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# Comparison Between DTU and Commercial Hydraulic Ram Pump Performance

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DTU Working Paper No.33 1992

# Comparison between DTU and Commercial Ram Hydraulic Ram Pump Performances

## UPDATE AND COMMENTS, APRIL 1996

Since this paper was written, the DTU Mark 6.4 pump has been phased out, to be replaced by first the M8.4 and more recently the S2. All these are pumps normally run with a 2" G.I. drivepipe and delivering to up to 100m using a drive flow of 40 to 120 litres/min. Preliminary results for the M8/S2 on a single setting are given at the end of this paper, indicating that, setting for setting, the M8 is superior to its predecessors. Generally the DTU later models are more efficient than the M6. Of course performance as measured in this paper is only part of the story. The DTU pumps are made largely of mild steel and are therefore more subject to corrosion than most 'commercial' machines. In recent years there has been a trend towards use of plastics in ram pumps as pvc or ABS piping replaces galvanised iron. However plastic pumps can rarely operate reliably at delivery heads exceeding 40 meters. There is also a growing interest in providing the air-cushioning of the output via an enclosed air packet (for example closed cell foam) instead of an air vessel with a free air-water surface. This arrangement can effectively increase the usable drive head by allowing the impulse valve exhaust to emerge under water.

In the paper, the early comparisons with commercial pumps use data from a study by T H Delft which were obtained from slightly larger models (from the respective manufacturers' ranges), and with a much higher drivehead, than the comparisons in the rest of the paper.

Details of the current (1996) DTU designs, namely S1 (for use with a 1" steel drivepipe), S2 (2" steel) and P90 (90 mm. pvc) are given in DTU Technical Releases TR11, TR14 and TR12 respectively.

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T.D.Jeffery
April 1991

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# 1. INTRODUCTION

This paper details the performance of the DTU Mark 6.4 hydraulic ram pump in comparison to commercial models run under similar conditions. Details of the performance of a number of commercial pumps tested at Delft University, Netherlands are used for comparison.

## 1.1 Delft University

Between 1982 and 1984 J. Tacke of Delft University of Technology carried out tests on a number of commercially available hydraulic ram pumps. These were published in 1988 with comprehensive details of all results obtained and the development of a mathematical model for prediction of ram performance. As part of this programme field tests were conducted by the Foundation of Dutch Volunteers in Rwanda. These aimed to investigate the technical performance and durability under operating conditions in a community setting, social acceptance and community participation in installing, operating and maintaining a hydraulic ram system.

The presentation by Delft of all laboratory test results is excellent and allows a good level of comparison for tests on subsequent designs. Unfortunately no details of the findings or conclusions resulting from the field trials in Rwanda are made available. However the DTU are greatly indebted to Delft for their provision of such a useful resouce.

## 1.2 DTU, University of Warwick

The Development Technology Unit has been investigating hydraulic ram pump design, performance and manufacture since 1985. This began with student projects and has grown into a full-time research programme largely funded by the Overseas Development Administration. The aims of the programme are:

a) to analyse in detail the operation of the ram pump gaining a comprehensive understanding of the operating principles and complex hydraulic interactions occuring within the pump.

b) to produce pump designs suitable for manufacture in developing countries using available materials and production processes.

c) to thoroughly test such designs for their performance and endurance (including extensive field trials) and offer findings for widespread dissemination.

d) to develop and prove methods for surveying and design of complete water supply installations.

e) to produce design charts and computer based tools to enable design and field engineers to confidently include hydraulic ram pumps as an option in their water supply schemes.

f) to provide technical expertise and training for two African based programmes installing ram pumps for village water supply and irrigation.

In terms of hardware development the DTU has two distinct working areas. The first is the development of designs of steel hydraulic ram pumps based on the 2" diameter BSP pipe that has been found to be widely available in developing countries and is of an appropriate capacity for small village water supply schemes. The second area of hardware development is the production of plastic hydraulic ram pumps based on widely available 110mm plastic pipe and especially suitable for irrigation close to water courses. Rough specifications and performance indications are given below.

| | Steel | Plastic |
|---|---|---|
| **Materials required** | | |
| | 2" Galvanised pipe | 110mm PVC pipe |
| | 2" Fittings | Small amount of |
| | Mild steel bar | mild steel parts |
| **Manufacturing process** | | |
| | Welding | Hand tools |
| | Drilling | |
| | Turning | |
| **Typical performance ranges** | | |
| | 40-140 | |
| Drive flow | 40/140 l/min | 200-350 l/min |
| Drive head | 2-25m | 0.5-2.5m |
| Delivery flow | 2-12 l/min | 2-25 l/min |
| Delivery head | up to 150m | up to 15m |
| Efficiency | 50-90% | 20-60% |
| Expected life | 10 years | 3 years |

This paper is concerned solely with the comparison of the 2" steel pump with its commercially available rivals. Such pumps have found the widest application to date in supplying water for domestic use.

During the research many designs of ram pump have been produced and tested. In 1990 a design was chosen as having proven itself sufficiently in terms of performance and durability to set a 'benchmark' against which furthest developments could be assessed. It is this model, Mark 6.4, that is used in the following comparison against commercial designs.

## 2. SUMMARY OF WORK CARRIED OUT AT DELFT

### 2.1 Selection of Pumps

Delft decided to select 12 rams from 6 manufacturers that were applicable in typical village or domestic water supply schemes. In all, details of pumps from 10 manufacturers were obtained and selection made based on the following criteria:

a) as many types of ram design as possible should be included.

b) tests should include both traditional and modern designs.

c) rams should show a reasonable price to performance ratio.

To enable the latter of the criteria, manufacturers were sent a set of conditions and asked to provide details of the pump they would recommend and its expected output and efficiency.

Table 1 shows the results of this comparison.

TABLE 1 - COMPARISON OF HYDRAULIC RAMS

Arrangement: Source Supply = 90 l/min

Supply Head Hs = 7.50 m

Delivery Head hd = 75 m

| Type of Hydraulic Ram | Drive [inch] | Pipe [mm] | Volume of Driving Water Required [l/min] | Pumping Rate q [l/min] | Efficiency trd [%] | Approx Price for Ram Alone [US$-1982] |
|---|---|---|---|---|---|---|
| Vulcan 21/2 | 2 | 65 | 36-114 | 6.10 | 68 | 1200 |
| Blake Hydram 31/2 | 2 | 65 | 45- 96 | 6.00 | 67 | 1000 |
| Sano No. 5/65 mm | 2 | 65 | 50-110 | 6.95 | 77 | 1000 |
| Rife 20 HDU | 2 | 50 | 38- 95 | 5.40 | 60 | 1100 |
| Schlumpf 5A23 | 2 | 50 | 50-100 | 5.50 | 61 | 2700 |
| Alto CH 66-110-18 | 2 | 65 | 50- 90 | 5.40 | 60 | 2100 |
| Briau D4 | 2 | 50 | 45- 90 | 5.40 | 60 | 3200 |
| CeCoCo - H50 | 2 | 50 | 25-115 | 6.90 | 77 | 3500 |
| WAMA No. 6 | 2 | 65 | 60-100 | 4.50 | 50 | 1500 |
| BZH-Ram W6 | 2 | 65 | 45- 90 | 2.70 | 30 | 1200 |

Delft concluded that in terms of performance, the choice should favour the first eight pumps and of these the first six provide the best performance to price ratio. From the information given the choice seems to be a reasonable one.

An alternative comparison to evaluate the performance to price ratio would have been to include a cost per litre delivered under these conditions. This significantly alters the ranking of pumps as is shown in Table 2.

TABLE 2

| Type of Hydraulic Ram | Pumping Rate q [C/min] | Efficiency (Trade) (%) | Approx Price for Ram Alone [US$-1982] | Cost per litre delivered | Rank |
|---|---|---|---|---|---|
| Vulcan 2½ | 6.10 | 68 | 1200 | 197 | 3 |
| Blake Hydram 3½ | 6.00 | 67 | 1000 | 167 | 2 |
| Sano No. 5/65 mm | 6.95 | 77 | 1000 | 144 | 1 |
| Rife 20 HDU | 5.40 | 60 | 1100 | 204 | 4 |
| Schlumpf 5A23 | 5.50 | 61 | 2700 | 491 | 8 |
| Alto CH 66-110-18 | 5.40 | 60 | 2100 | 389 | 6 |
| Briau D4 | 5.40 | 60 | 3200 | 593 | 10 |
| CeCoCo - H50 | 6.90 | 77 | 3500 | 507 | 9 |
| WAMA No. 6 | 4.50 | 50 | 1500 | 333 | 5 |
| BZH-Ram W6 | 2.70 | 30 | 1200 | 444 | 7 |

It would also have been interesting to include details from rams currently manufactured in developing countries. Details of the rams selected are given in Table 3.

### 2.2 Assessment of Experimental Procedure

The tests conducted were fairly comprehensive with each ram being observed for approx. 1 month. The test rig employed allowed a supply head of between 0.5 and 3.0 m with a drive pipe length of 12m. Such a low drive head range is clearly the product of laboratory limitations and does not reflect typically observed ranges in the field of 2 to 20m.

Flows were measured by collecting water for a timed period and weighing it. For each setting this was repeated a number of times to give a more accurate average flow. This is potentially a very accurate method of flow measurement but is open to numerous experimental errors. However it does avoid the need to use flow meters that have their own inaccuracies despite careful calibration.

The designs of ram pump tested exhibit a number of different types of impulse valve. Four of the six have traditional valves above the axis of the pump body but the Schlumpf has its valve below the axis. No mention is made in the text of the Delft work as to where the supply head was measured from. To allow accurate comparison the head should be taken from the orifice of the impulse valve, not the axis of the pump body. In reality both the SANO and Schlumpf pumps may in some situations be able to utilise a given supply head more effectively by their impulse valve design.

TABLE 3 - HYDRAULIC RAMS SELECTED

| Type of Hydraulic Ram | Manufacturer | Drive Pipe Diameter [ins] | [mm] | Intake capacity [l/min] | Description |
|---|---|---|---|---|---|
| Blake Hydram No. 2<br>Blake Hydram No. 3.5 | John Blake Ltd<br>England | 1.5<br>2.5 | 40<br>65 | 12-25<br>45-96 | A well-established standard design made of cast-iron. Both waste valve and delivery valve consist of a rubber disc covering a perforated gunmetal seat. |
| Alto J 26-80-8<br>Alto CH 50-110-18 | J.M. Desclaud<br>France | 1<br>2 | 25<br>50 | 8-15<br>30-60 | A recently renewed pump design made of steel pipe components, but using conventional valve designs. Weight-loaded gunmetal waste valve; spring-loaded rubber clack as delivery valve. |
| Vulcan 1"<br>Vulcan 2" | Green & Carter<br>England | 1<br>2 | 25<br>50 | 4-18<br>23-46 | A standard design made of cast-iron; like the Blake Hydram available for a long time. Both waste valve and delivery valve consist of a rubber disc covering a grid shaped, gunmetal seat. |
| SANO No. 1-25 mm<br>SANO No. 4-50 mm | Pfister + Langhanss<br>Germany | 1<br>2 | 25<br>50 | 6-16<br>30-65 | A rather unconventional' design, nowadays made of fire zinc-coated steel. Both waste valve and delivery valve are spring-actted and substantially made of gunmetal. |
| Davey No. 3<br>Rife 20 HDU | Rife Hydr. Eng<br>Mfg. Co. | 1<br>2 | 25<br>50 | 5-15<br>38-95 | Rife: a fairly standard design made of cast-iron. Weight-loaded rubber waste valve, mounted on a rocker-arm; delivery valve is a rubber disc covering a grid iron seat.<br>Davey: less efficient, less expensive low base configuration, using a weight-loaded gunmetal waste valve and a weight-loaded leather washer as delivery valve. |
| Schlumpf 4A5<br>Schlumpf 4A23 | Schlumpf Ag<br>Maschinenfabrik<br>Switzerland | 1.5<br>1.5 | 40<br>40 | 30-60<br>30-60 | A design available in 2 models. Model A23 uses a spring-loaded rubber waste valve mounted on a rocker and a weight-loaded rubber washer as delivery valve. The less efficient model A5 uses a weight-loaded rubber waste valve. |

The laboratory experiments also included the use of piezo-electric pressure transducers, displacement transducers and strain guages to observe in detail the changes occuring. Although the resolution of these observations is low they are well presented and provide useful insights into pump operation.

The major criticism of the information presented by Delft is that they supply no indication of how each pump was setup when the results were taken. They simply state that 'waste valve adjustment' was 'kept constant' over the whole range of tests. To ensure a fair comparison the waste valves were presumably initially adjusted to the manufacturers recommendation that would give the best overall performance (efficiency and power output) under typical operating conditions. If this was not the case then the results are practically worthless as some of the pumps may have been badly tuned whilst others were well tuned for the given operating conditions.

## 2.3 Summary of results

The results presented by Delft are comprehensive within the limitations of their test rig. Delft provide data for 3 supply heads for each pump over a range of delivery heads. Of these the highest (3m) has been taken as being the most representative and all results presented below are for this fixed supply head. Table 4 shows some results for efficiency and power at typical supply to delivery head ratios.

