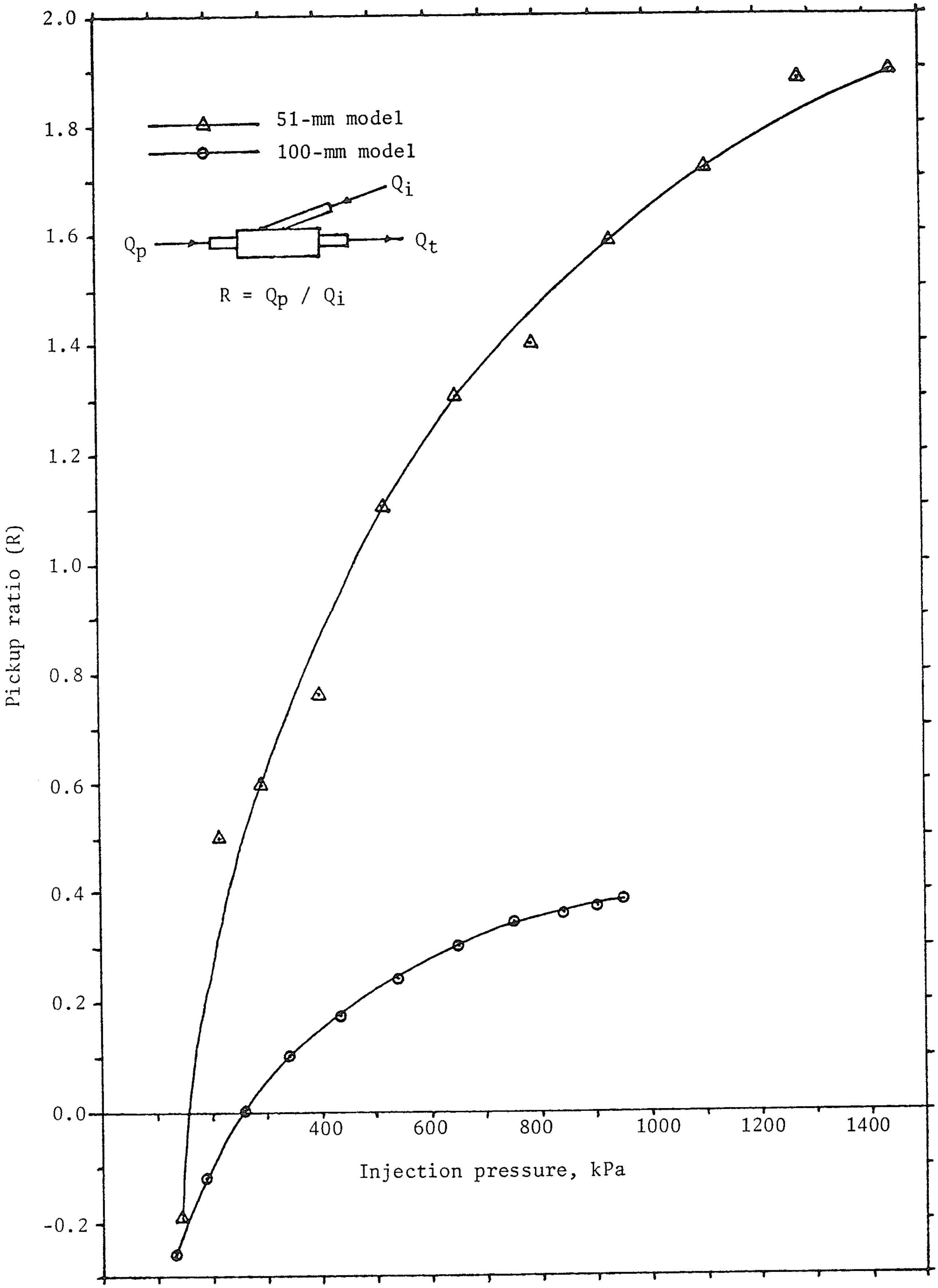


Figure 15: Injection pressure versus pickup ratio (R)

