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TESTING OF SOLAR PUMPSETS

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Contents

1. Introduction

In the course of 1984 Dutch Interchurch Aid (SOH/AID) ordered three solar pumpsets for use in the Solar Energy Experimentation Programme (SEE).
This programme is part of the Rajshahi Agricultural Development Project (RADP) of the Christian Committee for Development in Bangladesh (CCDB).

In december 1984 the solar pumpsets have been tested, prior to their shipment to Bangladesh. This report describes the results of those tests.

All solar panels for these three pumpsets were tested. Of the pumps however one could not be included because it could not be delivered in time.

The pumpsets were tested at the laboratory of the windmillgroup of the Twente University of Technology (TUT), being a member of the Consultancy Services Windenergy Developing Countries (CWD). The tests are executed by André Peeters Weem, who is also the author of this report.

Apart from all who contributed to the testing with valuable advice and actual assistance special thanks are due to the Working Group on Development Techniques (WOT), the TUT and the CWD for the use that could be made of the solar panel test equipment , the measuring instruments and the pump test stand.

We wish the CCDB lots of succes with the following steps in the SEE-programme,

André Peeters Weem

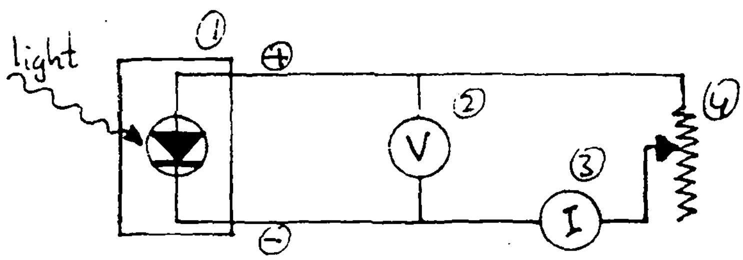
Klaas Kieft

2 TESTING of the SOLAR PANELS

2.1 General

To get an impression of the performance of foto-voltaic solar panels it is necessary to measure the generated power at a given irradiation. The power (P) is measured in Watts, the irradiation(E) in Watts/meter^2. Besides the output power also the open circuit Voltage (Voc) and short circuit Current (Isc) are important characteristics.

The goal of the experiments was measuring the values of Voc, Isc and P for two types of panels, the small BPX 47a and the larger BPX 47b/18, under laboratory conditions, i.c. at a controlled irradiation.
This irradiation was produced by a lightsource equipped with halogen light with a total electric power input of 2.5 kW.
The solar panel was connected to a variable electrical load (variable resistance). V and I were measured, see fig.1 and annex 1.



1): solar panel

2): Voltmeter

3): Current meter

4): Load (Variable resistor)

fig. 1 Solar panel, test circuit

2.2 Testing

Four different tests were performed:
1) Measuring the power output under artificial light.
2) Comparison of the performance of all panels.
3) Measuring the power output under sunlight.
4) determining an I-V characteristic under artificial light.

From the values of V and I the ouput power P=V.I was calculated, see annex 2.

The results of the first test were poor: at an irradiation of 850 W/m^2 the panels should produce 8 Watt and a short circuit Current Isc of more than 600 mA. But a power output of P=3.5W and Isc=270mA were measured.
Looking for the cause of this lack of power it was found that the light, produced by the electric lightsource, cannot be compared to sunlight with the same energy. An electric lightsource produces 10% of its radiation as visible light, about 90% is Infrared radiation. As the solar panels are insensitive to infrared radiation they only convert a small part of the irradiated energy into electric power, see annex 3.

Given the fact that measurements under artificial light cannot be compared to measurements using sunlight, all the panels were tested under electric light and Isc and Voc were measured and for two panels I-V characteristics were recorded.
The results of the second test were good. There appeared to be only a small difference in performance between the panels, see annex 2.

On a sunny day (solar irradiation up to 600 w/m^2) two panels were tested outdoors.
The results are given in table 1 and in fig.3. In table 1 also the manufacturers specifications are given.

Table 1, Solar panels, results of outdoor tests

panel type:	BPX 47a		BPX 47b/18	
manufacturers specifications:				
	$E=1000W/m^2$:	P= 11W	$E=1000W/m^2$:	P= 16W
	$E=1000W/m^2$:	Isc= 720mA	$E=1000W/m^2$:	Isc= 2.1A
test results:				
	$E= 300W/m^2$:	P= 3W	$E= 630W/m^2$:	P= 10.3W
	$E= 530W/m^2$:	Isc= 400mA	$E= 600W/m^2$:	Isc= 1.36A

The temperature of the panels during the tests: T= $20^{\circ}C$

The test results can be compared to the manufacturers specifications because Isc increases proportional to the irradiation.
For more results see annex 2.

2.3 Conclusions:

The panels are performing well, there are only small differences between the panels.
The expected output of the small panels (BPX 47a) is 10 Watt at an irradiation of $1000W/m^2$. The ouput Voltage for maximum power ranges from 14 to 15 V and output current from 650 to 700 mA.
The expected output value of the large panels (BPX 47b/18) at $1000W/m^2$ is 16 Watt at an output Voltage between 7 and 8 V and an ouput current between 2 and 2.1A.
These numbers are calculated for a panel temperature of $25^{\circ}C$.
If this temperature rises to $60^{\circ}C$ (maximum temperature of the panels) the output (P and Voc) will drop 10% according to manufacturers specifications.

3 Performance of the Grundfoss pumps

3.1 General

Two deepwell pumps of the type Grundfoss SP 8-4 and two Grundfoss inverters were tested on a test stand. With this test stand elevation-heads from 2 to 25 meters could be simulated. It was equipped with a flow- and a pressuremeter in the watercircuit so the hydraulic power output of the pump could be measured.

The electric power input of the pump-inverter combination was monitored by using Voltage and currentmeters.
The electric output of an array of solar cells was simulated by a DC powersupply that was connected to the inverter.
This Grundfoss inverter changes the DC input into a three-phase AC output. The frequency of the output changes with the DC input power. Because of this changes in frequency also the speed (revolutions per minute) of the pump will change which means that the power, used by the pump changes.
In this way the power output of the pump is depending on the power produced by the solar cells. The DC Voltage produced by the solar panels is kept at a constant value by the inverter, only the current changes.
This is done to keep the panels working under optimal conditions, i.c. at values of Voltage and current that are the most efficient.