TABLE 4 SUMMARY OF TEST RESULTS

| Pump | Efficiency (%) | | | Power (Watts) | | |
|---|---|---|---|---|---|---|
| | at 30m | at 60m | max | at 30m | at 60m | max |
| Blake No 2 (1¼") | 70.5 | 67 | 70.5 | 15.2 | 12.8 | 15.1 |
| Blake No 3½ (2½") | 72.5 | 68 | 73 | 38.2 | 12.8 | 15.1 |
| Alto (1") | 29 | - | 47 | 2.2 | - | 4.3 |
| Alto (2") | 41 | 23 | 42 | 10.3 | 3.4 | 7.3 |
| Vulcan (1") | 58 | 58 | 59 | 5.1 | 3.9 | 4.8 |
| Vulcan (2") | 75 | 55 | 77 | 15.2 | 5.9 | 15.9 |
| SANO No 1 (1") | 64 | 57 | 67 | 3.4 | 2.9 | 4.0 |
| SANO No 4 (2") | 67 | 66 | 69 | 20.6 | 19.6 | 20.2 |
| Davey No 3 (1") | 54 | - | 60 | 3.4 | - | 4.7 |
| Rife 20HDU (2") | 43 | 48 | 48 | 19.1 | 19.6 | 12.7 |
| Schlumpf 4A5 (1¼") | - | - | 62 | - | - | 15.2 |
| Schlumpf 4A23 (1¼") | 43 | 15 | 62 | 8.8 | 2.0 | 17.2 |

Five of the pumps tested are of similar specification to the DTU models and were therefore selected for analysis and comparison. Graphs 1 and 2 show power and efficency curves for these five pumps. The large variations between pumps can be seen quite clearly and comparison is complicated by the marked differences in the power and efficiency curves. At low heads for instance the Vulcan 2" ram is the most efficient but has the lowest output power and will only run up to a delivery head of 85 m.

2.4 Conclusions about commercial pumps

Delft offer no conclusions or direct comparisons between the various pumps tested. The results are complex and comparison has to be based on many factors in order to produce sensible recommendations. In any given situation the exact requirements will vary. The points given below are an attempt to pick out the main items in order to draw some conclusions.

1) The Vulcan 2" has the highest efficiency recorded at 76.9% and at low heads (up to 36 m) has the best effiency of all the pumps.

2) The Rife 2" has the lowest efficiency up to 70 m and never increases over 50%. However it has the widest range of delivery heads over which it will operate. Overall it would be fair to say that the Rife pump has the poorest efficiency.

3) Overall the Blake 2½" is the most efficient closely followed by the smaller Blake 1½". They show good efficiencies over the normal operating range and will pump over a wide range of delivery heads.

4) Similarly the SANO 2" shows good efficiencies over a wide range of delivery heads and is more efficient than the Blake pump over about 75 m.

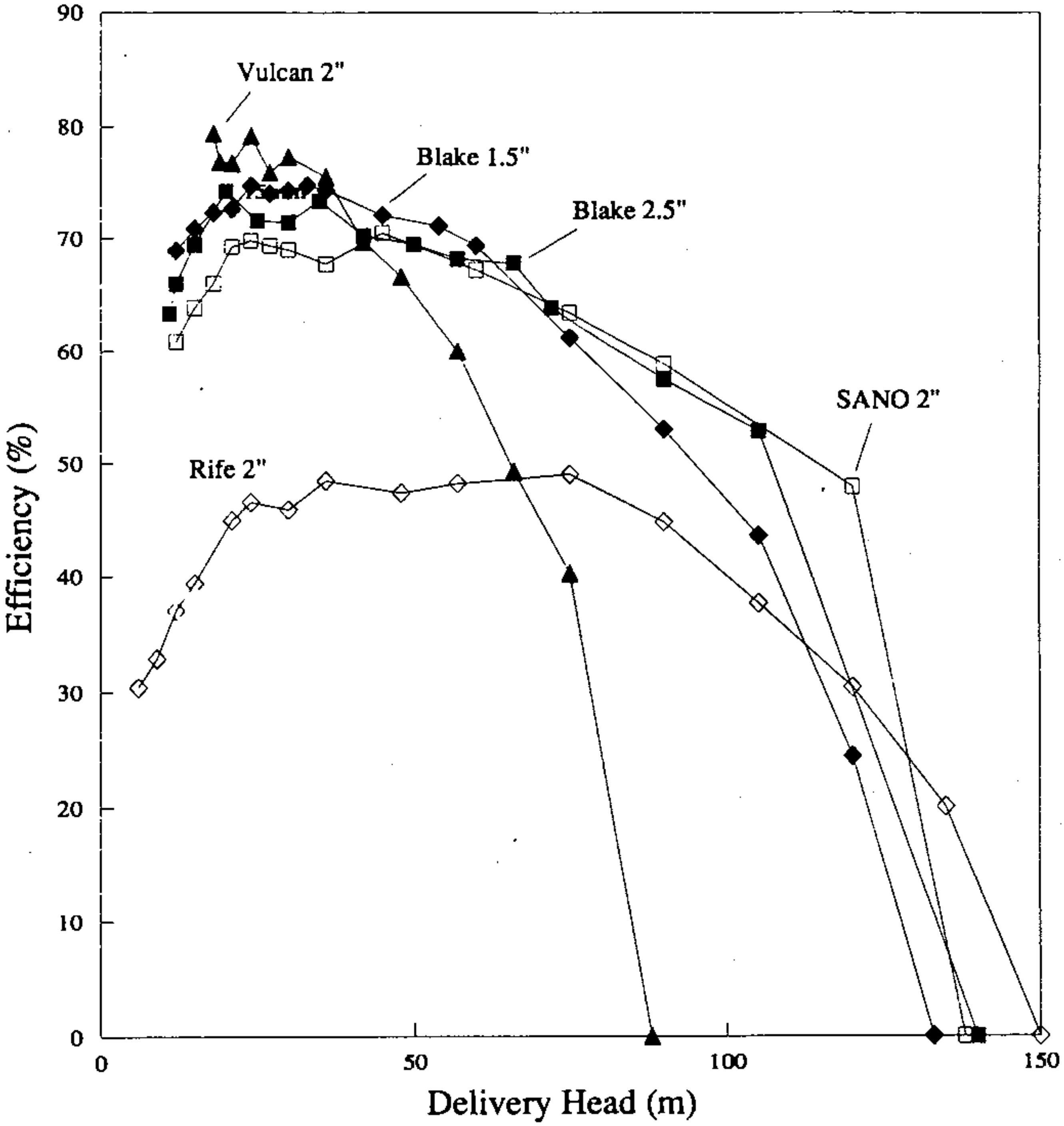
5) The Vulcan 2" has the lowest power output over its small range of delivery heads.

6) Blake 2½" is clearly the most powerful pump over its entire range.

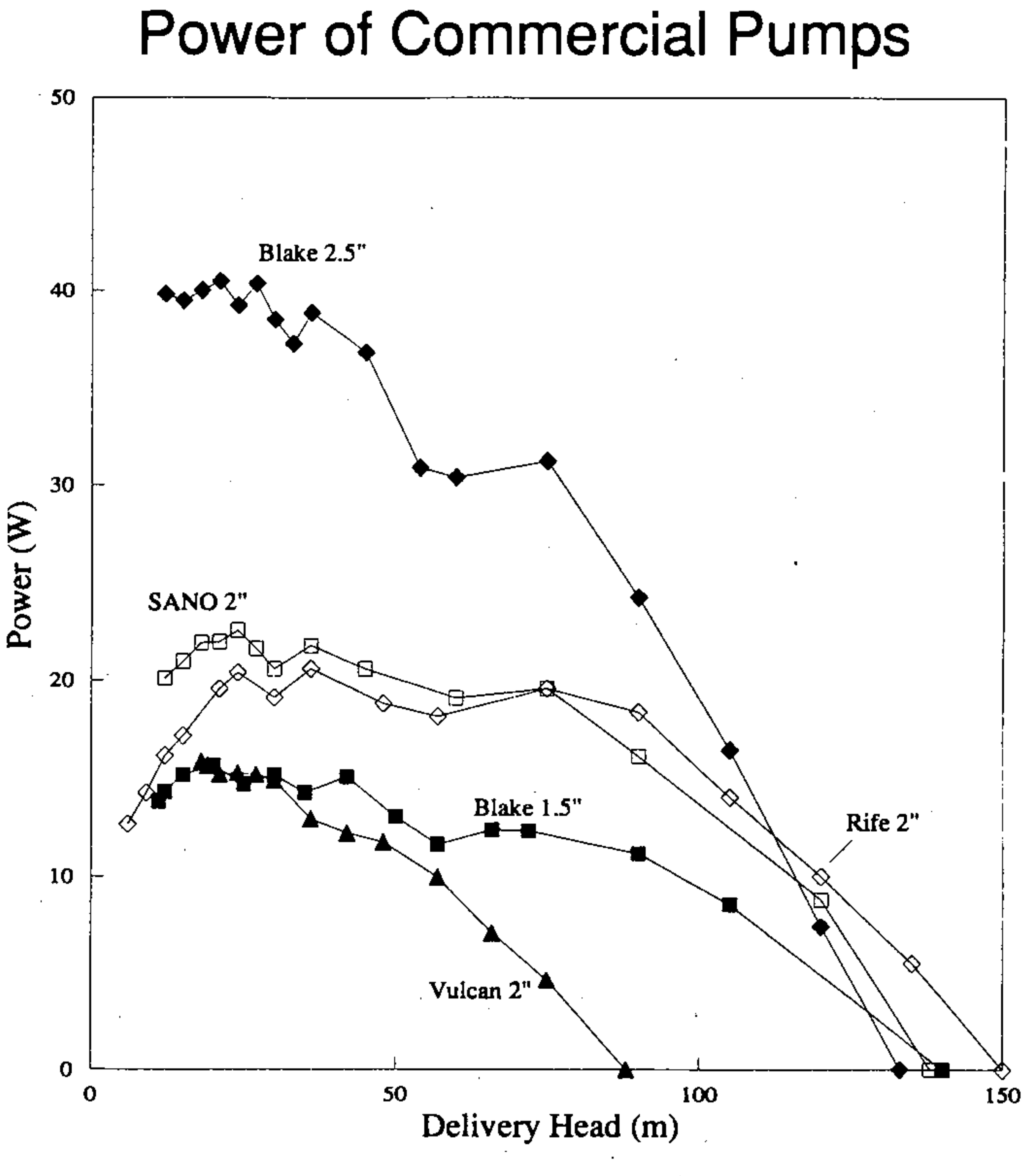
7) At low delivery heads (up to 75 m) the SANO 2" has a slightly higher output than the Rife 2" which above 75 m is better. However there is little to choose between them over the complete range of operation.

8) Attempting to combine both power and efficiency it would seem reasonable to conclude that the Blake 2½" offers the best overall performance. Of the remainder the SANO 2" would seem to be the best compromise.

# Efficiency of Commercial Pumps



GRAPH 2



Power of Commercial Pumps
Power (W)
Delivery Head (m)
50
40
30
20
10
0
0
50
100
150
Blake 2.5"
SANO 2"
Blake 1.5"
Rife 2"
Vulcan 2"

## 2.5 Non-Dimensional Comparison

Delft use a further means of pump comparison by graphically presenting the ratio of delivery to supply flow (q/Q) over a range of delivery to supply head (h/H) ratios. Thus a non dimensional comparison between pumps is possible. For any given head ratio the greater the ratio of flows the better the performace of the pump. Graph 3 shows these ratio curves for the five pumps chosen. Only two conclusions can sensibly be drawn from this comparison:

1) The Rife 2" is notably worse than all its rivals.

2) There is little to choose between all of the other makes of pump.

Despite this lack of obvious conclusions the ability to compare pumps using non dimensional parameters may prove valuable.

# 3. SUMMARY OF DTU TESTS

## 3.1 Experimental rig and procedure

The DTU has established performance testing rigs at the University to allow comprehensive analysis of prototype pumps. The major restrictions imposed by the rigs location are:

i) drive pipe length - limited to 10.5 m and horizontal
ii) drive head - restricted to 2, 3, 4 or 5 m

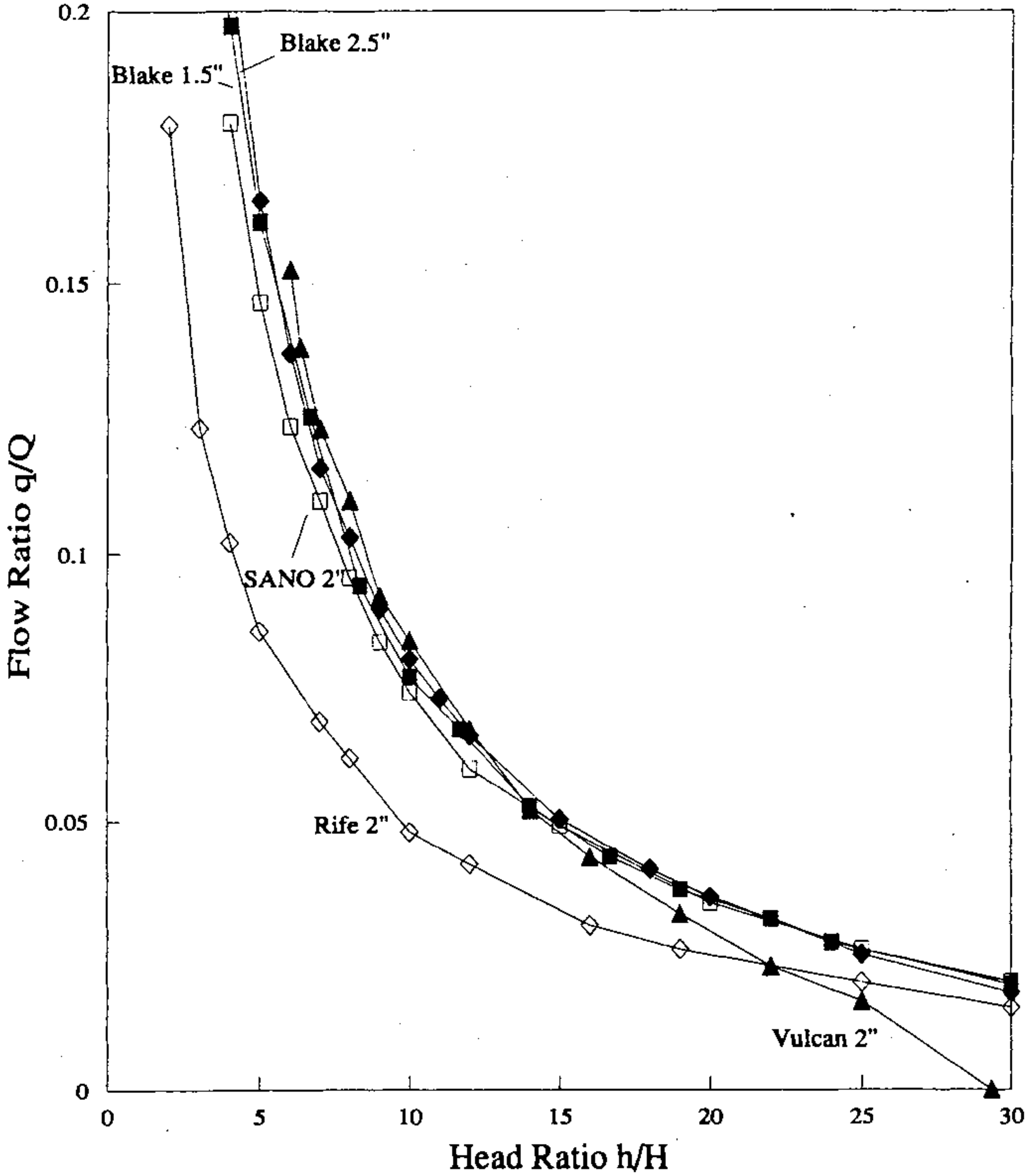
The delivery head is controlled using a needle valve providing an accurately variable orifice over which the desired head can be dropped (measured by a pressure guage). Both drive and delivery flows are measured by float type flow meters for fast and accurate readings.