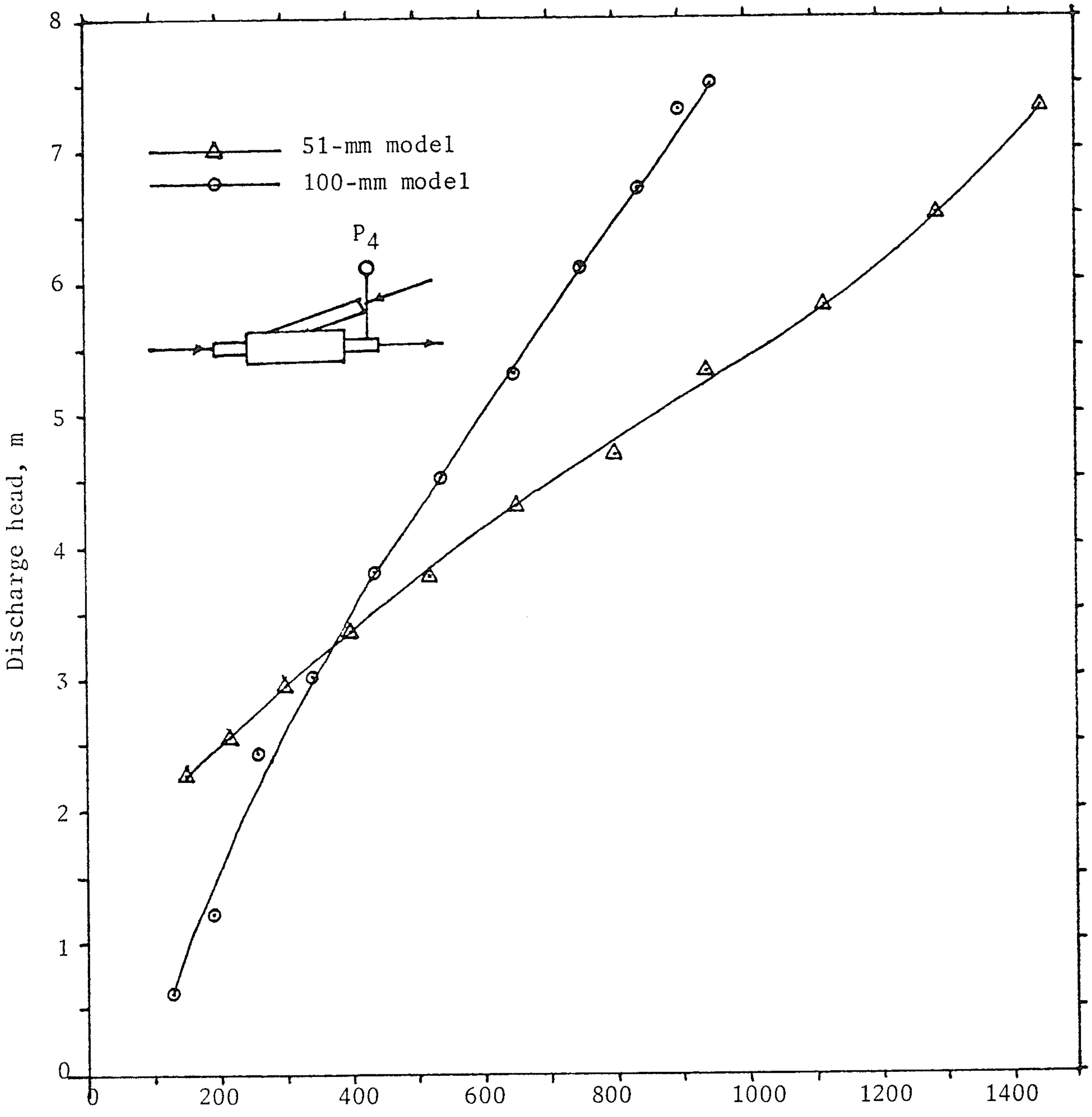


Figure 16: Injection pressure versus discharge head

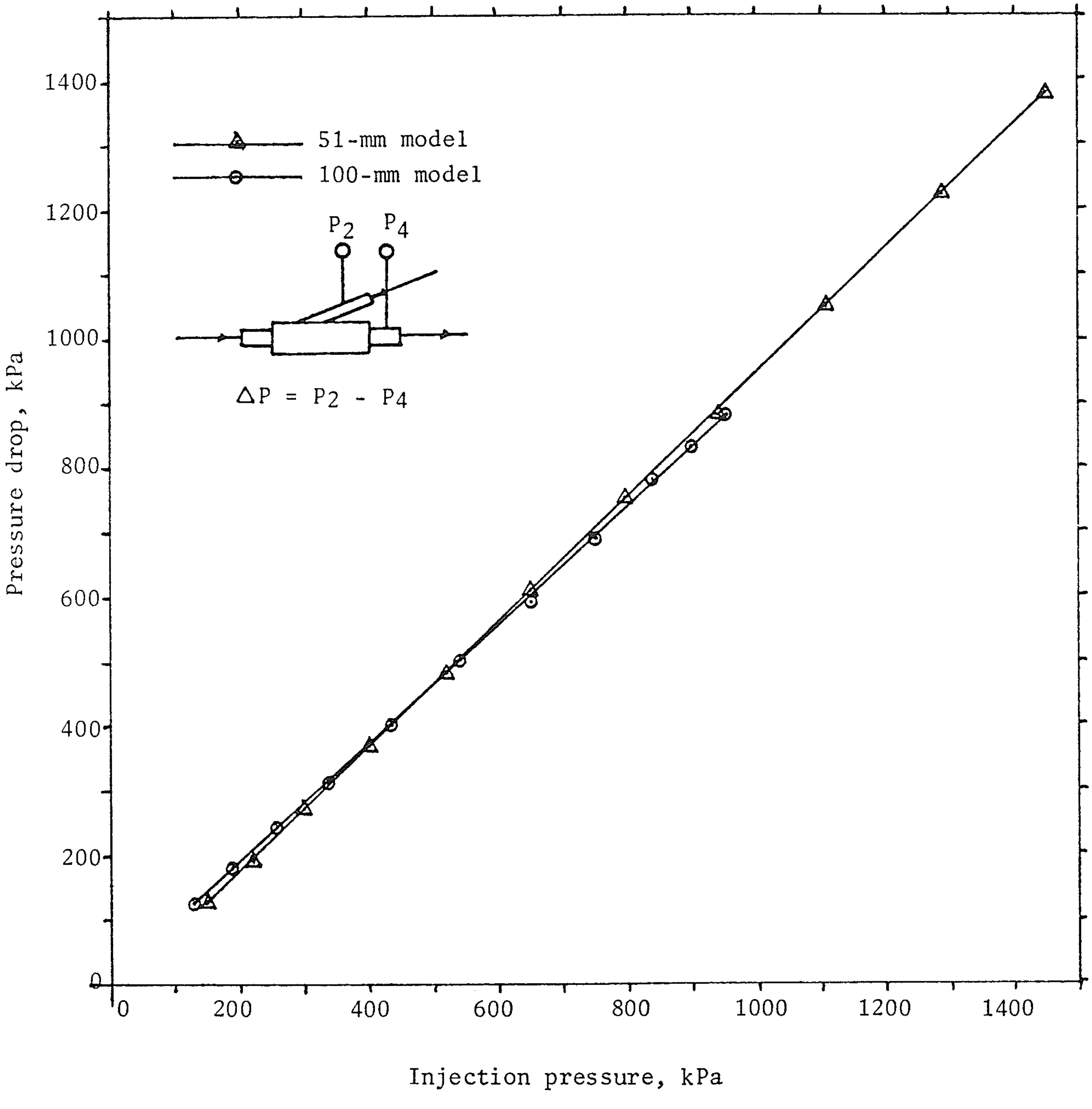


Figure 17: Injection pressure versus pressure drop

5.2 PERFORMANCE WITH MANURE SLURRY

Table 1 contains total solids content of manure slurry samples from the storage pit as determined in the laboratory.

While pumping manure slurry it was observed that initially the Hillis pump removed water above the sludge which had settled at the bottom of the pit. The rate of removal of this water was high at the beginning and reduced as the pump began to encounter thick sludge. The sludge at the pickup end had a solids content of 12 percent and greater. When the sludge surrounding the pickup end was removed a small cavity was formed. As long as the wall forming this cavity continued collapsing and filling the cavity, the pump continued to remove sludge.

After some time the wall of the cavity became fixed and the cavity remained in place. At this point the Hillis pump started taking air in through the pickup end which was readily noted by its audible sound. At the same time only the clean water which was delivered by the centrifugal pump appeared at the end of discharge line from the Hillis pump. The discharge line was then closed for awhile. This action resulted in a flow of water rushing into the cavity through the pickup end causing the wall of the cavity to collapse. When the discharge line was opened again, the movement of slurry through the Hillis pump resumed. After a few flow reversing cycles this technique became ineffective in the effort to continue the removal of sludge without changing the location of the Hillis pump in the pit.

Sludge was successfully removed from the immediate vicinity of each new location of the pump. Thrust towards the pickup end imparted by the injected high pressure water made it impossible to change the location of the pump with the effort expended by two people. Movement of the Hillis pump from place to place inside the pit could only be accomplished when the external centrifugal delivery pump was not operating.

It was also found to be important that the number of bends throughout the pipe lines in the set up be minimized to insure smooth operation. When bends were necessary care was exercised to eliminate sharp curves and kinks.

5.3 PERFORMANCE WITH GRAVEL

This test also demonstrated the need to change the Hillis pump location in the gravel being transported. This movement presented the same difficulty as was encountered in the pumping of manure slurry and could only be accomplished manually when the external pump was not operating. Table 2 contains results of the laboratory sieve analysis of the gravel.