3.2 Testing

Several tests have been done to determine the performance of the pumps.
The flow (q) is determined as a function of the elevation head (H) for different values of the input power (Pdc).(test 1)
The flow is also measured as a function of the input power at a constant elevation head. Because the input Voltage is fixed at 98V q is given as a function of the input current, Idc. (test 2)
Also the efficiency of the combination pump-inverter is measured (test 4), the efficiency of the inverter only (test 5), the starting of the pump is examined (test 3) and the frequency and phase-angle of the AC-current were measured (test 6).
These tests were done for one pump-inverter combination, the other has also been tested in the same way (test 7).

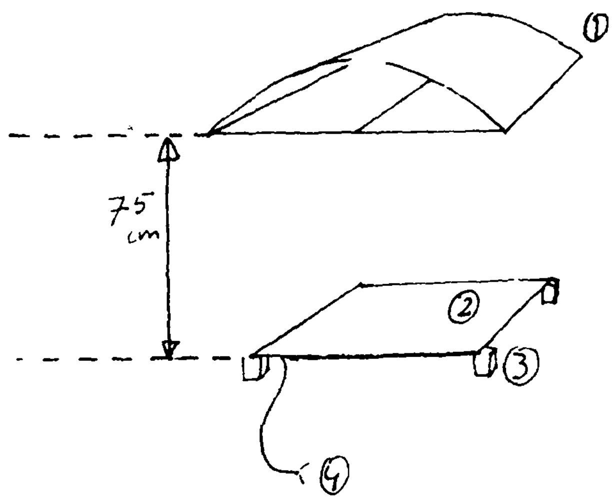
3.3 Results

The results of these tests indicate that the Grundfoss pump-inverter combination performs well. See annex 5. The maximum efficiency that was measured is 50% for the combination at an electric power input of 400 Watt. At lower inputs the efficiency decreases.

42 Solar panels of the type BPX 47a are capable of delivering 420 Watts. According to the test results the SP 8-4 pump should deliver 160 liters of water per minute over 7 meter elevation head at this power input of 420 W. The minimum power that is needed to lift water over 7 meter is 120 Watts, the flow will be very low at this powerinput.

A1 Description of the set-up for testing of the solar panels.

A1.1 The light source used in the teststand (see drawing, fig. 2) consisted of a parabolic reflector with halogen lights in the focal line. The electric power of the light was 2.5kW, the colortemperature of the artificial light is 3000K. The light was not evenly spread over the surface because the reflector did not have a perfect parabolic shape. For this reason 13 spots on the lighted surface were measured and the irradiation was determined. The intensity of the light is the mean value of the 13 measured intensities: $E=850\ W/m^2$.



1): light source

2): solar panel

3): supports (to allow cooling air under the panel)

4): electrical connections

fig. 2 Test stand for photo-voltaic cells

A1.2 The intensity of the irradiation is measured using a Kipp-solarimeter, type CM 5. This solarimeter is equipped with a small black surface which heats up because of the incident radiation. The rise in temperature is transmitted to a thermocouple, which produces a voltage, increasing with temperature. The solarimeter was calibrated at giving 11.28 mV at $1kW/m^2$. This voltage was measured with a digital galvanometer (Keithley 177) with an internal resistance of 1Megohm/Volt. The solarimeter is sensitive to radiation with a wavelength between $0.3.10^{-6}$ and $2.5.10^{-6}$m. This means that the solarimeter is sensitive to Infrared and visible light.

A1.3 Electric circuit

The solar panel was connected to an electric load. A variable resistor was used as load. The voltage was measured with a digital H&B Voltmeter, current was measured with an Unigor A43 unimeter. See fig.1.

A2 Test results, solar panels

During the measurements the intensity of the radiation from the lightsource was measured, it was found that it remained constant at 850 W/m^2.

A2.1 First test.
Panel: BPX 47a (nr.: 26050)
E=850 W/m^2, T_{panel}= 25°C.
results: Voc=17.2V
Isc=286 mA

According to the specifications the panel should give a Voc=20V and an Isc=650mA at E=850W/m^2.
The cause of the lack of performance of the panel is the frequency distribution of the light, produced by the lightsource. (see annex 3).

A2.2 Second test.
As a test of the differences between panels, and to check the electric connections of the panels, all panels have been measured.
Of all panels Voc and Isc were determined, at T_{panel}= 20°C and at an irradiation E=850 W/m^2.
The results are given in table 2.

Table 2, Results of solar panel tests

Type: BPX 47b/18

Number	Voc (Volt)	Isc (mA)
17413	9.9	755
17414	10.0	760
17415	10.1	724
17416	10.0	751
17446	10.0	744
17447	10.0	724
17448	10.0	746
17449	10.0	738
16310	10.1	735
16309	10.2	724
16308	10.1	725
16307	10.2	726
16339	10.0	663
16338	10.0	681
16337	10.1	719
16335	10.0	711
16318	10.1	747
16317	10.1	723
16316	10.1	734
16315	10.1	735