For their tests Delft used three drive head setting, 1, 2 and 3 m. However for comparison between DTU and commercial pumps only one drive head was chosen (3.0 m).

## 3.2 Pump Tuning

The DTU pump design selected for testing was the Mark 6.4 which typically uses a 2" BSP drive pipe but also runs using 1½" pipe (see Figure 1). As the Delft work gives no clear indication of how pumps were tuned a series of results were recorded using different settings of the impulse valve. Low stroke, low weight settings generally give high efficiency and low power output. Up to a point it is also true to say that high stroke,

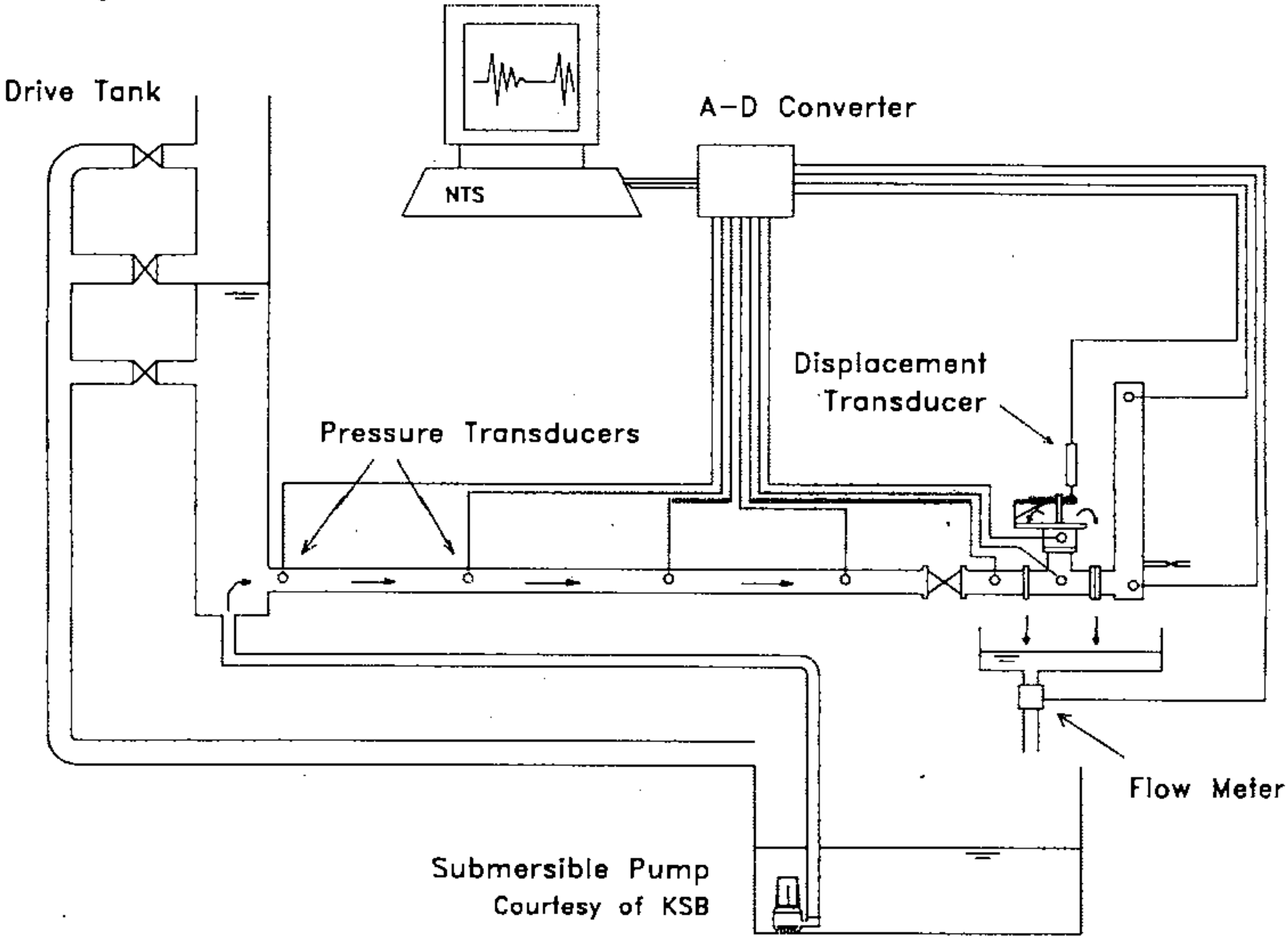
# Ratio Graph of Commercial Pumps



high weight settings give low efficiency and high output power.

Choosing which of these results are used to compare against the Delft ones is dealt with in Section 4.1.

Figure 1




3.3 Summary of test results

Table 5 gives a selection of results for identical conditions as those in Table 4 for the commercial pumps.

Graphs 4 and 5 show the variation in efficiency and power over the full range of potential delivery heads.

Graph 6 presents the non dimensional flow ratio to head ratio curves for these results.

The design of the M6.4 pump allows it to be tuned to suit a wide range of flow and head conditions, making one model applicable to many sites. The results show the wide range of efficiency and power obtainable under these given conditions and emphasize how important tuning can be. If drive water is limited then peak efficiency will be required to make best use of that available. If there is plenty of drive water pumps should be tuned to give maximum power output despite the lower efficiency of such a setting.

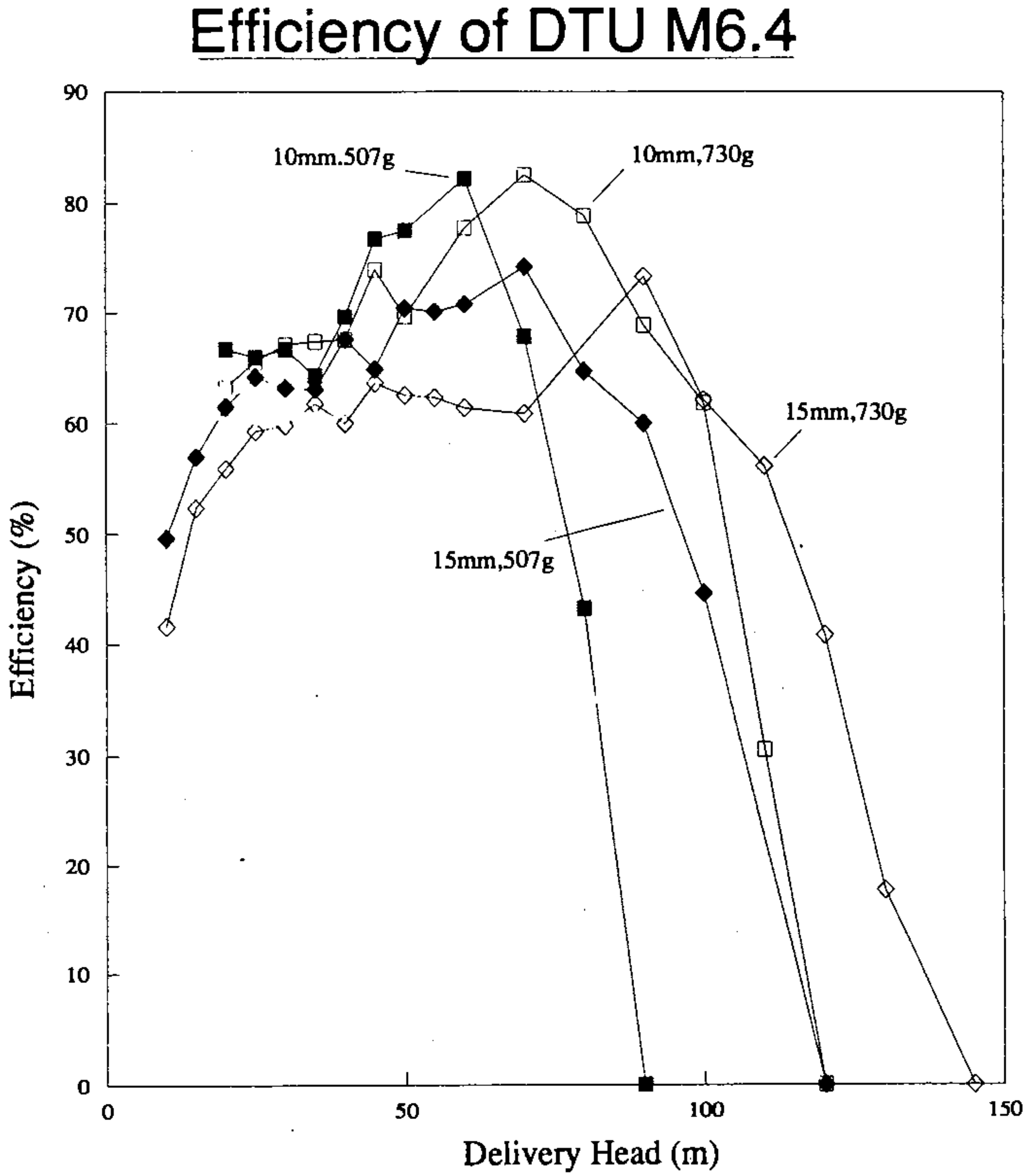
It is clear that both good efficiency and power are obtainable over a broad range of delivery heads and that the pump is capable of operating at very high head ratios.
The stroke of teh M6.4 design can range between 5 mm 40 mm with infinite adustment between these limits. The minimum weight of the valve assembly is 507g comprising the plug, stem, nuts etc. although recent modification to the pump enables further reduction. Maximum weight is limited by the physical dimensions but 1000g should be considered as the upper limit.

The results show for just a few combinations of stroke and weight how the efficiency and power output characteristics of the pump can be dramatically altered. Low stroke and weight give high efficiency but low power over a limited range of delivery heads whereas high stroke and weight give lower efficiency but high power output over a wider possible range of heads. Tuning of the pump to best suit any particular set of conditions is a complicated process to explain and is dealt with in other DTU literature.