TABLE 1

Total solids content of manure slurry taken from the storage pit

Sample #	Mass of crucible + dry matter (from original sample of 100mL) (g)	Mass of crucible (g)	Mass of dry matter (g)	Mean (g)	Total solids content per litre (g/L)
1.	114.55	100.61	13.94		
2.	114.20	100.01	14.19	12.85	128.5
3.	115.20	103.52	11.68		
4.	109.57	98.00	11.57		

Drying temperature = 103 °C

Drying time= 25 h

TABLE 2

Results of the sieve analysis completed in the laboratory for the gravel which was pumped

Serial #	Size of gravel (mm)	Mass (kg)	% Mass
1.	38 - 32	0.12	0.34
2.	32 - 25	0.65	1.85
3.	25 - 19	3.75	10.68
4.	19 >	30.58	87.13

Bulk density of the gravel = 1847 kg/m^3

Chapter VI

CONCLUSIONS

All conclusions have been drawn from the results and observations applicable to performance test conditions only.

6.1 PERFORMANCE WITH WATER

1. At low injection pressure some of the injected flow rate was lost through the pickup end of the Hillis pump.

2. Injection pressure increased with an increase in the external pump speed.

3. An increase in the injection pressure up to a certain limit substantially increased the negative pressure developed at the pickup end of the Hillis pump. This led to an increase in the flow rate picked up and thereby to a high pickup ratio.

4. The increase in the discharge head and the pressure drop across the Hillis pump was nonlinear and linear respectively, with an increase in the injection pressure.

5. Efficiency of the Hillis pump was very low. The efficiency was found to be 14 and 10 percent for the 51-mm and 100-mm model respectively.

6.2 PERFORMANCE WITH MANURE SLURRY AND GRAVEL

The Hillis pump transported manure slurry and gravel successfully. It was necessary to move the pump from place to place in the material being transported for satisfactory operation. For applications as a materials handling device the Hillis pump having a high pickup ratio will always be better. The necessity of a large water supply for use as a driving fluid with the external pump is a major limitation to the use of the Hillis pump.

Chapter VII

RECOMMENDATIONS

In general it is recommended;

1. that the design of the Hillis pump be modified with the objective of increasing its efficiency while maintaining the simplicity which is characteristic of present models.
2. that the Hillis pump be mounted on a mechanical device which will facilitate its movement easily and effectively through the material to be transported.
3. that new or modified model designs be of small scale, so that performance tests can be conducted in the laboratory with improved instrumentation for monitering and with less labour.
4. that further investigations utilize an external pump having performance characteristics such that the injection pressures delivered would be significantly above the 1300 kPa limit achieved in this study when 51-mm model was studied. A pump capable of delivering water at pressures to a maximum of 2500 kPa will be desirable.

For further investigations applicable to the design of the models investigated in this thesis it is recomended;

1. that the effect of change in diameter, length, angle, arrangement (ring, spiral) and number of the orifice tubes on the pressure drop, discharge head and negative pressure developed at the pickup end of the pump be investigated.

2. that the shape of the orifice tubes be modified at the entrance to minimize entry losses.

3. that sharp corners in the plenum chamber be rounded to reduce friction losses.

4. that the shape of the arm receiving high pressure water to the plenum chamber be modified at the joint to the plenum chamber to reduce exit losses.

5. that a method to accomplish agitation of the material to be transported at the pickup end of the pump be added to the present design.

REFERENCES

Anonymous. 1972. Jet pumps and ejectors proceedings. Proc. Symp. Jet pumps and Ejectors. BHRA Fluid Engineering-I. Chem. E., England.

Clark J. J. and A. M. Robertson. 1976. A flat blade turbine stirrer for slurry. Farm Building Progress, January, pp 25-28.

Hoemsen R. P. 1977. Performance evaluation of the Hillis pump. An undergraduate thesis, Department of Agricultural Engineering, University of Manitoba, Winnipeg, Canada.

Holman J. P. and W. J. Gajda, Jr. 1978. Experimental Methods for Engineers. McGraw Hill Book Company, New York. pp 221-261.

Kumar M., H. D. Bartlett and N. N. Mohsenin. 1972. Flow properties of animal waste slurries. Transactions of the ASAE. pp 718-722.

Lapp H. M. 1976. Unpublished report on a demonstration for pneumatic conveying of wheat with a Hillis pump. Department of Agricultural Engineering, University of Manitoba, Winnipeg, Canada.

Roberson J. A. and C. T. Crowe. 1975. Engineering Fluid Mechanics. Houghton Mifflin Company, Boston, U.S.A. pp 420-420.

Wasp E. J., J. P. Kenny and R. L. Gandhi. 1977. Solid liquid flow-slurry pipe line transportation. Trans. Tech. Publications.

Appendix A

EQUIPMENT SPECIFICATION DETAILS

Equipment specification details

1. Perkins Diesel engine

   a) Cylinders - 4

   b) Volume - 3870 x 103 mm^3 (236 in^3)

   c) Power (without fan and cooling system) - 53 kW (71 bhp)

   d) Power (with fan and cooling system) - 45 kW (61 bhp)

   e) Rpm (adjustable maximum) - 2250

   f) Engine pulley outer diameter - 277 mm (10.9 in)

2. Ingersoll Rand centrifugal pump

   a) Impeller diameter - 254 mm (10.0 in)

   b) Suction inlet diameter - 76 mm (3.0 in)

   c) Delivery outlet diameter - 38 mm (1.5 in)

   d) Pump pulley outer diameter - 180 mm (7.1 in)

   e) Rpm (maximum) - 3500

f) Total head (maximum) - 171 m (560 ft)

g) Discharge (maximum, at total head 111 m (365 ft)) - 0.02 m3/s (255 USGPM)

3. Tachometer

a) Manufacturer - Smiths Industrial Division, London N.W.2, ATH4

b) Range

i) 0 - 500 Scale

ii) 0 - 5000 Scale x 10

iii) 0 - 50000 Scale x 100

4. Flowmeters

Three orifice meters were fabricated in the workshop of the Department of Agricultural Engineering, University of Manitoba, Winnipeg. Two of them had specifications below;

a) Orifice plate diameter (d) - 61 mm (2.4 in)

b) Pipe diameter (D) - 76 mm (3.0 in)

c) Upstream pipe length - 10D

d) Downstream pipe length - 3D

e) Upstream pressure tap location - D

f) Downstream pressure tap location - D/2

g) Flow coefficient (K) - 0.70

The third had an orifice plate diameter (d) of 81 mm (3.2 in), pipe diameter (D) of 100 mm (4.0 in) and flow coefficient (K) 0.76 with the remaining specifications being the same as for the previous two orifice meters. The values of flow coefficient (K) for orifice meters were taken as reported by Roberson and Crowe in 1975.

Figure 18 shows the construction details of the orifice meter.