Table 2, results of solar panel tests, continued

Type: BPX 47a, E= 850 W/m^2, T= 20°C

Number	Voc (Volt)	Isc (mA)	Number	Voc (Volt)	Isc (mA)
26050	17.5	272	20958	19.0	265
26051	18.7	263	22378	18.8	268
26049	18.9	259	22379	18.9	270
22377	18.8	275	22406	18.9	269
23956	18.9	273	22403	18.9	269
23790	19.0	274	23698	18.9	260
23798	19.0	272	23696	18.9	271
23801	18.9	262	23699	19.1	263
23803	18.9	267	22398	18.9	268
23818	19.0	269	23700	19.0	267
23824	19.0	267	22394	18.8	269
23825	18.9	270	23890	18.9	270
23985	19.1	266	23891	19.1	273
24436	19.0	269	23892	19.1	271
24435	19.0	258	23893	18.9	273
24434	19.0	256	23894	19.0	278
24433	19.0	260	23895	18.9	274
24432	19.1	261	23896	19.0	276
24431	19.1	267	23897	18.9	275
24430	19.1	267	23898	18.7	273
24429	19.1	266	23899	19.0	279
24428	19.1	266	24039	19.0	261
24427	19.1	270	20991	18.9	253
23900	19.2	279	21012	19.0	259
23901	19.2	278	18792	19.1	258
23902	19.1	270	21010	18.9	264
23903	19.2	266	20956	18.9	266
23904	18.6	267	24040	19.1	261
23905	19.2	270	24051	19.0	258
23906	19.2	268	24078	19.0	257
23907	19.2	267	24079	19.0	254
23908	19.2	264	20909	19.0	255
23909	19.3	281	20910	19.0	266
20906	19.0	260	22261	19.0	275
20904	19.1	262	22262	19.0	274
20894	19.0	265	22190	19.0	269
20961	19.0	261	22193	19.0	270
20891	19.0	264	22194	19.0	274
20890	18.9	253	22196	18.9	275
20889	19.0	256	22198	19.1	281
20881	19.0	257	22216	19.0	275
20960	19.0	265	26050	18.8	268

21/12/1984
panel BPX 47a
sunlight
insolation: 300 W/m^2

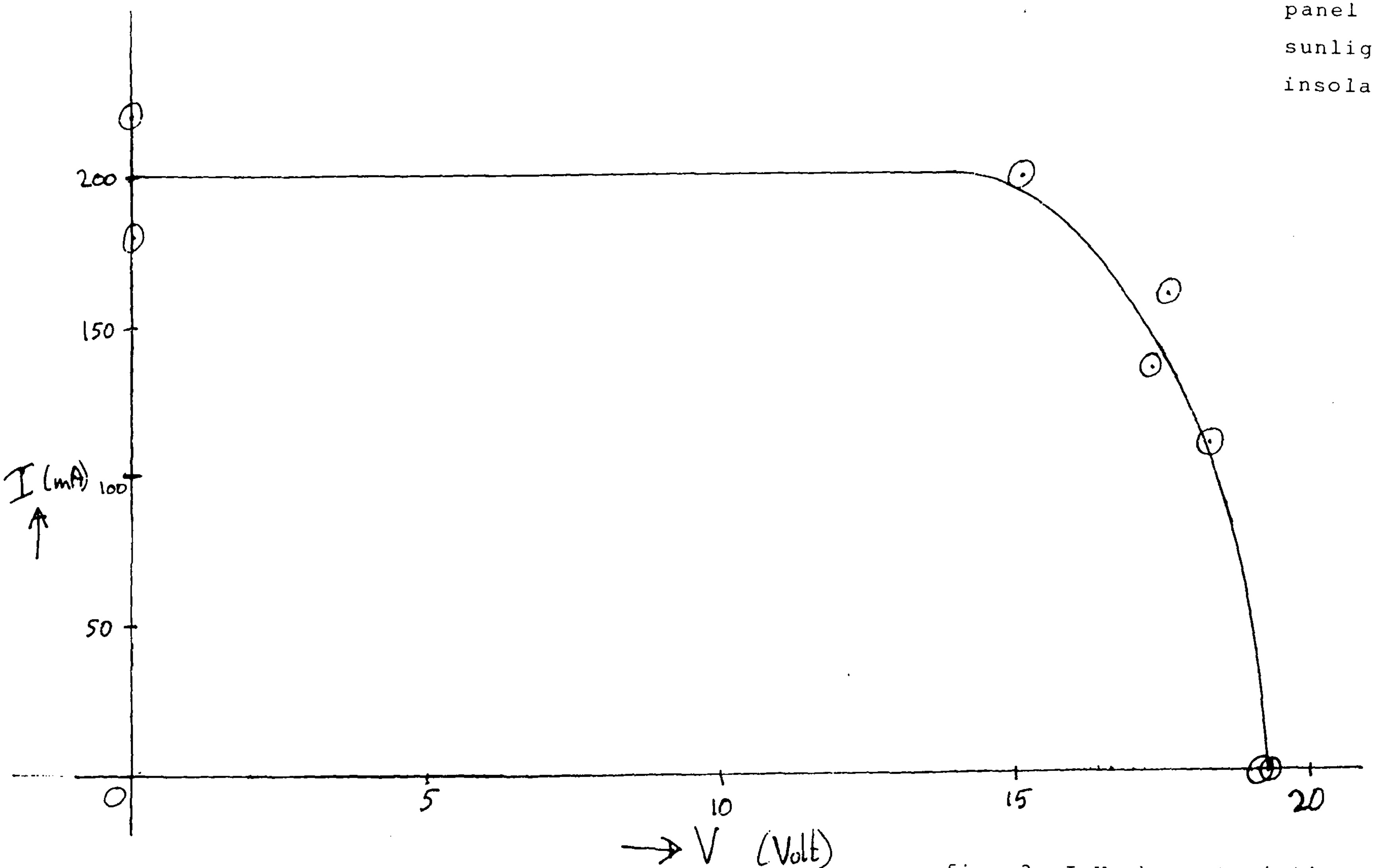


fig. 3 I-V characteristic

A2.3 Third test

Two panels, one of each type, were tested outdoors using the available sunlight.

Test set-up:

The panels were put against the front of a building on ground-level in such a way that they were perpendicular to the incident sunlight.

The solarimeter was placed parallel to the panels.

The electric circuit was the same as with the laboratory tests (see fig.1).

Because the intensity of the sunlight was not very constant and changed rapidly there occurred a small problem. The solarimeter needed about 15 seconds to give a stable reading so the sunlight had to be stable for at least 15 seconds. This situation did not occur much. The deviation between the results is large, by taking mean values it is possible to reduce the error in the readings.

Table 3, Results of outdoor tests of panel BPX 47a

	Lightintensity E (W/m^2)	Voltage (V)	Current (mA)	Power (Watt)
a)	195	18.9	0	
b)		19.3	0	
c)	266	15.1	176	2.7
d)	288	17.6	154	2.7
e)	301	18.3	110	2.0
f)	293	19.3	0	
g)	257	0	190	
h)	266	0	162	
i)	293	17.3	132	2.3
j)	301	19.1	0	
k)	355	0	163	
l)	532	0	400	
m)	372	0	300	

These results are used to draw a I-V characteristic (fig.3) for the BPX 47a panel.