TABLE 5 SUMMARY OF DTU M6.4 TEST RESULTS

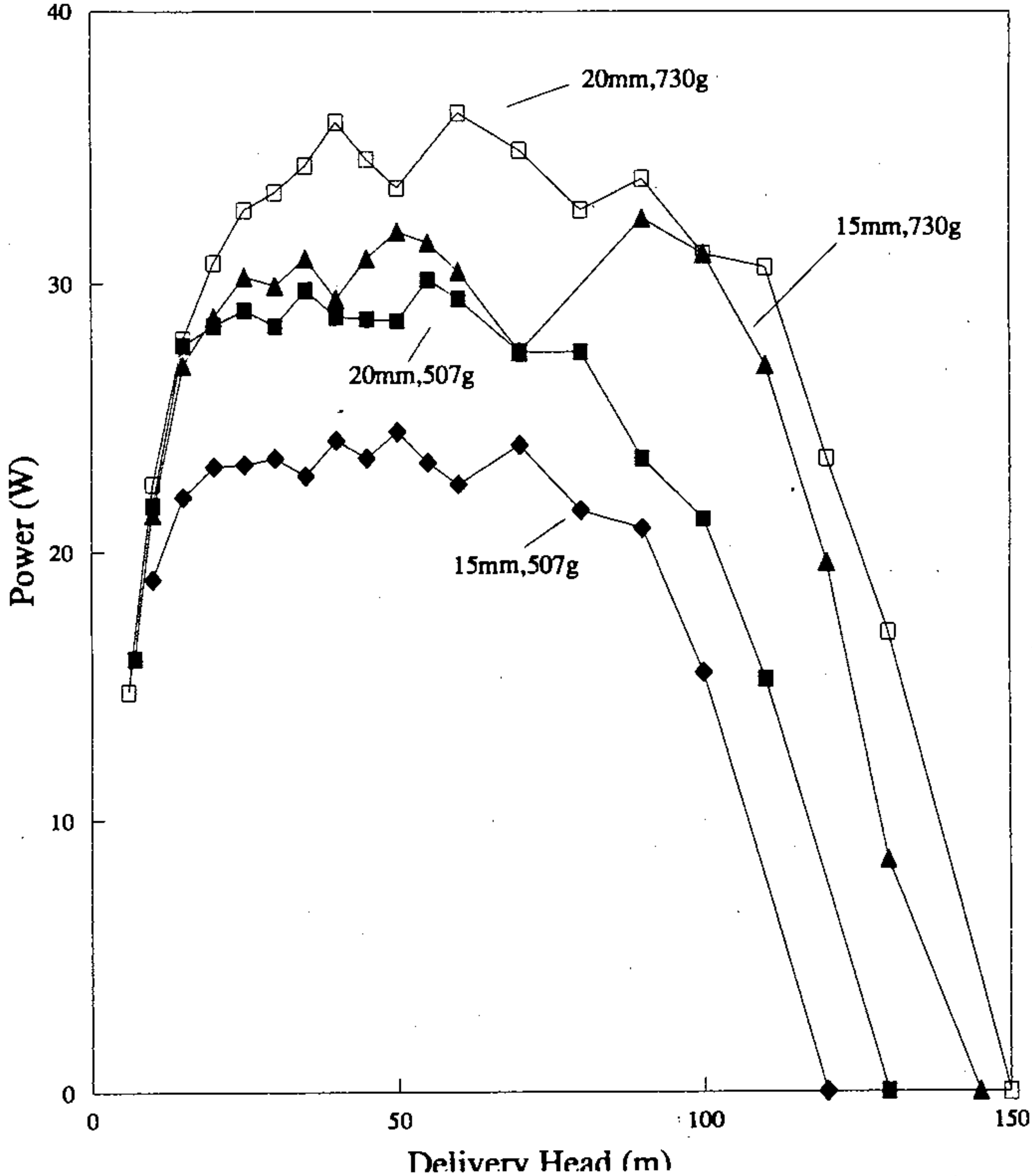
| | Pump Settings | | | Efficiency | | | Power | | |
|---|---|---|---|---|---|---|---|---|---|
| | Drive Pipe Dia(") | Stroke Length (mm) | Weight (g) | at 30m | at 60m | max | at 30m | at 60m | max |
| 1) | 1.5 | 10 | 507 | 68 | 83.3 | 88.9 | 16.7 | 17.2 | 18.3 |
| 2) | 1.5 | 15 | 507 | 59.7 | 64.8 | 68.7 | 22.6 | 22.6 | 24.6 |
| 3) | 1.5 | 20 | 507 | 50 | 54.7 | 60.4 | 24.5 | 25.5 | 28.1 |
| 4) | 2 | 10 | 507 | 66.7 | 82.2 | 82.2 | 15.7 | 18.1 | 18.1 |
| 5) | 2 | 15 | 507 | 63.2 | 70.8 | 74.2 | 23.5 | 22.6 | 24.5 |
| 6) | 2 | 20 | 507 | 58 | 62.5 | 65.9 | 28.5 | 29.4 | 30.1 |
| 7) | 2 | 10 | 730 | 67.1 | 77.8 | 82.6 | 24 | 24 | 27.5 |
| 8) | 2 | 15 | 730 | 59.8 | 61.4 | 73.3 | 30.2 | 30.4 | 32.4 |
| 9) | 2 | 20 | 730 | 51.9 | 58.7 | 61.6 | 33.4 | 36.3 | 36.3 |

GRAPH 4

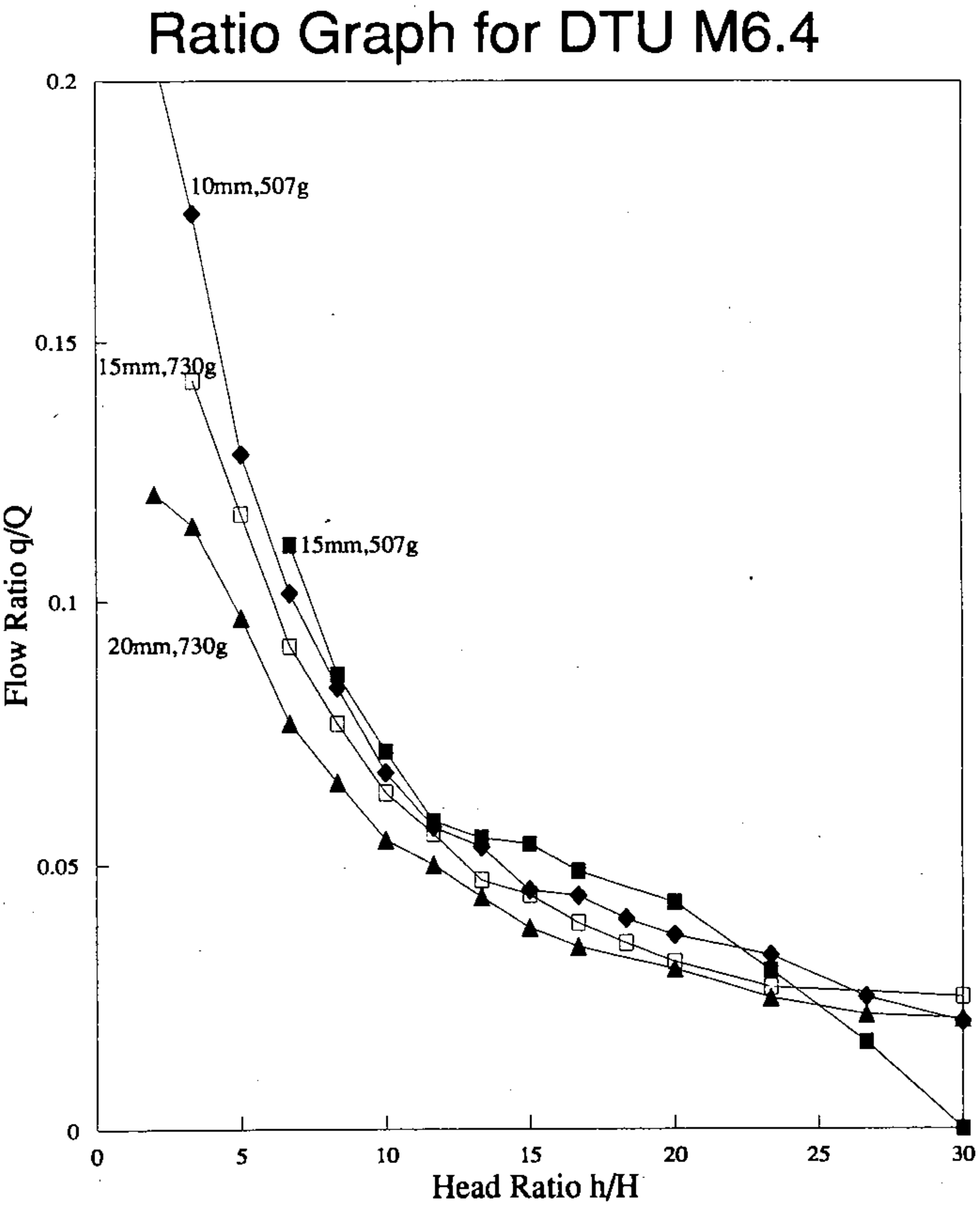


Efficiency of DTU M6.4
10mm.507g
10mm,730g
15mm,730g
15mm,507g
Efficiency (%)
Delivery Head (m)
0
10
20
30
40
50
60
70
80
90
0
50
100
150

# Power of DTU M6.4



GRAPH 6


Ratio Graph for DTU M6.4
Flow Ratio q/Q
Head Ratio h/H
0.2
0.15
0.1
0.05
0
5
10
15
20
25
30
10mm,507g
15mm,730g
15mm,507g
20mm,730g

## 4. COMPARISON OF DTU AND COMMERCIAL PUMPS

### 4.1 Problems in comparison

There are inevitably problems and potential inaccuracies in taking data from two separate sets of tests carried out on two different test rigs. The main areas of difficulty are outlined below along with some explanation of their significance and potential methods for overcoming them.

a) The drive pipe lengths of the two test rigs differ by 1.5 m with the Delft rig using an inclined pipe whereas the Warwick tests use a horizontal one. The length of the drive pipe of a hydraulic ram pump system affects (among other things) the time taken for pressure waves to traverse the length of the pipe, total friction in the system and the energy available for pumping. The exact effects of these parameters on pump performance are complicated to evaluate and given the relatively small difference can be assumed to have no major effect for the purposes of this comparison.

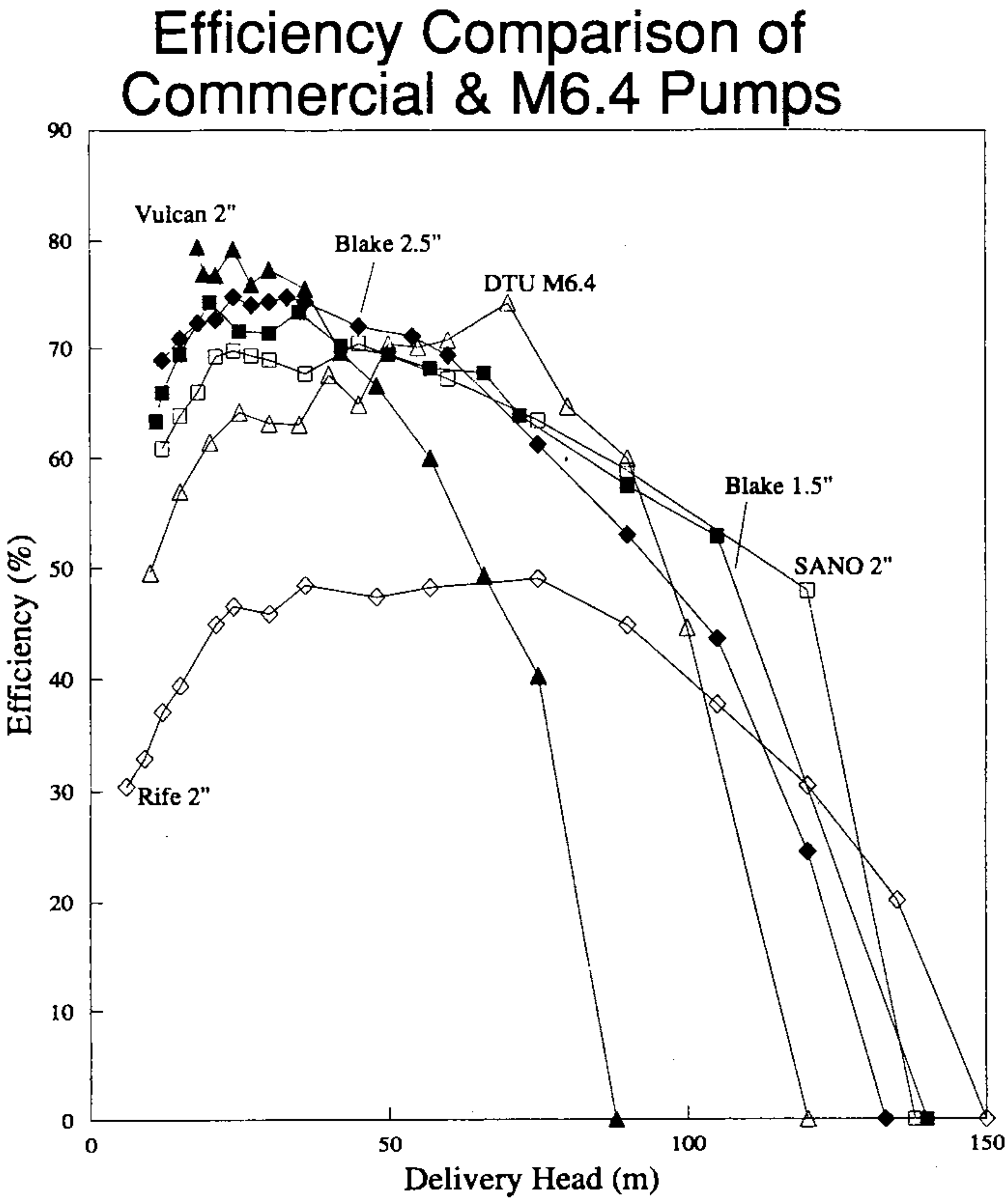
b) As has already been mentioned, the Delft work is unclear about the tuning of each of the pumps tested, other than the fact that they were left constant 'throughout testing once installed. To allow a sensible comparison it has been assumed that the commercial pumps tested by Delft were each set to some recommended point that gave a reasonable efficiency and power output across a broad range of conditions. In order to compare the DTU pump a best average setting from those taken has been chosen and also comparisons of the optimum settings for efficiency and power. The setting chosen for the general comparison is labelled as No. 5 in Table 5 using a standard 2" drive pipe, a valve stroke of 15 mm and weight of 507 g.

### 4.2 Efficiency comparisons

The efficiency of the DTU pump is of the same order as the better of the commercial models. Graph 7 shows the chosen average and peak efficiency settings of M6.4 against the 5 commercial pumps.

In a typical operating range say 20-80 m the DTU average setting gives efficiencies ranging between approx 63% and 74%. The DTU peak setting of those chosen returns results for the same range between 64% and 83%. Detailing the comparison between these settings and those for the commercial models is best don visually. The main points that can be drawn are:

GRAPH 7


Efficiency Comparison of
Commercial & M6.4 Pumps
Vulcan 2"
Blake 2.5"
DTU M6.4
Blake 1.5"
SANO 2"
Rife 2"
Efficiency (%)
Delivery Head (m)
0
10
20
30
40
50
60
70
80
90
0
50
100
150

a) The Blakes machines have the best efficiency over the widest range of delivery heads with between 62% and 75% in the 20-80 m operating band. This is very similar the DTU average setting although the shape of the curves is somewhat different giving maximum and minimum efficiencies at different heads.

b) The DTU M6.4 pump has a markedly different efficiency profile from all the commercial models with peak efficiency occurring at much higher heads.

c) The DTU M6.4 is capable of operating over a range of delivery heads as great as any of the commercial models.

Separate tests to determine the peak efficiency of the M6.4 have shown that it is capable of running at efficiencies of over 90%.

### 4.3 <u>Power Comparison</u>

Graph 8 shows the chosen average and peak power settings for the M6.4 against the 5 commercial pumps.