5. U-tube manometers

Two U-tube manometrers were used and each had specifications as noted below:

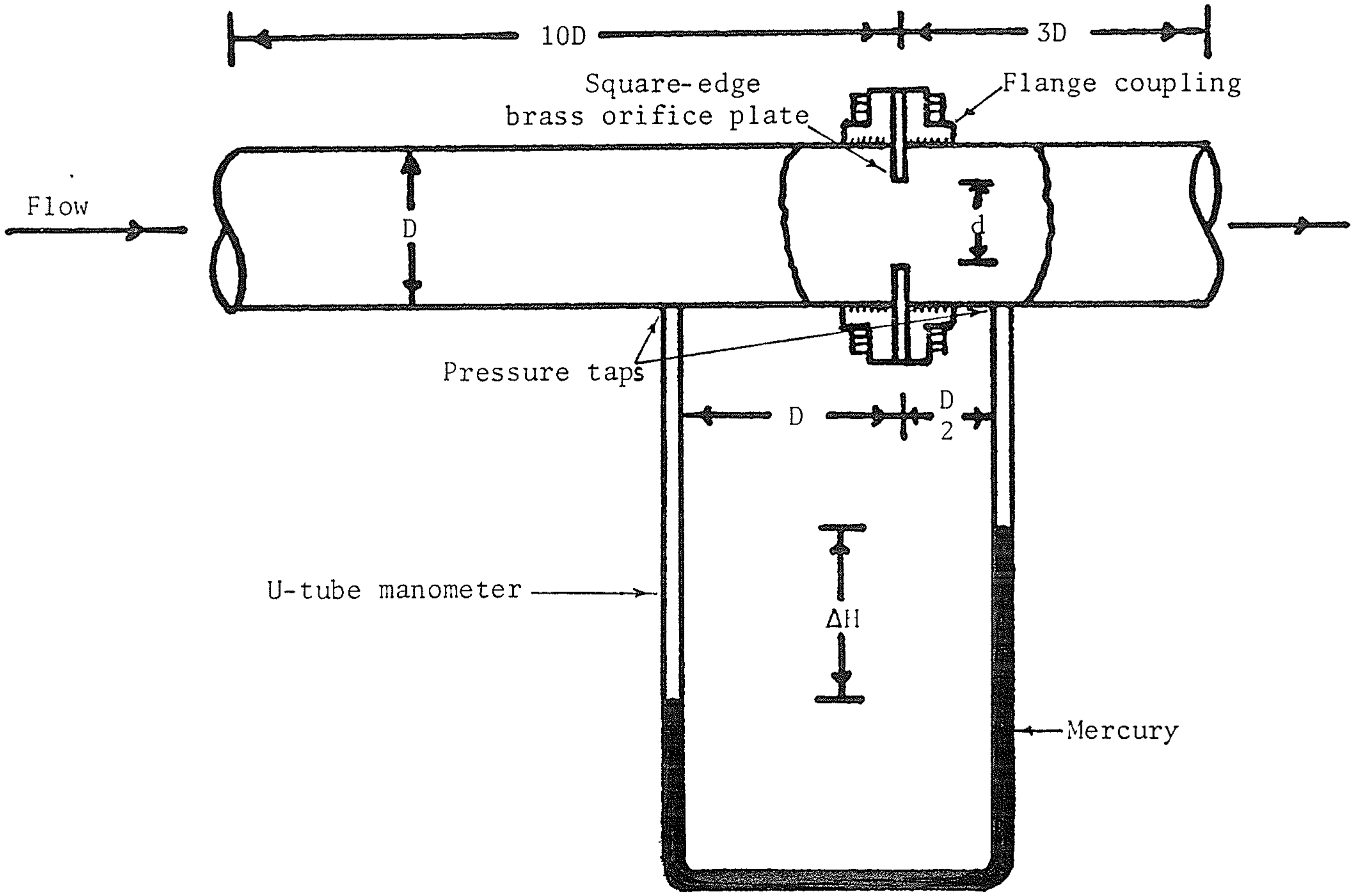
a) Manometer height - 1.2 m (3.8 ft)

b) Manometer tube internal diameter - 6.35 mm (0.25 in)

c) Manometer fluid - mercury

6. Pressure gages

Specifications for the two high-pressure gages used were:



$$Q = K A_o \sqrt{2 g_c \Delta H}$$

where, Q = discharge
K = flow coefficient
A_o = area of orifice
g_c = gravitational constant
ΔH = differential pressure head

Figure 18: Orifice meter details

a) Manufacturer - AMETEK, US, Gauge Division, Sellervile, Pennsylvania 18960

b) Range : 0 - 2070 kPa (0 - 300 psi)

c) Least count - 34 kPa (5 psi)

Specifications for the third which was a low-pressure gage were:

d) Manufacturer - ASHCROFT, USA

e) Range : 0 - 390 kPa (0 - 57 psi)

f) Least count - 6 kPa (1 psi)

7. Vacuum-pressure gage specifications

a) Manufacturer - AMETEK, US, Gauge Division, Sellerville, Pennsylvania 18960

b) Range : -760 mm Hg to 0 to +210 kPa (-30 in Hg to 0 to 30 psi)

c) Least count - 50 mm Hg, 6 kPa (2 in Hg, 1 psi)

8. Pipes or hoses

a) Fire hoses

i) Diameter 64 mm (2.5 in) and length 66.4 m (218 ft)

  - ii) Diameter 100 mm (4.0 in) and length 6.7 m (22 ft)

- b) PVC hose
  - i) Diameter 76 mm (3.0 in) and length 61 m (200 ft)

Appendix B

DISCHARGE FORMULA FOR ORIFICE METERS

DISCHARGE FORMULA FOR ORIFICE METERS

Flow through an orifice meter can be given as :

$$Q = K A_0 \sqrt{2 g_c \Delta H}$$

where,

Q = discharge, m^3/s

K = flow coefficient

A_0 = area of orifice, m^2

g_c = gravitational constant, m/s^2

ΔH = differential pressure head, m H_2O

$$\Delta H = \frac{Q^2}{K^2 A_0^2 \, 2 g_c}$$

$$\Delta H' = \frac{Q^2 \times 100}{K^2 (\pi/4)^2 d^4 \times 2 \times 9.81} \text{ cm } H_2O \times \frac{76 \text{ cm Hg}}{1033.23 \text{ cm } H_2O}$$

$$\Delta H' = \frac{0.6084\, Q^2}{K^2 d^4} \text{ cm Hg}$$

$$Q = K d^2 \sqrt{\frac{\Delta H'}{0.6084}}$$

$$Q = K' d^2 \sqrt{\Delta H'}$$

where,

$K' = K/\sqrt{0.6084}$

d = orifice plate diameter, m

$\Delta H'$ = differential pressure head, cm Hg

Therefore, for an orifice meter with $K = 0.70$ and $d = 0.061$ m

$$Q = 0.0036 \sqrt{\Delta H'}$$

and for an orifice meter with $K = 0.76$ and $d = 0.081$ m

$$Q = 0.0064 \sqrt{\Delta H'}$$

Appendix C

CALIBRATION DATA FOR GAGES

TABLE C-1

Serial #	Pressure applied (kPa)	Pressure indicated (kPa)	
		Pressure gage # 1	Pressure gage # 2
1.	103	68	90
2.	138	117	117
3.	172	152	165
4.	206	172	200
5.	241	220	234
6.	276	255	268
7.	310	296	303
8.	344	338	338
9.	379	372	372
10.	414	406	414
11.	448	448	448
12.	482	482	482
13.	517	517	517
14.	552	552	552
15.	586	586	586
16.	620	627	620
17.	655	655	662
18.	689	689	696
19.	724	730	730
20.	758	765	765
21.	792	800	800
22.	827	841	834
23.	862	876	868
24.	896	917	903
25.	930	944	938
26.	965	986	979
27.	1000	1027	1014
28.	1034	1062	1048
29.	1068	1096	1082
30.	1103	1130	1124
31.	1138	1165	1151
32.	1172	1206	1192
33.	1206	1241	1227
34.	1241	1276	1268
35.	1276	1310	1303
36.	1310	1344	1338
37.	1344	1378	1378
38.	1378	1413	1404