The values of Isc (Current at V=0) are used to calculate a value of Isc for E=300 W/m^2.

As Isc is proportional to E this can be done in the following way:

At 1000W/m^2: Isc = 720 mA so Isc = .72 mA per W/m^2 (from specific.)

At 266 W/m^2: Isc = 162 mA. (measured)

At 300 W/m^2: Isc = 162.(300/266) = 183 mA (calculated)

This way al five values of Isc can be used to calculate Isc_{300}

The result is:

At 300 Watt/m^2 : $Isc = \frac{(222+183+138+225+242)}{5} = 202$ mA

The results of measurements d,e,f,i,j and the calculated value of Isc are used to draw the graph in fig.3. As can be seen in fig. 3 this method is not perfect, it is difficult to draw the line through the points that were found.

For the panel BPX 47b/18 not enough measurements could be done to be able to draw a I-V chracteristic. The results of the measurements, as given below are satisfying. The panel performs well.

Table 4, Results of outdoor tests of panel BPX 47b/18

	Lightintensity E (W/m^2)	Voltage (V)	Current (A)	Power (W)
a)	600	10.6	0	0
b)	600	0	1.36	0
c)	630	9.0	1.14	10.3

A2.4 Fourth test

For both panels a complete I-V characteristic was made using artificial light as source of radiation.
The test stand and electric circuit are as in the other tests, see fig.1 and fig. 2.
The results are given in fig. 4. It can be seen that the output of the BPX 47a is 3.8 Watts. The artificial light that was used had an energy of 850 W/m^2, almost 3 times the energy of the sunlight used in the third test, which had an intensity of 300 W/m^2. The output of the panel though is only 30% more (3.8 vs. 3 Watts). This indicates that the energy of artificial light that can be converted by solar cells is only about 400 W/m^2 in this case.
In fig. 4 each I-V curve is drawn two times because each was measured in two directions, i.c. starting at V=0 (short circuit) and increasing the resistance of the load until the voltage reaches Voc (open circuit) and the decreasing the resistance again. The arrows in the curve indicate the direction.
The difference between the curves is caused by heating of the panels. On the way back (decreasing V, increasing I) the temperature of the panels was higher which reduces V and increases I. The heating up of the panels was caused mainly by the absorption of infrared radiation from the lightsource and to a smaller extent by dissipation of power in the cells due to the internal resistance of the cells.
This was shown by placing the panels under the light source without an electrical load, so there would be no current through the cells. In this case the panels would heat up with the same speed to the same temperature as with an electrical load connected.

21/12/1984

Panels: BPX 47a and BPX 47b/18
artificial light
irradiation: 850 W/m^2

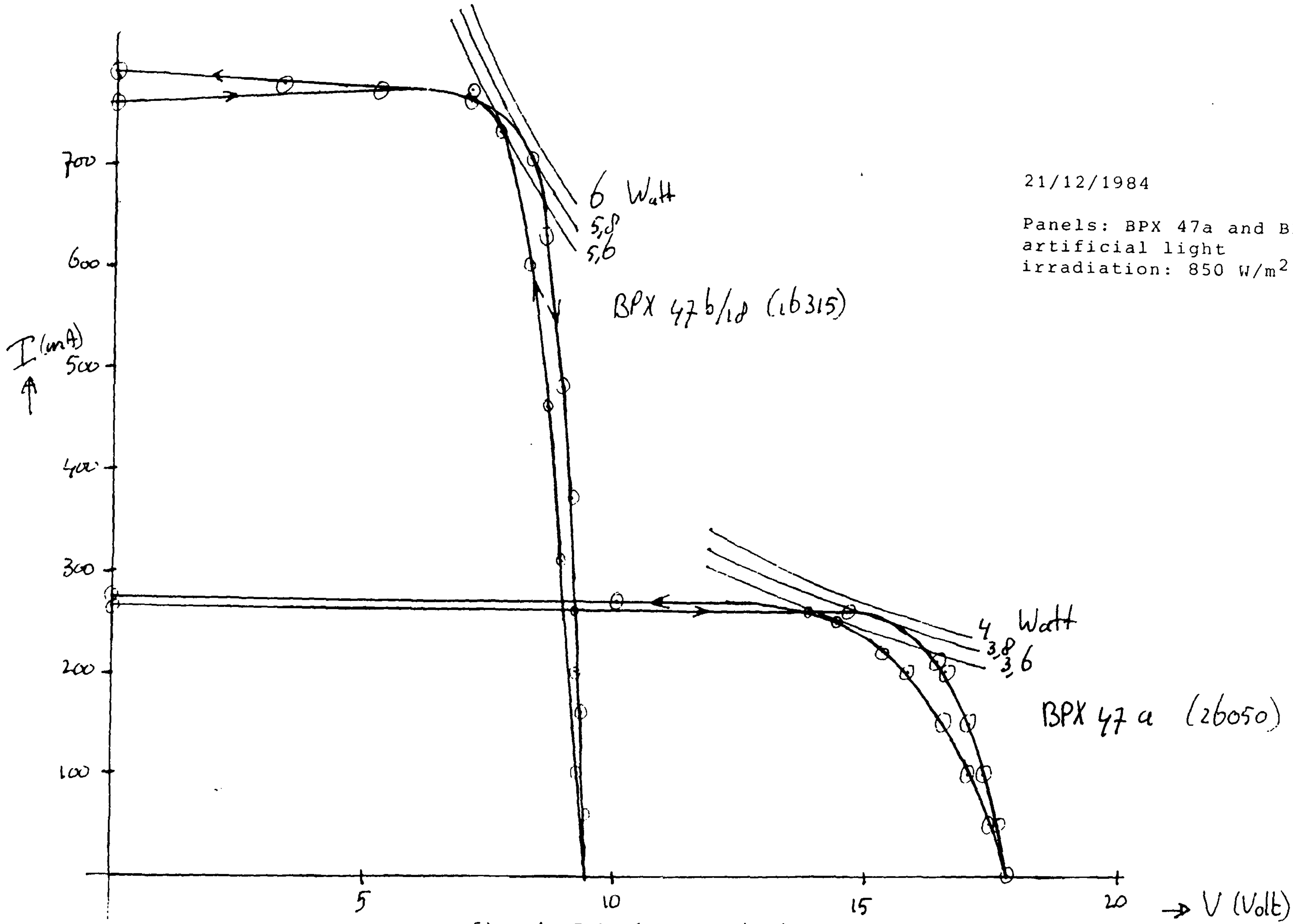


fig. 4 I-V characteristic

A3 Frequency distribution of artificial light and of sunlight.