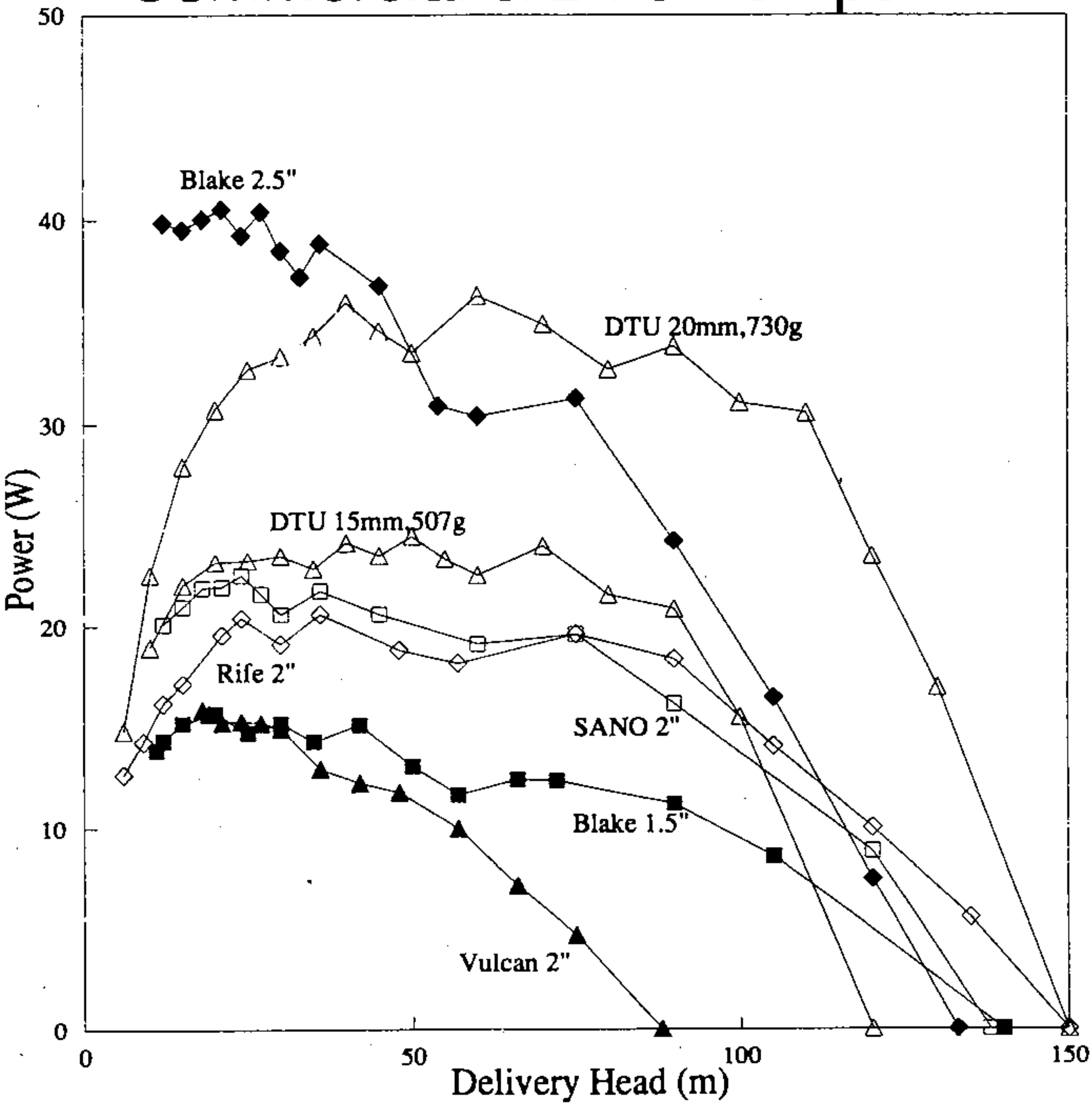
a) The average setting of the DTU M6.4 is clearly more powerful over a very wide range of delivery heads than all of the commercial models of the same size. The Blake 2½" model is clearly more powerful as should be expected from this considerably larger capacity pump.

b) The peak setting of the M6.4 used gives power output similar to and, at higher heads, better than even the Blake 2½" model. Increased weight on the M6.4 would further increase the power output although the limitation of the pipe size and drive head would probably limit peak power to around 40 watts.

## 5. <u>COST COMPARISON</u>

Table 2 in section 2.1 shows the costs of 10 rams in US$ in 1982 as given by Delft. These costs are for the pumps alone with no drive pipe, delivery pipe, shipping etc. included, and range from US$ 1000 to 3500. No updated prices are available for comparison with the DTU pump so an annual inflation rate of 5% has been assumed. A comparative cost for the DTU pumps is hard to ascertain as they have only been manufactured as one-off prototypes to date in the UK. The design of all the DTU pumps is intended to allow manufacture in the country of use, avoiding any shipping and importation problems but working to the constraints imposed in non-industrialised areas.

# Power Comparison of Commercial & DTU Pumps



The Baptist Community of Western Zaire (CBZO) have a village water supply programme installing the DTU M6.4 in its rural areas. Currently the manufacture of these pumps is being contracted to a workshop in Kinshasa who are producing them in small batches as requested. The total cost of these units in Zaire is approx. US$450 but once proper manufacture has started it is estimated that this will reduce to $250-$300.

The actual cost to an end user in a developing country of a ram pump will include any shipping and importation costs if it is made eslewhere. To accurately compare the DTU pumps made in country with imported commercial models the costs associated with transportation should be included. However such costs are so dependant upon the shipping distance, customs duties etc. that they would be impossible to estimate with any accuracy.

Table 6 takes the information from Table 2 and adds to the costs an allowance for inflation. It also includes information about the DTU Mark 6.4 pump for the conditions specified by Delft. The information concerning expected delivery flow was arrived at by projecting measured performance figures for different conditions. The DTU is in the process of developing a sophisticated computer simulation and model which are being used in pump analysis and will form the basis of comprehensive design charts. Ultimately this will be able to predict the performance of any pump that has been suitably calibrated under any set of conditions with a good degree of accuracy.

The predicted performance of the DTU pump ranks it 5th in terms of delivery flow and efficiency. The comparison of costs shows the vast difference in the price of the pumping unit and the cost per litre delivered. This illustrates the legitimacy of the approach of producing high performance pumps at low cost in the country of use. If a true comparison to include transportation costs were made the results would clearly be more conclusive still.

TABLE 6 - COST COMPARISON

| Type of Hydraulic Ram | Pumping Rate q [l/min] | Efficiency (Trade) [%] | Approx Price for Ram Alone [US$-1982] | Cost per litre delivered | Rank |
|---|---|---|---|---|---|
| Vulcan 21/2 | 6.10 | 68 | 1800 | 295 | 4 |
| Blake Hydram 31/2 | 6.00 | 67 | 1500 | 250 | 3 |
| Sano No. 5/65 mm | 6.95 | 77 | 1500 | 216 | 2 |
| Rife 20 HDU | 5.40 | 60 | 1650 | 306 | 5 |
| Schlumpf 5A23 | 5.50 | 61 | 4050 | 737 | 9 |
| Alto CH 66-110-18 | 5.40 | 60 | 3150 | 584 | 7 |
| Briau D4 | 5.40 | 60 | 4800 | 890 | 11 |
| CeCoCo - H50 | 6.90 | 77 | 5250 | 761 | 10 |
| WAMA No. 6 | 4.50 | 50 | 2250 | 500 | 6 |
| BZH-Ram W6 | 2.70 | 30 | 1800 | 666 | 8 |
| DTU M6.4 2" | 5.5 | 65 | 300 | 55 | 1 |

## 6. SUMMARY OF CONCLUSION

The following points summarise the conclusions that can be drawn from these tests.

a) The DTU Mark 6.4 pump gives efficiencies comparable with the more efficient commercial pumps over a wide range of condition.

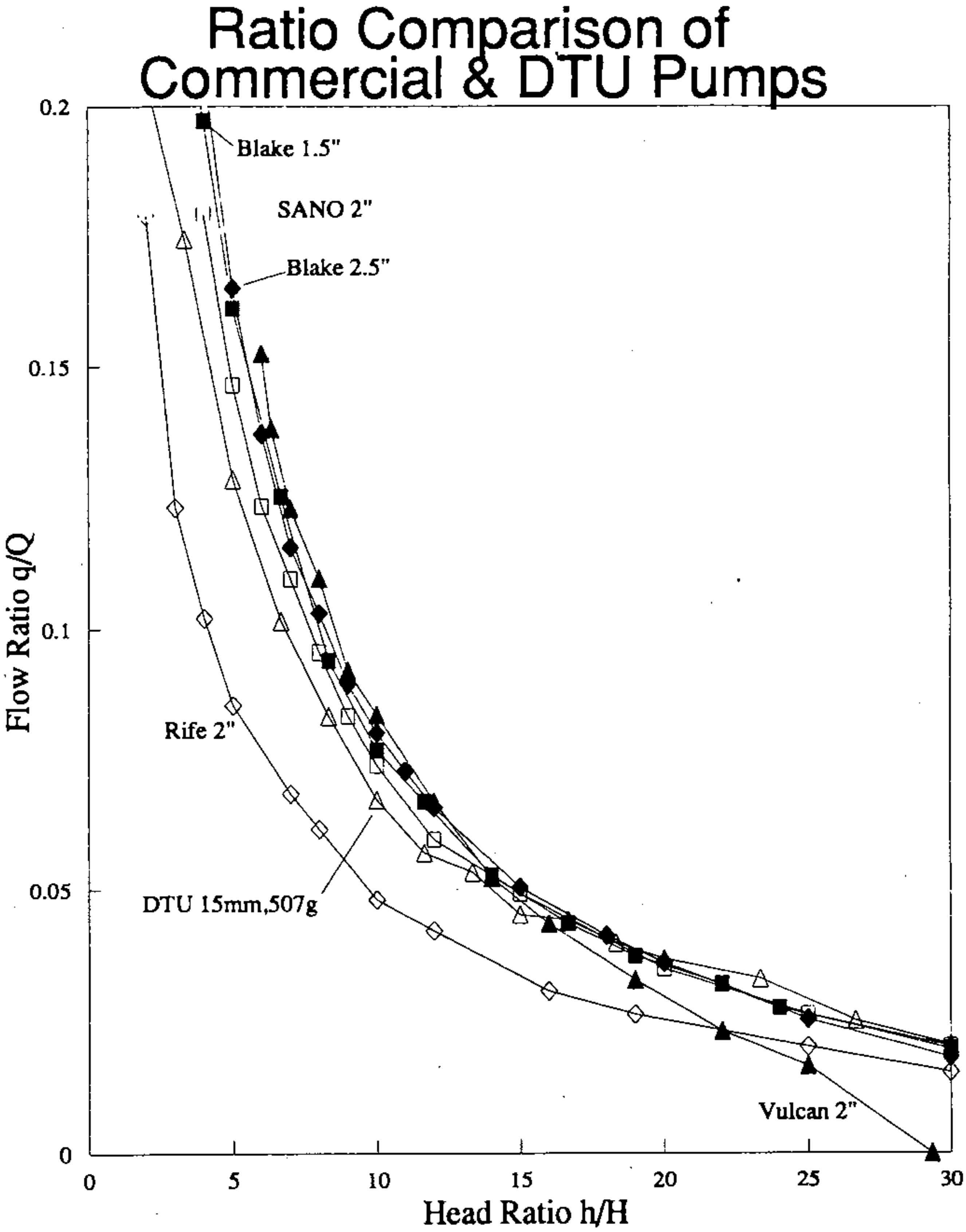
b) The M.6.4 produces a higher output power than all commercial models of the same size over a wide range of conditions.

c) The M6.4 has a cost to output ratio considerably lower than all of its commercial rivals.

The tests show that it is possible to produce simple and comparatively cheap hydraulic ram pumps that can match and exceed the performance of commericial models. Whilst endurance tests to date indicate that the DTU pumps are likely to exhibit adequate durability no data is yet available for a long term comparison with commercial rivals. The current design specification is to produce low maintenance pumps whose steel components have a 10 year life and rubber components last approximately 6 months.

More detailed information concerning the design, manufacture, installation and performace of DTU pumps is available on request.