If, P_a = pressure applied and P_i = pressure indicated then from the above data we get;

for pressure gage # 1

$$P_a = 0.95P_i + 29$$

for pressure gage # 2

$$P_a = 0.97P_i + 16$$

TABLE C-2

Sr #	Pressure gage # 3 (vacuum-pressure)		Pressure gage # 4	
	Vacuum applied (mm Hg)	Vacuum indicated (mm Hg)	Pressure applied (kPa)	Pressure indicated (kPa)
1.	246	127	34	31
2.	332	254	68	64
3.	430	381	103	96
4.	558	495	138	134
5.	680	596	172	168
6.	-	-	206	206
7.	-	-	241	241
8.	-	-	276	279
9.	-	-	310	314
10.	-	-	344	348
11.	-	-	379	382

If, P_a = pressure applied and P_i = pressure indicated then from the above data we get;
for pressure gage # 3

$$P_a = 0.92P_i + 107$$

for pressure gage # 4

$$P_a = 0.97P_i + 6$$

Appendix D

TEST DATA FOR THE 51-MM MODEL

TABLE D-1

September 1979

Test # 1

51-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure P_1** (kPa)	Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading ΔH_2** (cm Hg)
1	**811**	**1250**	172	0.3	124	+12 kPa	17	0.2
2	**974**	**1500**	255	0.4	206	-5	20	0.9
3	**1136**	**1750**	344	0.6	290	-25	26	1.5
4	**1298**	**2000**	462	0.9	393	-50	31	2.4
5	**1461**	**2250**	592	1.0	524	-127	38	3.8
6	**1623**	**2500**	717	1.4	662	-203	41	4.2
7	**1785**	**2750**	841	1.5	800	-292	48	8.2
8	**1948**	**3000**	1014	1.6	951	-381	50	10.0
9	**2110**	**3250**	1186	2.0	1116	-508	55	13.7
10	**2272**	**3500**	1378	2.2	1310	-610	62	16.8
11	**2435**	**3750**	1586	2.6	1489	-660	72	19.2

TABLE D-2

September 1979

Test # 2

51-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure P_1** (kPa)	**Upstream manometer reading ΔH_1** (cm Hg)	**Hillis pump injection pressure P_2** (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading ΔH_2 (cm Hg)**
1	**811**	**1250**	172	0.3	124	+6 kPa	17	0.1
2	**974**	**1500**	248	0.4	206	-12	20	0.9
3	**1136**	**1750**	344	0.6	290	-38	24	2.1
4	**1298**	**2000**	462	0.9	400	-76	28	3.0
5	**1461**	**2250**	600	1.0	517	-140	31	4.6
6	**1623**	**2500**	730	1.2	662	-228	36	6.4
7	**1785**	**2750**	882	1.5	806	-318	41	8.8
8	**1948**	**3000**	1034	1.6	944	-432	46	11.4
9	**2110**	**3250**	1206	2.0	1116	-546	52	14.4
10	**2272**	**3500**	1392	2.1	1282	-648	58	18.0
11	**2435**	**3750**	1586	2.4	1475	-660	66	20.7

TABLE D-3

September 1979

Test # 3

51-mm Hillis pump

Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	Centrifugal pump delivery pressure P_1 (kPa)	Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	Downstream manometer reading ΔH_2 (cm Hg)
1	811	1250	172	0.3	138	+10 kPa	14	0.1
2	974	1500	255	0.4	206	-12	20	0.9
3	1136	1750	344	0.8	290	-46	22	1.8
4	1298	2000	462	0.9	393	-88	28	3.4
5	1461	2250	592	1.0	517	-140	31	4.6
6	1623	2500	724	1.2	648	-228	34	6.7
7	1785	2750	876	1.5	800	-330	41	8.8
8	1948	3000	1034	1.6	951	-432	44	11.2
9	2110	3250	1220	2.0	1130	-546	52	14.3
10	2272	3500	1413	2.1	1313	-660	58	17.4
11	2435	3750	1586	2.4	1468	-665	68	20.4

TABLE D-4

September 1979

Test # 4

51-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	Centrifugal pump delivery pressure P_1 (kPa)	Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	Downstream manometer reading ΔH_2 (cm Hg)
1	811	1250	172	0.3	158	+7 kPa	17	0.1
2	974	1500	255	0.4	206	-12	20	0.9
3	1136	1750	344	0.8	290	-38	24	1.5
4	1298	2000	462	0.9	393	-76	29	2.7
5	1461	2250	600	1.0	517	-152	31	4.2
6	1623	2500	730	1.4	655	-228	38	6.4
7	1785	2750	882	1.5	806	-330	41	8.5
8	1948	3000	1034	1.6	951	-444	48	11.2
9	2110	3250	1220	2.0	1144	-546	54	14.3
10	2272	3500	1413	2.1	1324	-660	60	17.4
11	2435	3750	1586	2.4	1482	-665	68	20.4

TABLE D-5

September 1979

Test # 5

51-mm Hillis pump

Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	Centrifugal pump delivery pressure P_1 (kPa)	Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	Downstream manometer reading ΔH_2 (cm Hg)
1	811	1250	172	0.3	124	+8 kPa	17	0.1
2	974	1500	255	0.4	206	-12	20	0.9
3	1136	1750	344	0.8	296	-38	24	2.1
4	1298	2000	462	0.9	400	-88	28	2.9
5	1461	2250	592	1.0	517	-152	31	4.6
6	1623	2500	724	1.2	662	-228	36	6.7
7	1785	2750	882	1.5	806	-342	41	9.1
8	1948	3000	1034	1.6	951	-432	48	11.6
9	2110	3250	1227	2.0	1130	-533	54	14.4
10	2272	3500	1413	2.1	1324	-660	60	17.6
11	2435	3750	1586	2.4	1462	-665	66	20.4

Appendix E

TEST DATA FOR THE 100-MM MODEL

TABLE E-1

September 1979

Test # 1

100-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure P_1** (kPa)	Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading ΔH_2** (cm Hg)
1	974	1500	110	4.6	103	+6 kPa	00	0.9
2	1136	1750	165	6.1	165	+6 kPa	00	1.8
3	1298	2000	262	7.9	248	0	17	2.7
4	1461	2250	344	9.4	344	-12	24	4.0
5	1623	2500	462	11.6	434	-25	31	5.4
6	1785	2750	565	13.7	538	-76	41	7.0
7	1948	3000	668	15.8	634	-102	48	8.5
8	2110	3250	710	16.4	662	-114	48	8.8
9	2272	3500	792	18.0	758	-152	55	10.4
10	2435	3750	910	19.8	841	-178	62	11.6
11	2597	4000	965	21.3	917	-228	68	12.8