Looking for the reason of the lack of power produced by the panels under the lightsource it was found that the light of an electric lightsource cannot be compared to sunlight. To illustrate this the spectral distribution of sunlight and the sensitivity of the panels are given in fig. 5. The colortemperature of sunlight is 5500K. From this figure it can be seen that the panels are sensitive only to light with a wavelength shorter than 1.10^{-6}m. The artificial lightsource produces light with a colortemperature of 3000K. This indicates that an electric lightsource produces most of it's radiation in the infrared region with a wavelength greater than 1.10^{-6}m. Exact data on how much infrared is produced by the used halogen lights were not available, but if it is in the same amount as normal electric light it will be about 90% of the radiated energy that is in the long wave region.
As the solarimeter is sensitive to radiation with a wavelength up to $2.5 \cdot 10^{-6}$m it cannot be used to determine the amount of visible light inciding on the solar panels because it will "see" a lot of infrared radiation and this will influence the measurements.

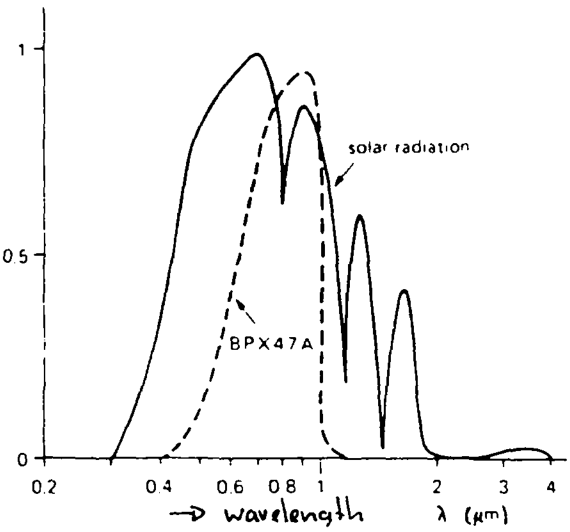
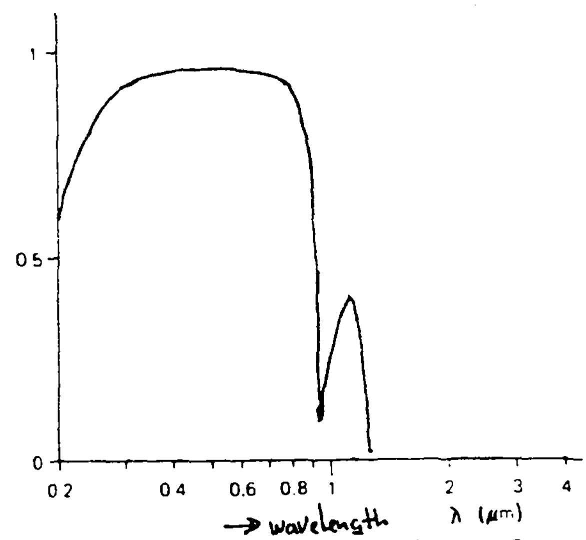


fig.5 Solar radiation spectral distribution and spectral sensitivity of BPX 47a.

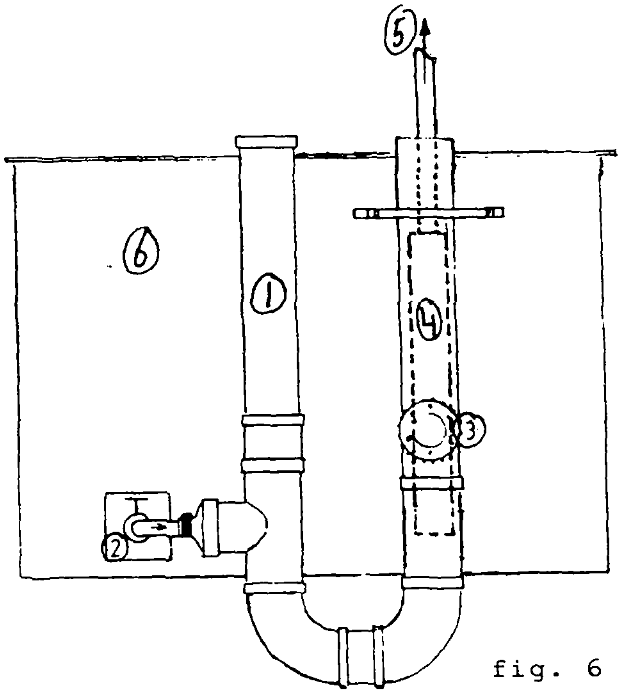


Spectral transmission of a 40 mm waterlayer

Some experiments have been done to reduce the amount of infrared in the light of the lightsource. A layer of water can be used as a filter. The spectral absorption of a layer of 40mm water is given in fig.5b.As it was impossible to find a mechanical solution to the problem of putting a water-layer of 40 mm over an area of $\frac{1}{4}m^2$ between the lightsource and the solarpanel this kind of filter could not be used. If a waterlayer of 30 mm was placed between the solarimeter and the lightsource the reading of the solarimeter was reduced with a factor 2.5. This means that about 70% of the radiation is absorbed by the waterlayer, which indicates that at least 70% of the artificial light has a wavelength greater than 1.10^{-6}m.

A4 Pump test stand.

A4.1 The test stand used to measure the characteristics of the pump existed of a watertank (volume $2m^3$) to which a syphon was placed. In this syphon the pump was mounted. The outlet of the pump is connected to a pressure-regulating valve. With this valve an elevation head up to 25m could be simulated by increasing the waterpressure. In the watercircuit also a flowmeter, an analogue and an electronic pressuremeter are used.