GRAPH 9



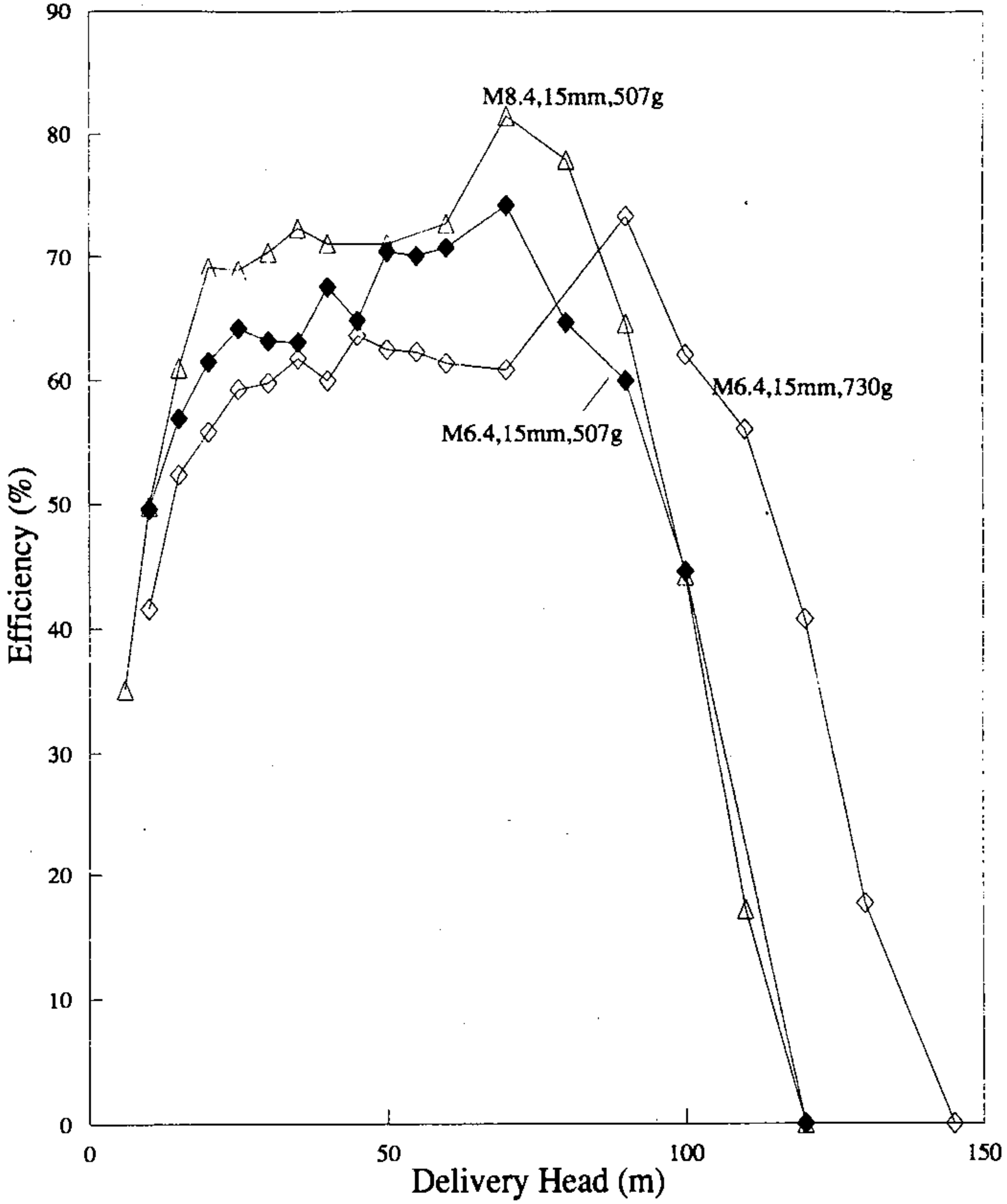
Ratio Comparison of Commercial & DTU Pumps
Blake 1.5"
SANO 2"
Blake 2.5"
Rife 2"
DTU 15mm,507g
Vulcan 2"
Flow Ratio q/Q
Head Ratio h/H
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30

Appendix A **CONTINUING DTU PUMP DEVELOPMENT**

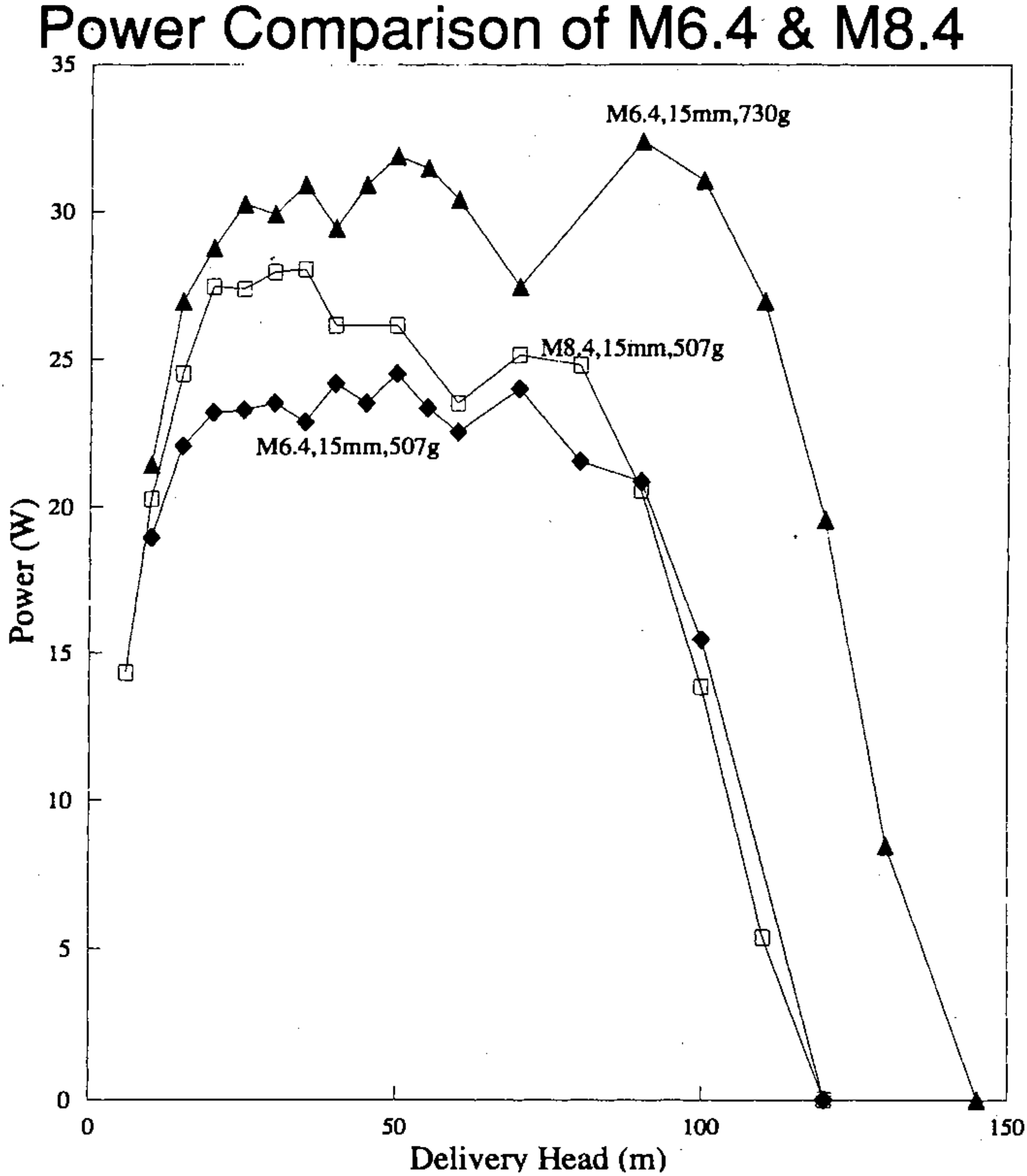
The Mark 6.4 pump was set as a DTU standard in 1990 to allow organisations interested in using the pummp to have a standard model to work with. Since that time a number of developments have occurred in the on-going research programme and new design initiatives produced. One such is the development of the Mark 8.4 that uses the same valves as the M6.4 but replaces the 2" fittings used in the pump body witha body of 4" velded construction. This alteration dramatically reduces the peak overpressure experienced the system, damps out the high frequency oscillations experienced during the cycle and increases both the efficiency and power output for any given set of conditions.

Graphs 10 and 11 allow comparison of the M8.4 with the M6.4 under identical conditions.

# Efficiency Comparison of M6.4 & M8.4



GRAPH 11



Power Comparison of M6.4 & M8.4
M6.4,15mm,730g
M8.4,15mm,507g
M6.4,15mm,507g
Power (W)
Delivery Head (m)
0
5
10
15
20
25
30
35
0
50
100
150

Appendix B **TABLES OF PERFORMANCE RESULTS**

Tablulated results used in production of Graphs.

The following pages list the information supplied by Delft and that gained under similar conditions on the DTU pump. In all cases the **Supply Head = 3m.**

1) Blake Hydram No2 Drive pipe dia = 1.5" Supply Head = 3.00m

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 11 | 3.666667 | 0.686 | 7.7 | 36.9 | 0.208672 | 55.64589 | 63.30344 | 13.84845 |
| 12 | 4 | 0.686 | 7.3 | 37 | 0.197297 | 59.18919 | 65.91422 | 14.3226 |
| 15 | 5 | 0.663 | 6.2 | 38.45 | 0.161248 | 64.49935 | 69.42889 | 15.2055 |
| 20 | 6.666667 | 0.667 | 4.8 | 38.3 | 0.125326 | 71.01828 | 74.24594 | 15.696 |
| 25 | 8.333333 | 0.669 | 3.6 | 38.3 | 0.093995 | 68.9295 | 71.59905 | 14.715 |
| 30 | 10 | 0.645 | 3.1 | 40.3 | 0.076923 | 69.23077 | 71.42857 | 15.2055 |
| 35 | 11.66667 | 0.683 | 2.5 | 37.25 | 0.067114 | 71.58837 | 73.37526 | 14.30625 |
| 42 | 14 | 0.64 | 2.2 | 41.65 | 0.052821 | 68.66747 | 70.23945 | 15.1074 |
| 50 | 16.66667 | 0.696 | 1.6 | 36.8 | 0.043478 | 68.11594 | 69.44444 | 13.08 |
| 57 | 19 | 0.737 | 1.25 | 33.6 | 0.037202 | 66.96429 | 68.14921 | 11.64938 |
| 66 | 22 | 0.714 | 1.15 | 36.2 | 0.031768 | 66.71271 | 67.73762 | 12.40965 |
| 72 | 24 | 0.695 | 1.05 | 38.4 | 0.027344 | 62.89062 | 63.87833 | 12.3606 |
| 90 | 30 | 0.697 | 0.76 | 38.9 | 0.019537 | 56.6581 | 57.48865 | 11.1834 |
| 105 | 35 | 0.758 | 0.5 | 32.6 | 0.015337 | 52.14724 | 52.87009 | 8.58375 |
| 140 | 46.66667 | | 0 | | 0 | 0 | 0 | 0 |

2) Blake Hydram No 3.5 Drive pipe dia = 2.5" Supply Head = 3.00m

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 12 | 4 | 0.671 | 20.3 | 97.6 | 0.207992 | 62.39754 | 68.87193 | 39.8286 |
| 15 | 5 | 0.664 | 16.1 | 97.5 | 0.165128 | 66.05128 | 70.86268 | 39.48525 |
| 18 | 6 | 0.657 | 13.6 | 99.2 | 0.137097 | 68.54839 | 72.34043 | 40.0248 |
| 21 | 7 | 0.646 | 11.8 | 101.9 | 0.1158 | 69.47988 | 72.64732 | 40.5153 |
| 24 | 8 | 0.667 | 10 | 97 | 0.103093 | 72.16495 | 74.76636 | 39.24 |
| 27 | 9 | 0.633 | 9.15 | 102.1 | 0.089618 | 71.69442 | 74.02247 | 40.39268 |
| 30 | 10 | 0.664 | 7.85 | 97.8 | 0.080266 | 72.23926 | 74.30194 | 38.50425 |
| 33 | 11 | 0.686 | 6.9 | 94.6 | 0.072939 | 72.93869 | 74.77833 | 37.22895 |
| 36 | 12 | 0.652 | 6.6 | 100 | 0.066 | 72.6 | 74.29644 | 38.8476 |
| 45 | 15 | 0.672 | 5 | 99.1 | 0.050454 | 70.63572 | 72.04611 | 36.7875 |
| 54 | 18 | 0.735 | 3.5 | 85.1 | 0.041128 | 69.91774 | 71.10609 | 30.9015 |
| 60 | 20 | 0.727 | 3.1 | 86.3 | 0.035921 | 68.25029 | 69.35123 | 30.411 |
| 75 | 25 | 0.644 | 2.55 | 101.5 | 0.025123 | 60.29557 | 61.26862 | 31.26938 |
| 90 | 30 | 0.697 | 1.65 | 91.7 | 0.017993 | 52.18103 | 53.02625 | 24.27975 |
| 105 | 35 | 0.761 | 0.96 | 76.1 | 0.012615 | 42.89093 | 43.60239 | 16.4808 |
| 120 | 40 | 0.828 | 0.38 | 61.7 | 0.006159 | 24.01945 | 24.48454 | 7.4556 |
| 133 | 44.33333 | 0.88 | 0 | 50.3 | 0 | 0 | 0 | 0 |

3) Vulcan 2"    Drive pipe dia = 2"    Supply Head = 3.00m

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 18 | 6 | 0.422 | 5.4 | 35.4 | 0.152542 | 76.27119 | 79.41176 | 15.8922 |
| 19 | 6.333333 | 0.41 | 5.05 | 36.55 | 0.138167 | 73.68901 | 76.88301 | 15.68783 |
| 21 | 7 | 0.425 | 4.44 | 36.05 | 0.123162 | 73.89736 | 76.75969 | 15.24474 |
| 24 | 8 | 0.428 | 3.9 | 35.5 | 0.109859 | 76.90141 | 79.18782 | 15.3036 |
| 27 | 9 | 0.413 | 3.45 | 37.45 | 0.092123 | 73.69826 | 75.91687 | 15.23003 |
| 30 | 10 | 0.42 | 3.05 | 36.4 | 0.083791 | 75.41209 | 77.31305 | 14.96025 |
| 36 | 12 | 0.455 | 2.2 | 32.75 | 0.067176 | 73.89313 | 75.53648 | 12.9492 |
| 42 | 14 | 0.445 | 1.78 | 34 | 0.052353 | 68.05882 | 69.64785 | 12.22326 |
| 48 | 16 | 0.44 | 1.5 | 34.55 | 0.043415 | 65.12301 | 66.5742 | 11.772 |
| 57 | 19 | 0.453 | 1.07 | 32.8 | 0.032622 | 58.71951 | 60.02362 | 9.971865 |
| 66 | 22 | 0.481 | 0.66 | 28.8 | 0.022917 | 48.125 | 49.28717 | 7.12206 |
| 75 | 25 | 0.522 | 0.38 | 23.2 | 0.016379 | 39.31034 | 40.28838 | 4.65975 |
| 88 | 29.33333 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