TABLE E-2

September **1979**

Test # 2

100-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure P_1** (kPa)	**Upstream manometer reading ΔH_1** (cm Hg)	**Hillis pump injection pressure P_2** (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading ΔH_2** (cm Hg)
1	974	1500	124	4.8	110	+6 kPa	00	0.6
2	1136	1750	172	6.4	152	+6 kPa	00	1.5
3	1298	2000	262	7.9	228	0	19	2.4
4	1461	2250	358	10.0	324	-5	26	3.6
5	1623	2500	462	11.6	414	-25	31	4.8
6	1785	2750	586	14.0	538	-64	41	6.7
7	1948	3000	676	15.8	634	-102	48	8.2
8	2110	3250	814	18.2	758	-152	55	10.4
9	2272	3500	910	19.5	841	-190	62	11.6
10	2435	3750	979	21.0	910	-216	68	12.2
11	2500	3850	1006	21.9	938	-228	68	12.8

September 1979

Test # 3

TABLE E-3

100-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure** P_1 (kPa)	**Upstream manometer reading** ΔH_1 (cm Hg)	**Hillis pump injection pressure** P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading** ΔH_2 (cm Hg)
1	**974**	**1500**	110	4.8	96	+10 kPa	00	0.6
2	**1136**	**1750**	172	6.4	172	+6 kPa	14	1.2
3	**1298**	**2000**	262	8.2	262	0	20	2.1
4	**1461**	**2250**	358	10.0	344	-12	26	3.0
5	**1623**	**2500**	468	11.8	427	-25	33	4.2
6	**1785**	**2750**	600	14.0	538	-46	41	7.0
7	**1948**	**3000**	703	16.1	641	-114	48	8.5
8	**2110**	**3250**	827	18.2	772	-165	58	10.6
9	**2272**	**3500**	910	19.8	854	-190	62	11.6
10	**24 35**	**3750**	979	21.6	910	-228	68	12.8
11	2500	3850	1020	22.0	965	-241	70	13.4

September 1979

Test # 4

TABLE E-4

100-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure** P_1 (kPa)	Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading** ΔH_2 (cm Hg)
1	974	1500	103	4.8	90	+8 kPa	00	0.6
2	1136	1750	172	6.4	193	+6 kPa	00	1.2
3	1298	2000	262	8.2	262	0	20	2.4
4	1461	2250	358	10.0	330	-12	24	3.0
5	1623	2500	468	11.8	427	-25	33	4.2
6	1785	2750	592	14.0	538	-56	41	6.1
7	1948	3000	706	16.2	655	-102	48	9.1
8	2110	3250	827	18.6	772	-152	58	10.1
9	2272	3500	938	20.1	862	-178	63	11.2
10	2435	3750	979	21.3	910	-203	68	12.2
11	2500	3850	1020	22.2	951	-216	72	13.1

TABLE E-5

September 1979

Test # 5

100-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure** P_1 (kPa)	Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading** ΔH_2 (cm Hg)
1	**974**	1500	117	4.8	138	+8 kPa	00	0.6
2	**1136**	1750	179	6.4	193	+6 kPa	00	1.5
3	**1298**	2000	255	8.8	255	0	17	2.4
4	**1461**	2250	344	9.6	290	-25	26	3.6
5	**1623**	2500	462	11.8	420	-38	33	4.8
6	**1785**	2750	565	14.0	524	-64	41	6.7
7	**1948**	3000	689	16.2	655	-102	48	8.2
8	**2110**	3250	800	18.0	758	-140	56	10.0
9	**2272**	3500	910	20.1	862	-178	63	11.2
10	**2435**	3750	979	21.3	930	-208	68	12.5
11	2520	3880	1034	22.2	979	-228	72	13.1

September 1979

Test # 6

TABLE E-6

100-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure P_1 (kPa)**	Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading ΔH_2 (cm Hg)**
1	**974**	1500	110	4.6	124	+8 kPa	00	0.6
2	**1136**	1750	186	6.4	186	+6 kPa	00	1.5
3	**1298**	2000	262	7.6	262	0	20	2.4
4	**1461**	2250	358	9.8	358	-30	24	4.0
5	**1623**	2500	462	11.6	427	-46	31	5.4
6	**1785**	2750	586	14.0	538	-76	41	7.0
7	**1948**	3000	710	16.4	662	-127	48	8.8
8	**2110**	3250	814	18.2	744	-157	55	10.4
9	**2272**	3500	938	20.1	862	-203	63	11.8
10	**2435**	3750	979	21.3	930	-228	68	13.1
11	2500	3850	1034	22.2	972	-241	72	13.7

September 1979

Test # 7

TABLE E-7

100-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure P_1** (kPa)	**Upstream manometer reading ΔH_1** (cm Hg)	**Hillis pump injection pressure P_2** (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading ΔH_2** (cm Hg)
1	974	1500	117	4.8	138	+6 kPa	00	0.9
2	1136	1750	186	6.4	186	+3 kPa	00	1.5
3	1298	2000	262	7.9	262	-5	19	2.7
4	1461	2250	365	9.8	358	-25	24	4.0
5	1623	2500	462	11.6	448	-46	31	5.2
6	1785	2750	572	14.0	565	-71	38	7.0
7	1948	3000	689	16.2	676	-114	48	7.9
8	2110	3250	841	18.9	806	-178	58	10.6
9	2272	3500	910	20.1	896	-203	63	11.8
10	2435	3750	1014	21.6	979	-241	70	13.1
11	2520	3880	1034	22.6	1006	-254	72	13.7

September 1979

Test # 8

TABLE E-8

100-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure P_1** (kPa)	Upstream manometer reading ΔH_1 (cm Hg)	**Hillis pump injection pressure P_2** (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading ΔH_2** (cm Hg)
1	**974**	1500	124	5.2	144	+6 kPa	00	1.2
2	**1136**	**1750**	193	6.7	186	0	14	1.8
3	**1298**	**2000**	262	7.9	262	-12	19	3.0
4	**1461**	**2250**	358	9.8	344	-25	26	4.2
5	**1623**	**2500**	468	11.6	448	-46	33	5.4
6	**1785**	**2750**	586	14.0	565	-76	41	7.3
7	**1948**	**3000**	703	15.8	676	-127	48	8.8
8	**2110**	**3250**	814	18.2	772	-165	56	10.6
9	**2272**	**3500**	910	20.1	868	-203	62	12.1
10	**2435**	**3750**	979	21.3	944	-228	68	13.7
11	2520	3880	1034	22.6	979	-254	72	14.3