1) syphon
2) waterinlet
3) inspection window
4) deepwell pump
5) water outlet
6) storage tank

fig. 6 Deepwell pump test stand

A4.2 Calibration of the meters

Flowmeter. The flowmeter was calibrated by filling a vessel with water, at a constant flow, and by measuring the weight of the amount of water and the time needed to fill the vessel. The flow can be calculated by dividing the weight by the time. The values found like this are compared with the reading of the flowmeter and with the analogue outputvoltage of the flowmeter. The results, given in table 5 , are mean values of two measurements.

Table 5, Calibration of the flowmeter

reading flowmeter l/min.	Vout flowmeter Volt	weight of water kg	filling time sec.	flow calc. l/min	deviation %
30	0.21	10	16.5	36	20
60	0.45	10	9	67	11
90	0.71	71	36	118	30
120	0.92				
150	1.16				

Using the mean value of the deviation,the following relations are found:
The real flow is 1.2 times the reading of the flowmter.
The flow q is related to the analogue Vout: q=160.Vout, or $Vout=6.3 \cdot 10^{-3} \cdot q$.
As the analogue Vout voltage of the flowmeter has a smaller deviation than the reading, the flow is calculated by using the Vout value.

Pressuremeter.
The electronic pressuremeter was calibrated with the help of a special calibration instrument. It was done in such way that an analogue output voltage of the instrument of 1V corresponds with 0.2 atmosphere, or that 5 Volts correspond with 1 atmosphere, being 10.2 meters watercolumn. Also has to be taken in account that the pressure-feeler was not mounted on the same level as the pump, but 0.5m up of the pumpoutlet. So the pressure on the pump is the reading (in Volts) of the instrument times 10.2/5 plus 0.5meter.

A4.3 Recorder.
The analogue outputsignals of the pressure-and flowmeter are fed to a recorder, so a flow - Head (q-H) characteristic could be made.

A4.4 Pressure regulator.
In the teststand a pressure-regulator was used. The regulator consisted of a valve, that could be opened by the water-pressure against the tension of a spring. The springforce closing the valve is set at a minimumvalue of about 2m watercolumn. The springforce could be increased by raising the pressure under a membrane connected to the valve (see fig. 7). The pressure in the chamber under the membrane was increased using Nitrogen, coming from a high-pressure cilinder.

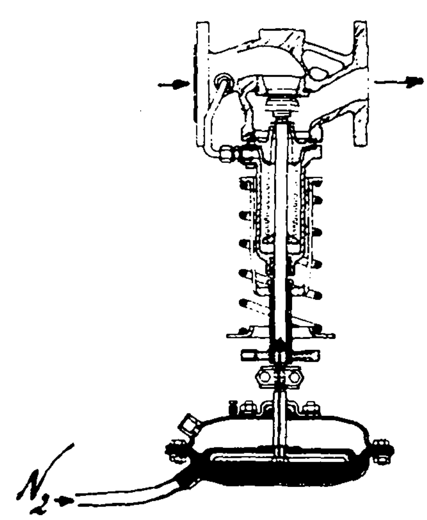
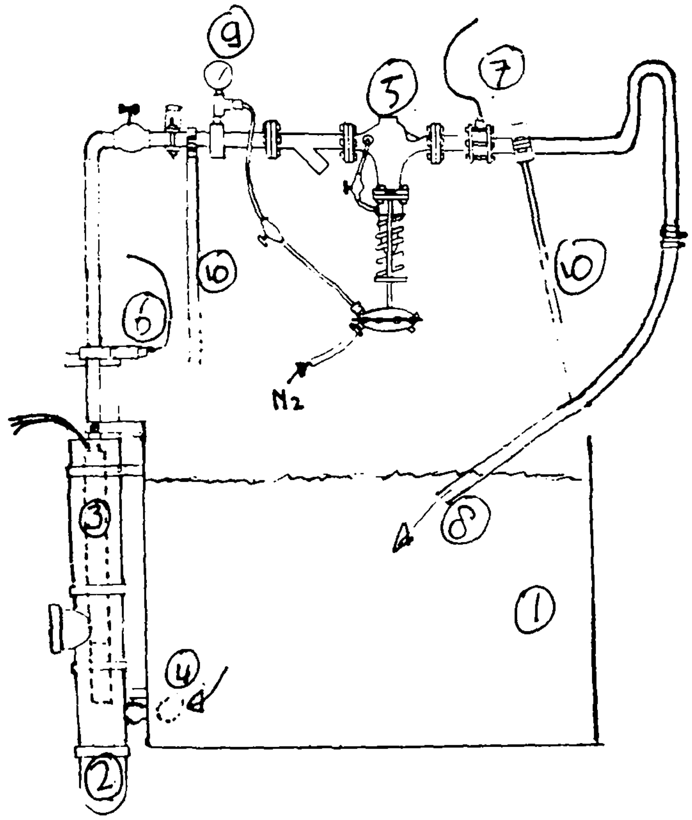


fig. 7 pressure regulating valve

A drawing of the total set-up is given in fig. 8 .



1) storage tank
2) syphon
3) deepwell pump
4) water inlet
5) pressure regulator
6) pressure meter
7) flowmeter
8) water outlet
9) analogue pressure meter
10) pipe supports

fig. 8 Deepwell pump test stand

A4.5 Power Supply

To simulate the power output of an array of solar panels a DC power supply was used. This power supply consisted of 3 units, each producing a variable and stabilised DC output up to 50 Volts and 5Amp. Three units in series could produce 150 V and 5 A DC ouptput. Voltage and current could be limited at every desired value up to 150V and 5A. Voltage and Current were measured using multimeters.

Connection to the pump.

The power supply was connected to the Grundfoss pump-inverter unit in the same way solar panels would have to be connected. (see fig. 9.)
The main switch is a standard Grundfoss-switch.
V and I are a voltage and a currentmeter, both Unigor A43 unimeters.