4) SANO No4 2"    Drive pipe dia = 2"    Supply Head = 3.00m

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 12 | 4 | 0.656 | 10.25 | 57.1 | 0.17951 | 53.85289 | 60.87602 | 20.1105 |
| 15 | 5 | 0.645 | 8.55 | 58.4 | 0.146404 | 58.56164 | 63.85362 | 20.96888 |
| 18 | 6 | 0.622 | 7.45 | 60.3 | 0.123549 | 61.77446 | 65.97786 | 21.92535 |
| 21 | 7 | 0.641 | 6.4 | 58.3 | 0.109777 | 65.86621 | 69.24266 | 21.9744 |
| 24 | 8 | 0.618 | 5.75 | 60.15 | 0.095594 | 66.91604 | 69.80273 | 22.563 |
| 27 | 9 | 0.633 | 4.9 | 58.7 | 0.083475 | 66.78024 | 69.33962 | 21.63105 |
| 30 | 10 | 0.648 | 4.2 | 56.7 | 0.074074 | 66.66667 | 68.96552 | 20.601 |
| 36 | 12 | 0.608 | 3.7 | 61.9 | 0.059774 | 65.75121 | 67.68293 | 21.7782 |
| 45 | 15 | 0.653 | 2.8 | 58.8 | 0.049296 | 69.01408 | 70.4698 | 20.601 |
| 60 | 20 | 0.663 | 1.95 | 56.1 | 0.034759 | 66.04278 | 67.18346 | 19.1295 |
| 75 | 25 | 0.613 | 1.6 | 61.45 | 0.026037 | 62.48983 | 63.44171 | 19.62 |
| 90 | 30 | 0.665 | 1.1 | 54.95 | 0.020018 | 58.05278 | 58.876 | 16.1865 |
| 120 | 40 | 0.798 | 0.45 | 37.1 | 0.012129 | 47.30458 | 47.93609 | 8.829 |
| 138 | 46 | | 0 | | 0 | 0 | 0 | 0 |

5) Rife 20HDU 2"    Drive pipe dia = 2"    Supply Head = 3.00m

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 6 | 2 | 0.965 | 12.9 | 72 | 0.179167 | 17.91667 | 30.38869 | 12.6549 |
| 9 | 3 | 0.882 | 9.7 | 78.7 | 0.123253 | 24.65057 | 32.91855 | 14.27355 |
| 12 | 4 | 0.865 | 8.25 | 80.8 | 0.102104 | 30.63119 | 37.05783 | 16.1865 |
| 15 | 5 | 0.853 | 7 | 81.85 | 0.085522 | 34.20892 | 39.39223 | 17.1675 |
| 21 | 7 | 0.847 | 5.7 | 83.1 | 0.068592 | 41.15523 | 44.93243 | 19.57095 |
| 24 | 8 | 0.828 | 5.2 | 84.2 | 0.061758 | 43.2304 | 46.53244 | 20.4048 |
| 30 | 10 | 0.858 | 3.9 | 81.1 | 0.048089 | 43.2799 | 45.88235 | 19.1295 |
| 36 | 12 | 0.835 | 3.5 | 83.25 | 0.042042 | 46.24625 | 48.41499 | 20.601 |
| 48 | 16 | 0.866 | 2.4 | 78.7 | 0.030496 | 45.74333 | 47.34895 | 18.8352 |
| 57 | 19 | 0.89 | 1.95 | 74.9 | 0.026035 | 48.86248 | 48.2108 | 18.17303 |
| 75 | 25 | 0.858 | 1.6 | 80 | 0.02 | 48 | 49.01961 | 19.62 |
| 90 | 30 | 0.84 | 1.25 | 82.4 | 0.01517 | 43.99272 | 44.82965 | 18.39375 |
| 105 | 35 | 0.888 | 0.82 | 75.3 | 0.01089 | 37.02523 | 37.70363 | 14.07735 |
| 120 | 40 | 0.947 | 0.51 | 66.5 | 0.007669 | 29.90977 | 30.44322 | 10.0062 |
| 135 | 45 | 0.999 | 0.25 | 55.75 | 0.004484 | 19.73094 | 20.08929 | 5.518125 |
| 154 | 51.33333 | | 0 | | 0 | 0 | 0 | 0 |

6) DTU M6.4 2" 1.5" Drive pipe Stroke = 10mm Weight 507g

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 8 | 2.666667 | 0.965 | 10 | 52 | 0.238095 | 39.68254 | 43.01075 | 13.08 |
| 12 | 4 | | 8.1 | 51 | 0.188811 | 56.64336 | 54.82234 | 15.8922 |
| 15 | 5 | | 6.8 | 52 | 0.150442 | 60.17699 | 57.82313 | 16.677 |
| 20 | 6.666667 | | 5.2 | 51 | 0.113537 | 64.3377 | 61.68446 | 17.004 |
| 25 | 8.333333 | | 4.2 | 52 | 0.087866 | 64.43515 | 62.27758 | 17.1675 |
| 30 | 10 | | 3.4 | 50 | 0.072961 | 65.66524 | 63.67041 | 16.677 |
| 35 | 11.66667 | | 3 | 51 | 0.0625 | 66.66667 | 64.81481 | 17.1675 |
| 40 | 13.33333 | | 2.4 | 48 | 0.052632 | 64.91228 | 63.49206 | 15.696 |
| 45 | 15 | | 2.2 | 48 | 0.048035 | 67.24891 | 65.73705 | 16.1865 |
| 50 | 16.66667 | | 2.1 | 47 | 0.046771 | 73.27394 | 71.2831 | 17.1675 |
| 56 | 18.66667 | | 2 | 42 | 0.05 | 88.33333 | 84.84848 | 18.312 |
| 60 | 20 | | 1.75 | 42 | 0.043478 | 82.6087 | 80 | 17.1675 |
| 70 | 23.33333 | | 1.2 | 42 | 0.029412 | 65.68627 | 64.81481 | 13.734 |
| 80 | 26.66667 | | 0.6 | 41 | 0.014851 | 38.11881 | 38.46154 | 7.848 |
| 90 | 30 | | 0 | 40 | 0 | 0 | 0 | 0 |

7) DTU M6.4 2" Drive pipe 1.5" Stroke 15mm Weight 507g

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 7 | 2.333333 | 0.965 | 14.5 | 77 | 0.232 | 30.93333 | 36.97632 | 16.59525 |
| 10 | 3.333333 | | 11.7 | 79 | 0.173846 | 40.56464 | 42.9989 | 19.1295 |
| 15 | 5 | | 9 | 79 | 0.128571 | 51.42857 | 51.13636 | 22.0725 |
| 20 | 6.666667 | | 7 | 78 | 0.098592 | 55.86854 | 54.90196 | 22.89 |
| 25 | 8.333333 | | 5.5 | 78 | 0.075862 | 55.63218 | 54.89022 | 22.48125 |
| 30 | 10 | | 4.6 | 77 | 0.063538 | 57.18232 | 56.37255 | 22.563 |
| 35 | 11.66667 | | 4.05 | 77 | 0.055517 | 59.21864 | 58.29735 | 23.17613 |
| 40 | 13.33333 | | 3.4 | 74 | 0.048159 | 59.39566 | 58.5702 | 22.236 |
| 45 | 15 | | 3.1 | 76 | 0.042524 | 59.53361 | 58.78635 | 22.80625 |
| 50 | 16.66667 | | 2.8 | 74 | 0.039326 | 61.61049 | 60.76389 | 22.89 |
| 55 | 18.33333 | | 2.5 | 71 | 0.036496 | 63.26034 | 62.35828 | 22.48125 |
| 60 | 20 | | 2.3 | 71 | 0.033479 | 63.6099 | 62.7558 | 22.563 |
| 70 | 23.33333 | | 2.15 | 73 | 0.030346 | 67.77229 | 66.75538 | 24.60675 |
| 80 | 26.66667 | | 1.75 | 68 | 0.026415 | 67.79874 | 66.90562 | 22.89 |
| 90 | 30 | | 1.35 | 62 | 0.022259 | 64.5507 | 63.93054 | 19.86525 |
| 100 | 33.33333 | | 1.15 | 61 | 0.019215 | 62.12754 | 61.67873 | 18.8025 |
| 110 | 36.66667 | | 0.7 | 60 | 0.011804 | 42.1023 | 42.28446 | 12.5895 |
| 120 | 40 | | 0 | 58 | 0 | 0 | 0 | 0 |

8) DTU M6.4 2" Drive pipe 1.5" Stroke 20mm Weight 507g

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 6 | 2 | 0.965 | 13.5 | 101 | 0.154286 | 15.42857 | 23.58079 | 13.2435 |
| 10 | 3.333333 | | 11.8 | 100 | 0.133787 | 31.21693 | 35.18187 | 19.293 |
| 15 | 5 | | 9.4 | 100 | 0.103753 | 41.5011 | 42.96161 | 23.0535 |
| 20 | 6.666667 | | 7.2 | 100 | 0.077586 | 43.96552 | 44.77612 | 23.544 |
| 25 | 8.333333 | | 6 | 100 | 0.06383 | 46.80851 | 47.16981 | 24.525 |
| 30 | 10 | | 4.9 | 98 | 0.052632 | 47.36842 | 47.61905 | 24.0345 |
| 35 | 11.66667 | | 4.2 | 98 | 0.044776 | 47.76119 | 47.94521 | 24.0345 |
| 40 | 13.33333 | | 3.9 | 100 | 0.040583 | 50.05203 | 50.04812 | 25.506 |
| 45 | 15 | | 3.5 | 98 | 0.037037 | 51.85185 | 51.72414 | 25.75125 |
| 50 | 16.66667 | | 3.25 | 97 | 0.034667 | 54.31111 | 54.03159 | 26.56875 |
| 55 | 18.33333 | | 2.9 | 96 | 0.031149 | 53.99212 | 53.758 | 26.07825 |
| 60 | 20 | | 2.6 | 95 | 0.028139 | 53.4632 | 53.27869 | 25.506 |
| 70 | 23.33333 | | 2.3 | 94 | 0.025082 | 56.01599 | 55.72863 | 26.3235 |
| 80 | 26.66667 | | 2.15 | 95 | 0.023156 | 59.43278 | 59.01527 | 28.122 |
| 90 | 30 | | 1.7 | 93 | 0.01862 | 53.99781 | 53.85428 | 25.0155 |
| 100 | 33.33333 | | 1.3 | 90 | 0.014656 | 47.3882 | 47.46258 | 21.255 |
| 125 | 41.66667 | | 0 | 0 | 0 | 0 | 0 | 0 |

9) DTU M6.4 2" Drive pipe 2" Stroke 20mm Weight 507g

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 7 | 2.333333 | 0.965 | 14 | 108 | 0.148936 | 19.85816 | 26.77596 | 16.023 |
| 10 | 3.333333 | | 13.3 | 108 | 0.140444 | 32.77015 | 36.5485 | 21.7455 |
| 15 | 5 | | 11.3 | 106 | 0.119324 | 47.72967 | 48.16709 | 27.71325 |
| 20 | 6.666667 | | 8.7 | 105 | 0.090343 | 51.19418 | 51.01143 | 28.449 |
| 25 | 8.333333 | | 7.1 | 103 | 0.074035 | 54.29267 | 53.73903 | 29.02125 |
| 30 | 10 | | 5.8 | 100 | 0.061571 | 55.41401 | 54.82042 | 28.449 |
| 35 | 11.66667 | | 5.2 | 102 | 0.053719 | 57.30028 | 56.59204 | 29.757 |
| 40 | 13.33333 | | 4.4 | 100 | 0.046025 | 56.7643 | 56.19413 | 28.776 |
| 45 | 15 | | 3.9 | 98 | 0.041445 | 58.02338 | 57.40922 | 28.69425 |
| 50 | 16.66667 | | 3.5 | 97 | 0.037433 | 58.64528 | 58.04312 | 28.6125 |
| 55 | 18.33333 | | 3.35 | 96 | 0.036158 | 62.67314 | 61.81849 | 30.12488 |
| 60 | 20 | | 3 | 96 | 0.032258 | 61.29032 | 60.60606 | 29.43 |
| 70 | 23.33333 | | 2.3 | 89 | 0.026528 | 59.24644 | 58.78058 | 26.3235 |
| 80 | 26.66667 | | 2.1 | 85 | 0.025332 | 65.01809 | 64.29392 | 27.468 |
| 90 | 30 | | 1.6 | 86 | 0.018957 | 54.9763 | 54.79452 | 23.544 |
| 100 | 33.33333 | | 1.3 | 86 | 0.015348 | 49.62613 | 49.63727 | 21.255 |
| 110 | 36.66667 | | 0.85 | 84 | 0.010222 | 36.46021 | 36.73149 | 15.28725 |
| 130 | 43.33333 | | 0 | | | ERR | ERR | 0 |

10) DTU M6.4 2" Drive pipe 2" Stroke 15mm Weight 507g

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 6 | 2 | 0.965 | 13.3 | 78 | 0.205564 | 20.55641 | 29.13472 | 13.0473 |
| 10 | 3.333333 | | 11.6 | 78 | 0.174699 | 40.76305 | 43.15476 | 18.966 |
| 15 | 5 | | 9 | 79 | 0.128571 | 51.42857 | 51.13636 | 22.0725 |
| 20 | 6.666667 | | 7.1 | 77 | 0.101574 | 57.55842 | 56.2822 | 23.217 |
| 25 | 8.333333 | | 5.7 | 74 | 0.083455 | 61.20059 | 59.59849 | 23.29875 |
| 30 | 10 | | 4.8 | 76 | 0.067416 | 60.67416 | 59.40594 | 23.544 |
| 35 | 11.66667 | | 4 | 74 | 0.057143 | 60.95238 | 59.82906 | 22.89 |
| 40 | 13.33333 | | 3.7 | 73 | 0.053391 | 65.84897 | 64.31986 | 24.198 |
| 45 | 15 | | 3.2 | 74 | 0.045198 | 63.27684 | 62.17617 | 23.544 |
| 50 | 16.66667 | | 3 | 71 | 0.044118 | 69.11765 | 67.56757 | 24.525 |
| 55 | 18.33333 | | 2.6 | 68 | 0.039755 | 68.90928 | 67.51653 | 23.3805 |
| 60 | 20 | | 2.3 | 65 | 0.036683 | 69.69697 | 68.35067 | 22.563 |
| 70 | 23.33333 | | 2.1 | 66 | 0.032864 | 73.39593 | 71.95301 | 24.0345 |
| 80 | 26.66667 | | 1.65 | 68 | 0.024868 | 63.82818 | 63.17301 | 21.582 |
| 90 | 30 | | 1.42 | 71 | 0.020408 | 59.18367 | 58.82353 | 20.8953 |
| 100 | 33.33333 | | 0.95 | 71 | 0.013562 | 43.84963 | 44.01205 | 15.5325 |
| 120 | 40 | | | | | | | |