September 1979

TABLE E-9

Test # 9

100-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure** P_1 (kPa)	**Upstream manometer reading** ΔH_1 (cm Hg)	**Hillis pump injection pressure** P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading** ΔH_2 (cm Hg)
1	**974**	1500	117	4.8	131	+8 kPa	00	1.2
2	**1136**	**1750**	193	6.4	193	+3 kPa	14	1.8
3	**1298**	**2000**	262	7.9	234	-12	20	2.2
4	**1461**	**2250**	344	9.8	310	-25	26	4.0
5	**1623**	**2500**	468	11.6	427	-46	33	5.4
6	**1785**	**2750**	572	14.0	538	-76	41	7.0
7	**1948**	**3000**	696	15.8	634	-114	48	8.8
8	**2110**	**3250**	814	18.2	758	-157	56	10.6
9	**2272**	**3500**	924	20.1	854	-203	63	11.8
10	**24 35**	**3750**	986	21.3	924	-228	68	13.8
11	2520	3880	1048	22.6	979	-254	72	13.7

TABLE E-10

September 1979

Test # 10

100-mm Hillis pump								
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	**Centrifugal pump delivery pressure P_1** (kPa)	Upstream manometer reading ΔH_1 (cm Hg)	**Hillis pump injection pressure P_2** (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	**Downstream manometer reading ΔH_2** (cm Hg)
1	**974**	1500	124	5.2	117	+6 kPa	00	0.9
2	**1136**	1750	193	6.4	193	0	14	1.8
3	**1298**	2000	262	7.6	262	-12	20	3.0
4	**1461**	2250	358	10.0	352	-30	26	4.0
5	**1623**	2500	468	11.6	448	-50	31	5.8
6	**1785**	2750	586	14.0	538	-88	41	6.7
7	**1948**	3000	689	15.8	641	-127	48	8.8
8	**2110**	3250	814	18.0	758	-165	55	10.6
9	**2272**	3500	917	20.1	862	-203	62	12.5
10	**2435**	3750	979	21.3	910	-228	68	13.1
11	2520	3880	1034	22.6	979	-254	72	14.4

Appendix F

CALCULATIONS FOR THE RESULTS

TABLE F-1

test data (51-mm Hillis pump						Calculations for the results										
						Corrected pressure from calibration equation										
y	Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	Downstream manometer reading ΔH_2 (cm Hg)	P_1 (kPa)	P_2 (kPa)	P_3 (mm Hg)	P_4 (kPa)	*Total flow rate Q_t (m^3/s)	Flow rate injected Q_i (m^3/s)	Flow rate picked up $Q_p=Q_t-Q_i$ (m^3/s)	Pickup ratio $R=Q_p/Q_i$	Discharge head of the Hillis pump (m)	Pressure drop in the Hillis pump $\Delta P=P_2-P_4$ (kPa)
	0.3	134	+8 kPa	16	0.2	192	146	+8 kPa (60 mm Hg)	22	0.0016	0.0020	-0.0004	-0.20	2.24	124
	0.4	206	-10	20	0.9	270	216	-116	25	0.0034	0.0022	0.0012	0.54	2.55	191
	0.7	291	-37	24	1.8	356	298	-141	29	0.0048	0.0030	0.0018	0.60	2.96	269
	0.9	396	-76	28	2.8	468	400	-176	33	0.0060	0.0034	0.0026	0.76	3.36	367
	1.0	518	-142	32	4.4	594	518	-238	37	0.0076	0.0036	0.0040	1.11	3.77	481
	1.2	658	-223	37	6.2	718	654	-312	42	0.0090	0.0039	0.0051	1.30	4.28	612
	1.5	804	-322	42	8.6	857	796	-403	46	0.0106	0.0044	0.0062	1.40	4.69	750
	1.6	949	-424	47	11.0	1008	936	-497	52	0.0119	0.0046	0.0073	1.58	5.30	884
	2.0	1127	-536	53	14.2	1180	1109	-600	57	0.0136	0.0050	0.0086	1.72	5.81	1052
	2.1	1310	-648	60	17.4	1360	1286	-703	64	0.0150	0.0052	0.0098	1.88	6.52	1222
	2.4	1475	-663	68	20.2	1536	1446	-716	72	0.0162	0.0056	0.0106	1.89	7.34	1374

TABLE F-1

September 1979

Test # 1 to 5

Mean of the test data (51-mm Hillis pump									Calculations for the results						
									Corrected pressure from calibration equation						
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	Centrifugal pump delivery pressure P_1 (kPa)	Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	Downstream manometer reading ΔH_2 (cm Hg)	P_1 (kPa)	P_2 (kPa)	P_3 (mm Hg)	P_4 (kPa)	*Total flow rate Q_t (m³/s)	Flow rate injected Q_i (m³/s)	Fl pi Q (m
1	811	1250	172	0.3	134	+8 kPa	16	0.2	192	146	+8 kPa (60 mm Hg)	22	0.0016	0.0020	-0
2	974	1500	254	0.4	206	-10	20	0.9	270	216	-116	25	0.0034	0.0022	0
3	1136	1750	344	0.7	291	-37	24	1.8	356	298	-141	29	0.0048	0.0030	0
4	1298	2000	462	0.9	396	-76	28	2.8	468	400	-176	33	0.0060	0.0034	0
5	1461	2250	595	1.0	518	-142	32	4.4	594	518	-238	37	0.0076	0.0036	0
6	1623	2500	725	1.2	658	-223	37	6.2	718	654	-312	42	0.0090	0.0039	0
7	1785	2750	872	1.5	804	-322	42	8.6	857	796	-403	46	0.0106	0.0044	0
8	1948	3000	1030	1.6	949	-424	47	11.0	1008	936	-497	52	0.0119	0.0046	0
9	2110	3250	1212	2.0	1127	-536	53	14.2	1180	1109	-600	57	0.0136	0.0050	0
10	2272	3500	1402	2.1	1310	-648	60	17.4	1360	1286	-703	64	0.0150	0.0052	0
11	3435	3750	1586	2.4	1475	-663	68	20.2	1536	1446	-716	72	0.0162	0.0056	0