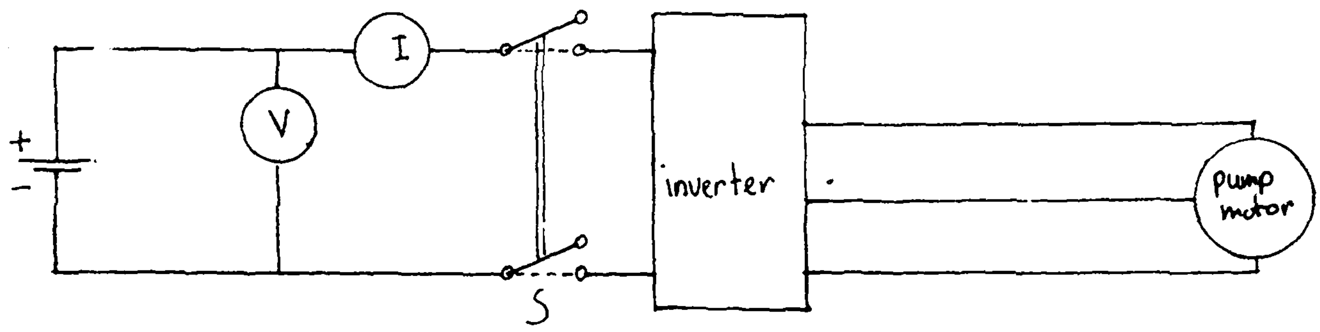


fig. 9 pump test stand, electric circuit

The Grundfoss inverter inverts the DC-input into an AC three-phase output. The frequency of the AC output depends upon the power of the DC input. This means that at a low power input the AC frequency is low, so the pump will turn slow and will not need much power. At high power input the frequency goes up, and with it the power delivered to the pump. The frequency can change, according to Grundfoss, from 6 to 60 Hz. Also the inverter controls the starting of the pump so that no external batteries are needed for starting.

A5 Results of the pumptests, 1st pumpset

The tests 1 to 6 have been done with the same inverter-pump combination. Annex 6 gives the results of the tests with the other combination.

A5.1 q-H characteristic

The flow q at a given elevation head H is an indication for the performance of the pump.
A q-H curve is measured for four different values of the input power Pdc. As Vdc is constant (98V) only the input current, Idc, changes from 1 up to 4 Amp.
The results are given in fig.10.
The curves for constant hydraulic power that are drawn in fig.10 are calculated the following way:

$$P_{hydr.} = \frac{m.g.h}{t}$$ where m=mass, g=gravity, h=heigth, t=time

or: $P_{hydr} = q.\rho.g.H$, where q=flow (m^3/s), ρ =density (kg/m^3) and g=gravity(m/s^2), H=elevation head (m)

$$q = \frac{P_{hydr}}{\rho.g.H} \quad m^3/s$$

for instance: assume Phydr= 180 Watt

$$q = \frac{P_{hydr}}{\rho.g.H} \quad m^3/s = \frac{60 \,.\, 180}{1 \,.\, 9.8 \,.\, H}$$

The hyperbolic curve that is described in this equation for q is drawn in fig. 10.
By determining the point of intersection between the q-H curve for the pump and the curve for constant power the point of the maximum power output is found. This seems to be at 9 meter Head, for the 4Amp curve, with an output of 190 Watt.
The exact output at this head can be calculated:

$$P = \frac{130 \,.\, 1 \,.\, 9.8 \,.\, 9}{60} = 191 \text{ Watt.}$$

With this value of Phydr the efficiency of the inverter-pump combination can be calculated.
The efficiency $\eta = \frac{P_{hydr}}{P_{dc}} \,.\, 100\%$ as Pdc is the power input.

$P_{dc} = V_{dc} \,.\, I_{dc} = 98 \,.\, 4 = 392$ Watt

So the maximum efficiency $\eta_{max} = \frac{191}{392} = 48\%$ for this power input.

A5.2 q = f(I).

At a constant head the flow was determined as a function of the input power, which is proportional to the input current Idc.
The results are given in fig. 11.
The first figure is determined by measuring q at constant value of H and for different values of I.