11) DTU M6.4 2" Drive pipe 2" Stroke 10mm Weight = 507g

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 20 | 6.666667 | 0.965 | 4.8 | 48 | 0.111111 | 62.96296 | 66.66667 | 15.696 |
| 25 | 8.333333 | | 3.8 | 48 | 0.085973 | 63.04676 | 65.97222 | 15.5325 |
| 30 | 10 | | 3.2 | 48 | 0.071429 | 64.28571 | 66.66667 | 15.696 |
| 35 | 11.66667 | | 2.7 | 49 | 0.058315 | 62.20302 | 64.28571 | 15.45075 |
| 40 | 13.33333 | | 2.35 | 45 | 0.0551 | 67.95623 | 69.62963 | 15.369 |
| 45 | 15 | | 2.15 | 42 | 0.053952 | 75.53325 | 76.78571 | 15.81863 |
| 50 | 16.66667 | | 2 | 43 | 0.04878 | 76.42276 | 77.51938 | 16.35 |
| 60 | 20 | | 1.85 | 45 | 0.042874 | 81.46002 | 82.22222 | 18.1485 |
| 70 | 23.33333 | | 1.25 | 43 | 0.02994 | 66.86627 | 67.82946 | 14.30625 |
| 80 | 26.66667 | | 0.6 | 37 | 0.016484 | 42.30769 | 43.24324 | 7.848 |
| 90 | 30 | | 0 | 0 | 0 | 0 | 0 | 0 |

12) DTU M6.4 2" Drive pipe 2" Stroke 10mm Weight 730g

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 20 | 6.666667 | 0.965 | 7.3 | 77 | 0.104735 | 59.34959 | 63.20346 | 23.871 |
| 25 | 8.333333 | | 5.9 | 75 | 0.085384 | 62.61457 | 65.55556 | 24.11625 |
| 30 | 10 | | 4.9 | 73 | 0.071953 | 64.75771 | 67.12329 | 24.0345 |
| 35 | 11.66667 | | 4.1 | 71 | 0.061286 | 65.3712 | 67.37089 | 23.46225 |
| 40 | 13.33333 | | 3.9 | 77 | 0.053352 | 65.80027 | 67.53247 | 25.506 |
| 45 | 15 | | 3.6 | 73 | 0.051873 | 72.82248 | 73.9726 | 26.487 |
| 50 | 16.66667 | | 2.8 | 67 | 0.043614 | 68.32814 | 69.65174 | 22.89 |
| 60 | 20 | | 2.45 | 63 | 0.040482 | 76.87861 | 77.77778 | 24.0345 |
| 70 | 23.33333 | | 2.3 | 65 | 0.036683 | 81.92451 | 82.5641 | 26.3235 |
| 80 | 26.66667 | | 2.1 | 71 | 0.030479 | 78.22932 | 78.87324 | 27.468 |
| 90 | 30 | | 1.63 | 71 | 0.023497 | 68.14185 | 68.87324 | 23.98545 |
| 100 | 33.33333 | | 1.15 | 62 | 0.016899 | 61.10655 | 61.82796 | 18.8025 |
| 110 | 36.66667 | | 0.5 | 60 | 0.008403 | 29.97199 | 30.55556 | 8.9925 |
| 120 | 40 | | 0 | 60 | 0 | 0 | 0 | 0 |

13) DTU M6.4 2" Drive pipe 2" Stroke 15mm Weight 730g

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 10 | 3.333333 | 0.965 | 13.1 | 105 | 0.142546 | 33.26079 | 41.5873 | 21.4185 |
| 15 | 5 | | 11 | 105 | 0.117021 | 46.80851 | 62.38095 | 26.9775 |
| 20 | 6.666667 | | 8.8 | 105 | 0.091476 | 51.83645 | 55.87302 | 28.776 |
| 25 | 8.333333 | | 7.4 | 104 | 0.076605 | 56.17667 | 59.29487 | 30.2475 |
| 30 | 10 | | 6.1 | 102 | 0.063608 | 57.24713 | 59.80392 | 29.9205 |
| 35 | 11.66667 | | 5.4 | 102 | 0.055901 | 59.62733 | 61.76471 | 30.9015 |
| 40 | 13.33333 | | 4.5 | 100 | 0.04712 | 58.11518 | 60 | 29.43 |
| 45 | 15 | | 4.2 | 99 | 0.044304 | 62.02532 | 63.63636 | 30.9015 |
| 50 | 16.66667 | | 3.9 | 104 | 0.036961 | 61.03896 | 62.5 | 31.8825 |
| 55 | 18.33333 | | 3.5 | 103 | 0.035176 | 60.97152 | 62.29773 | 31.47375 |
| 60 | 20 | | 3.1 | 101 | 0.031665 | 60.16343 | 61.38614 | 30.411 |
| 70 | 23.33333 | | 2.4 | 92 | 0.026768 | 59.82143 | 60.86957 | 27.468 |
| 90 | 30 | | 2.2 | 90 | 0.025057 | 72.66515 | 73.33333 | 32.373 |
| 100 | 33.33333 | | 1.9 | 102 | 0.018981 | 61.37196 | 62.0915 | 31.065 |
| 110 | 36.66667 | | 1.5 | 98 | 0.015544 | 55.44041 | 56.12245 | 26.9775 |
| 120 | 40 | | 1 | 98 | 0.010309 | 40.20619 | 40.81633 | 19.62 |
| 130 | 43.33333 | | 0.4 | 98 | 0.004098 | 17.34973 | 17.68707 | 8.502 |
| 145 | 48.33333 | | 0 | 98 | 0 | 0 | 0 | 0 |

14) DTU M6.4 2" Drive pipe 2" Stroke 20mm Weight 730g

| Delivery Head hd | Head Ratio | Period Time | Delivery Flow | Supply Flow | Flow Ratio | Rankine Eff | D'Aub Eff | Power |
|---|---|---|---|---|---|---|---|---|
| 6 | 2 | 0.965 | 15.1 | 140 | 0.120897 | 12.08967 | 21.57143 | 14.8131 |
| 10 | 3.333333 | | 13.8 | 134 | 0.114609 | 26.76869 | 34.32836 | 22.563 |
| 15 | 5 | | 11.4 | 129 | 0.096939 | 38.77551 | 44.18605 | 27.9585 |
| 20 | 6.666667 | | 9.4 | 132 | 0.076672 | 43.44753 | 47.47475 | 30.738 |
| 25 | 8.333333 | | 8 | 130 | 0.065574 | 48.08743 | 51.28205 | 32.7 |
| 30 | 10 | | 6.8 | 131 | 0.05475 | 49.27536 | 51.9084 | 33.354 |
| 35 | 11.66667 | | 6 | 126 | 0.05 | 53.33333 | 55.55556 | 34.335 |
| 40 | 13.33333 | | 5.5 | 131 | 0.043825 | 54.05046 | 55.97964 | 35.97 |
| 45 | 15 | | 4.7 | 128 | 0.036118 | 53.36577 | 55.07813 | 34.58025 |
| 50 | 16.66667 | | 4.1 | 123 | 0.034483 | 54.02299 | 55.55556 | 33.5175 |
| 60 | 20 | | 3.7 | 126 | 0.030253 | 57.4816 | 58.73016 | 36.297 |
| 70 | 23.33333 | | 3.05 | 126 | 0.024807 | 55.40192 | 56.48148 | 34.90725 |
| 80 | 26.66667 | | 2.5 | 118 | 0.021645 | 55.55556 | 56.49718 | 32.7 |
| 90 | 30 | | 2.3 | 112 | 0.020966 | 60.80219 | 61.60714 | 33.8445 |
| 100 | 33.33333 | | 1.9 | 112 | 0.017257 | 55.79776 | 56.54762 | 31.065 |
| 110 | 36.66667 | | 1.7 | 117 | 0.014744 | 52.58745 | 53.27635 | 30.5745 |
| 120 | 40 | | 1.2 | 119 | 0.010187 | 39.72835 | 40.33613 | 23.544 |
| 130 | 43.33333 | | 0.8 | 118 | 0.006826 | 28.89647 | 29.37853 | 17.004 |
| 150 | 50 | | 0 | 118 | 0 | 0 | 0 | 0 |

## Appendix C FURTHER NOTES AND COMMENTS ON THE WORK AT DELFT

The following are a series of points arising from the work at Delft that have not been mentioned in the main text of this paper.

1) Delft managed to record delivery valve movement of rubber type valves by bonding strain guages to the rubber. This technique overcomes the difficulty of recording and analysing delivery valve movement experienced by the DTU.

2) An electronic beat frequency counter was used at Delft to record the operating frequency and period of pumps under test. This is another technique worth pursuing for ongoing tests at Warwick.

3) There is some confusion and lack of consistancy between ram pump manufacturers and users as to how efficiency is measured. Delft produce the following summary

<u>Rankine</u> Drive tank water level is taken as the datum point and supply and delivery heads measured from that point. Therefore the net amount of potential energy in the water delivered = $\rho g q(h-H)$
the net amount of energy input = $\rho g Q H$

Hence Rankine efficiency $\eta_R = \dfrac{q \times (h-H)}{Q \times H}$

<u>D'Aubuisson</u> The impulse valve orifice is taken as the datum point and therefore

work done = $\rho g q h$
energy supply = $\rho g\ (Q + q)H$

D'Aubuisson Efficiency $\eta_D = \dfrac{q \times h}{(Q + q) \times H}$

<u>Manufacturers</u>

Most manufacturers take a simplified efficiency that actually produces a higher value of efficiency under any given set of conditions

$$\eta_m = \frac{q \times h}{Q \times H}$$

Delft prefer the Rankine expression which yields the lowest results particularly at low delivery heads.

The DTU currently uses the D'Aubuisson formula as the test rig measures the total flow into the pump (Q + q) rather than just the waste flow. This has been used throughout this report.

There seems little to choose between these two which produce similar results under normal operating conditions. The simplified efficiency used by many manufacturers is more inaccurate but produces more flattering figures!

4) Observation on relative position of delivery and impulse valves concerning air intake during recoil.

During recoil, large quantities of air can be drawn in through the open impulse valve as water flows back up the drive pipe. Only a small quantity of air can be drawn through the snifter valve so section A remains relatively full of water. As acceleration of water towards the pump re-occurs the majority of the air is expelled through the impulse valve and only the small volume entering from the snifter enters the air vessel.

If the recoil is large in this configuration and a significant quantity of air drawn in through the impulse valve, the column may receed past the vertical pipe section leading to the delivery valve. When acceleration occurs a significant pocket of air may be trapped under the delivery valve. This would tend to dampen out the next pressure pulse and reduce delivery flow.

5) The Alto ram from France has an inflatable rubber air compartment in the air vessel to ensure a permanent separation of air and water. This is an attractive option as it reduces the need for a reliable snifter to replenish air lost from the air vessel.

6) The SANO rams are fitted with a 'drip valve' in the air vessel that appears to be located at a point where the air/water interface should be. It presumably operates by passing water if the level in the air vessel rises above it. What is its operating mechanism?

8) Delft draw the following conclusions about pump performance and operation from results produced by their mathematical model.

- given an available source supply the pumping rate (q) is primarily determined by the supply head ($H_s$)and the delivery head ($h_d$).
- an increase of the delivery head ($h_d$) decreases the quantity pumped per cycle ($V_d$) and by that the pumping rate (q) decreases.
- an increase of the supply head ($H_s$) increases the pumping frequency and by that the pumping rate (q) increases.
- an increase of $u_c$ (ie. the velocity of the water in the drive pipe at waste valve closure) normally increases the pumping rate (q) while the pumping frequency decreases, but more water (Q) is needed to operate the ram. However, there is a limiation as to this point: an increase in $u_c$ such that the value of the ratio $u_c/u_o$ approaches unity (where $u_o$ is the maximum attainable velocity of the water in the drive pipe) implies a decrease in pumping rate (q) while, as before, the waste flow (Q) increases, a condition to be avoided.
- the larger the size (ie. drive pipe bore) of the ram, the more water (Q) is required to operate the ram and the more water (q) can be delivered to a higher level ($h_d$).

9) Delft recommend that if the delivery flow from one ramains insufficient a second ram should be placed below the first and utilise its drive water. However if there is sufficient drive head available to be able to do this would a better performance be gained by having two rams each working from a portion of the drive head or one ram working with the total head available?

10) Delft state that the drive pipe length should be approximately 4 to 7 times the supply head. They make no justification for this statement.

11) Delft state that the best pumping results are usually obtained when the cut off velocity is between 60% and 80% of the terminal velocity of the system.

12) Delft produce equations for predicting pump performance, which require certain information about the system to tbe known.

A loss coefficient for the whole system is required which covers all the losses in the drive pipe, pump and delivery pipe. Delft state that this can be found by holding open the impulse valve, measuring the flow rate at terminal velocity and inserting this into the equation

$$\text{max velocity} \quad V = \sqrt{\frac{2gH}{\text{loss coef}}}$$

This does not take into account the delivery system losses and can only be measured once the system is installed, preventing prediction of performance prior to installation. It would be more useful to have a loss coefficient measured for each pump and also to have a simple method of calculating pipe loss coefficient based on diameter and length.

The other requirement for use of Delft's model is to find the cut off velocity for the particular impulse valve setting. They state that this can be found when the maximum delivery head obtainable is known using

$$\text{Cutoff} = (g/c) \times h_{max}$$

They recommend that $h_{max}$ is found by closing the delivery side of the pump and letting the pump run up to its maximum head. This would provide a rather crude approximation producing a low result and could prove to be very dangerous.