* $Q_t = 0.0036 \sqrt{\Delta H_2}$

+ $Q_i = 0.0036 \sqrt{\Delta H_1}$

TABLE F-2

st data (100-mm Hillis pump)					Calculations for the results										
Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	Downstream manometer reading ΔH_2 (cm Hg)	Corrected pressure from calibration equation				*Total flow rate Q_t (m^3/s)	Flow rate injected Q_i (m^3/s)	Flow rate picked up $Q_p=Q_t-Q_i$ (m^3/s)	Pickup ratio $R=Q_p/Q_i$	Discharge head of the Hillis pump (m)	Pressure drop in the Hillis pump $\Delta P=P_2-P_4$ (kPa)
					P_1 (kPa)	P_2 (kPa)	P_3 (mm Hg)	P_4 (kPa)						
4.8	119	+7 kPa	0	0.8	139	131	+7 kPa (52 mm Hg)	6	0.0057	0.0078	-0.0021	-0.26	0.61	125
6.4	182	+4 kPa	6	1.6	200	192	+4 kPa (30 mm Hg)	12	0.0080	0.0091	-0.0011	-0.12	1.22	180
8.0	254	-4	19	2.5	276	262	-110	24	0.0101	0.0102	0.0001	0.00	2.44	238
9.8	335	-20	25	3.7	365	340	-125	30	0.0123	0.0112	0.0011	0.10	3.06	310
11.6	432	-37	32	5.0	470	435	-141	37	0.0143	0.0122	0.0021	0.17	3.77	398
14.0	542	-69	40	6.8	580	542	-170	44	0.0166	0.0134	0.0032	0.24	4.48	498
16.0	650	-113	48	8.6	686	646	-210	52	0.0188	0.0144	0.0044	0.30	5.30	594
18.0	756	-154	56	10.2	796	749	-248	60	0.0204	0.0152	0.0052	0.34	6.12	689
19.8	852	-190	62	11.6	890	842	-282	66	0.0218	0.0160	0.0058	0.36	6.73	776
21.2	918	-218	68	12.7	956	906	-308	72	0.0228	0.0166	0.0062	0.37	7.34	834
22.2	966	-240	71	13.4	1000	953	-328	74	0.0234	0.0170	0.0064	0.38	7.54	879

TABLE F-2

September 1979

Test # 1 to 10

Mean of the test data (100-mm Hillis pump)									Calculations for the results							
Sr #	Engine speed n (rpm)	Centrifugal pump speed N = 1.54 n (rpm)	Centrifugal pump delivery pressure P_1 (kPa)	Upstream manometer reading ΔH_1 (cm Hg)	Hillis pump injection pressure P_2 (kPa)	Pickup end pressure developed P_3 (mm Hg)	Hillis pump discharge pressure P_4 (kPa)	Downstream manometer reading ΔH_2 (cm Hg)	Corrected pressure from calibration equation P_1 (kPa)	Corrected pressure from calibration equation P_2 (kPa)	Corrected pressure from calibration equation P_3 (mm Hg)	Corrected pressure from calibration equation P_4 (kPa)	*Total flow rate Q_t (m^3/s)	Flow rate injected Q_i (m^3/s)	Flo pick Q_p (m
1	974	1500	116	4.8	119	+7 kPa	0	0.8	139	131	+7 kPa (52 mm Hg)	6	0.0057	0.0078	-0.
2	1136	1750	181	6.4	182	+4 kPa	6	1.6	200	192	+4 kPa (30 mm Hg)	12	0.0080	0.0091	-0.
3	1298	2000	261	8.0	254	-4	19	2.5	276	262	-110	24	0.0101	0.0102	0.
4	1461	2250	354	9.8	335	-20	25	3.7	365	340	-125	30	0.0123	0.0112	0.
5	1623	2500	465	11.6	432	-37	32	5.0	470	435	-141	37	0.0143	0.0122	0.
6	1785	2750	581	14.0	542	-69	40	6.8	580	542	-170	44	0.0166	0.0134	0.
7	1948	3000	692	16.0	650	-113	48	8.6	686	646	-210	52	0.0188	0.0144	0.
8	2110	3250	808	18.0	756	-154	56	10.2	796	749	-248	60	0.0204	0.0152	0.
9	2272	3500	906	19.8	852	-190	62	11.6	890	842	-282	66	0.0218	0.0160	0.
10	2435	3750	976	21.2	918	-218	68	12.7	956	906	-308	72	0.0228	0.0166	0.
11	2520	3880	1022	22.2	966	-240	71	13.4	1000	953	-328	74	0.0234	0.0170	0.

* $Q_t = 0.0064 \sqrt{\Delta H_2}$

+ $Q_i = 0.0036 \sqrt{\Delta H_1}$

Appendix G

SAMPLE CALCULATIONS

SAMPLE CALCULATIONS

1. Correction to various recorded pressures by use of calibration equation.

Data identity	Indicated discharge pressure P_i	Calibration equation of pressure gage #4	Corrected discharge pressure P_a
51-mm Hillis pump, mean of test # 1 to 5, observation # 5	32 kPa	$P_a = 0.97P_i + 6$	37 kPa

2. Calculations from the mean of observed data for obtaining results.

100-mm model, observation # 9.

(a) Total flow rate (Q_t) :

$$Q_t = 0.0064 \sqrt{\Delta H_2} \ m^3/s$$
$$= 0.0064 \sqrt{11.6}$$
$$= 0.0218 \ m^3/s$$

(b) Flow rate injected (Q_i) :

$$Q_i = 0.0036 \sqrt{\Delta H_1} \ m^3/s$$
$$= 0.0036 \sqrt{19.8}$$
$$= 0.0160 \ m^3/s$$

(c) Flow rate picked up (Q_p) :

$$Q_p = Q_t - Q_i$$
$$= 0.0218 - 0.0160$$
$$= 0.0058 \ m^3/s$$

(d) Pickup ratio (R) :

$$R = Q_p / Q_i$$
$$= 0.0058 / 0.0160$$
$$= 0.36$$

(e) Discharge head (Z_2) :

Neglecting friction losses and the velocity head which is very small, the discharge head can be obtained by converting discharge pressure (P_4) from kPa to m of water.

$$Z_2 = P_4 \text{ kPa} \times 0.1020 \frac{\text{m } H_2O}{\text{kPa}}$$
$$= 66 \times 0.1020$$
$$= 6.73 \text{ m } H_2O$$

(f) Suction head (Z_1) :

Neglecting friction losses and velocity head, the suction head is obtained by converting the pressure developed at the pickup end (P_3) from mm of Hg to m of water.

$$Z_1 = P_3 \text{ mm Hg} \times 0.0136 \frac{\text{m } H_2O}{\text{mm Hg}}$$
$$= -282 \times 0.0136$$
$$= -3.84 \text{ m } H_2O$$

3. Calculations for efficiency of the Hillis pump.

$$P = 9.81\ Q'\ H$$

where, P = power, watts

Q' = mass flow rate, kg/s

H = head, m

Efficiency (η) = output / input

$$\eta = \frac{9.81\ Q_y\ \frac{m^3}{s} \times 1000\ \frac{kg}{m^3} \times P_y\ kPa \times 0.10\ \frac{m\ H_2O}{kPa}}{9.81\ Q_x\ \frac{m^3}{s} \times 1000\ \frac{kg}{m^3} \times P_x\ kPa \times 0.10\ \frac{m\ H_2O}{kPa}}$$

$$\eta = \frac{Q_y\ \frac{m^3}{s} \times P_y\ kPa}{Q_x\ \frac{m^3}{s} \times P_x\ kPa}$$

where, Q_y = output flow rate (Q_t) , P_y = output pressure (P_4)

and Q_x = input flow rate (Q_i) , P_x = input pressure (P_2)

Therefore, at a maximum centrifugal pump speed (3500 rpm) for the 51-mm model

$$\eta = \frac{0.0150 \times 64}{0.0052 \times 1286} \times 100$$

$$\eta = 14.36\ \%$$

and for the 100-mm model

$$\eta = \frac{0.0218 \times 66}{0.0160 \times 842} \times 100$$

$$\eta = 10.68\ \%$$