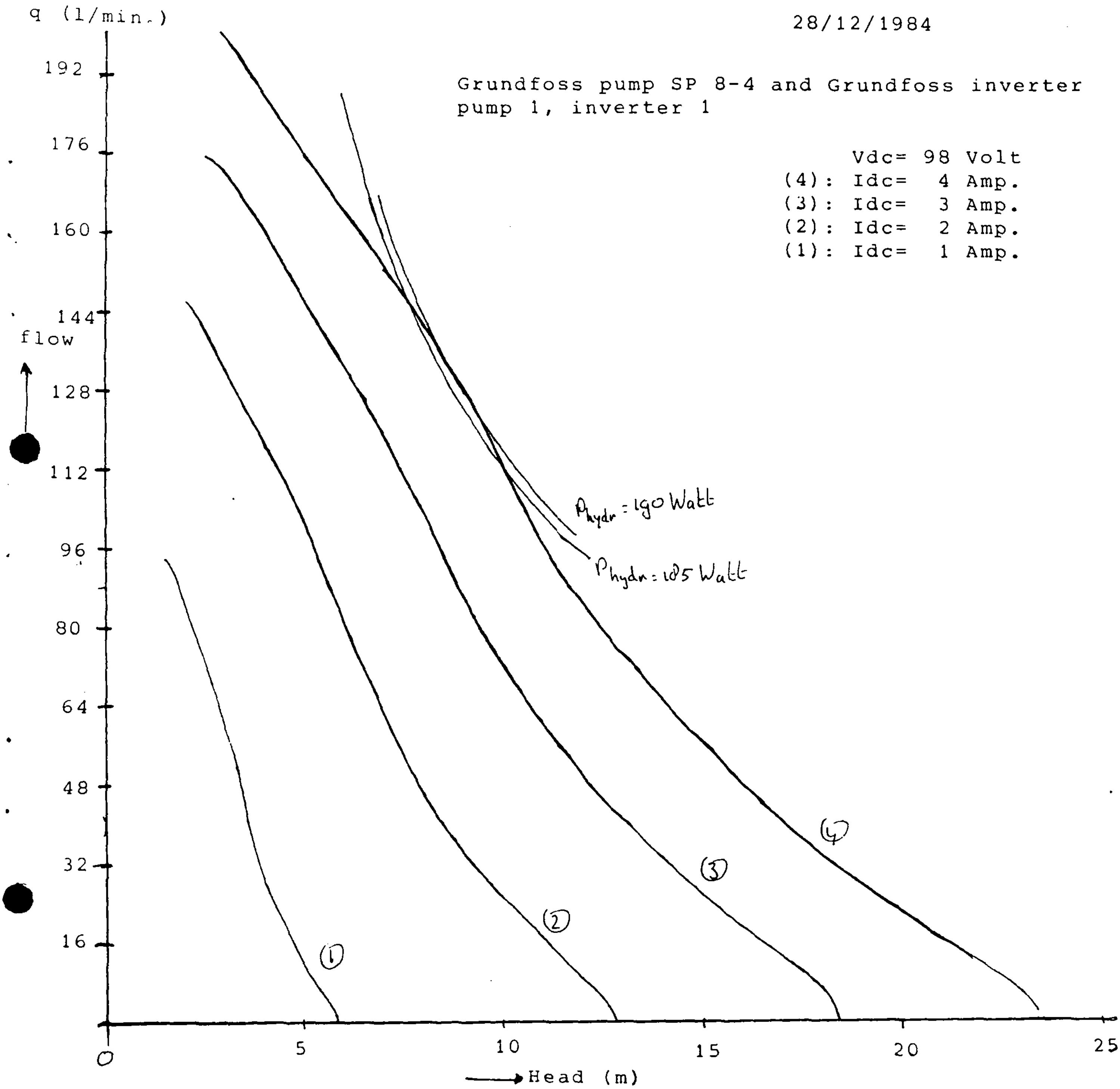


fig. 10 q - H characteristic

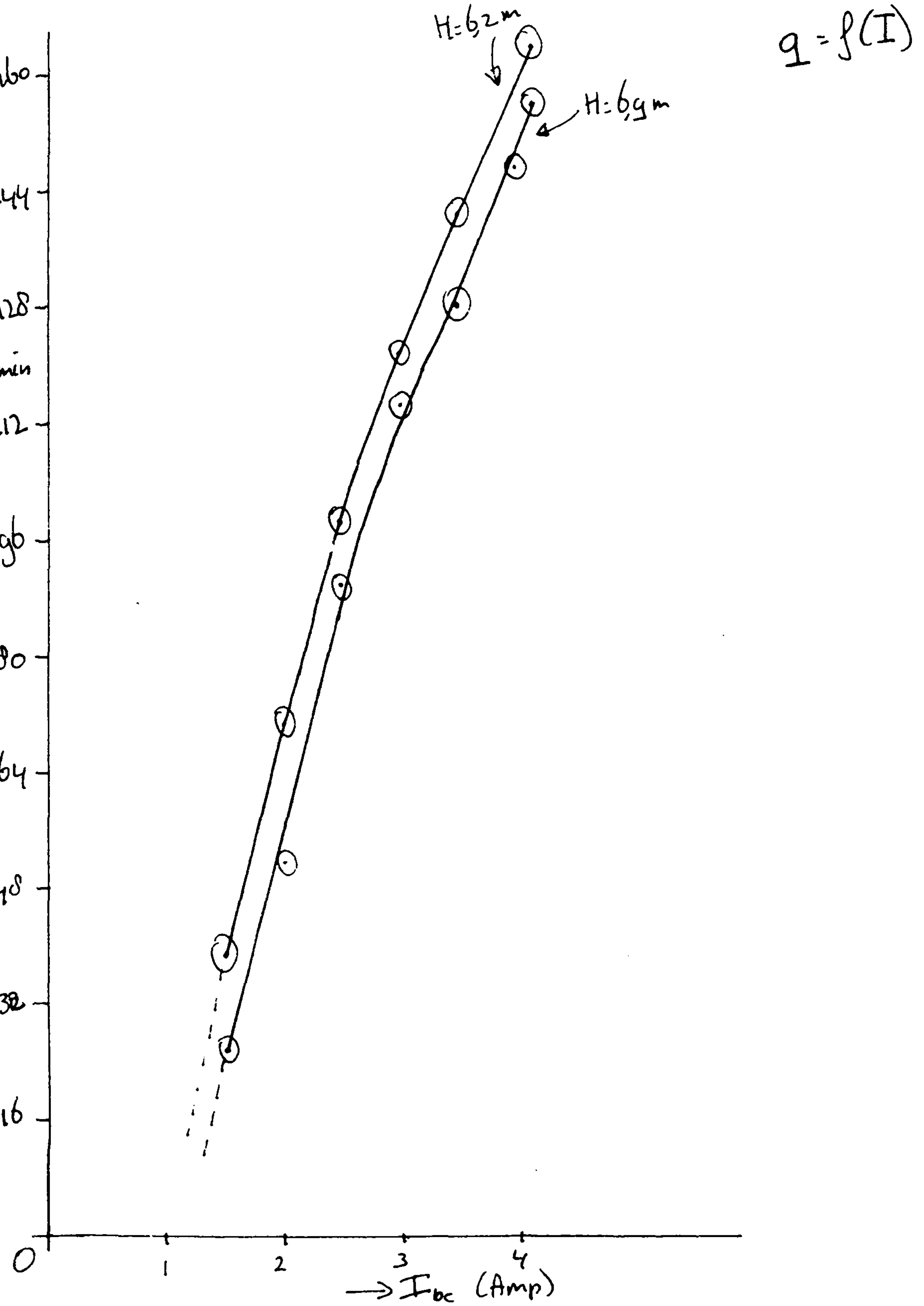


fig. 11 Flow as a function of the DC power input, at a constant head.

pump 1, inverter 1

The elevation head of 7 meter was chosen because it was said that the pump is going to be used to pump water over 7m. From the figure it can be seen that the pump needs at least 1.2 A to start against 6.9 m watercolumn. The flow will be almost nothing.

With the use of this graph q = f(I) it is possible to determine the amount of sunlight needed to give a certain flow at a given head.
For instance: H = 7 m. Say q = 25 l/min.
from the figure it can be seen that the needed input current Idc = 1.5 A.
Let's assume that BPX 47a solar panels are used in a 6 x 7 matrix.
The panels give an ouput of 720 mA at an irradiation of 1000 W/m^2. The output voltage is constant at 14.4 V.
Then each panel should give:

$$Idc = \frac{1.5}{6} = 250 \text{ mA.}$$

To produce this an irradiation E is needed: $\frac{E}{1000} = \frac{250}{720}$

This gives the result: E = 340 W/m^2. E is the intensity of the sunlight that will make the solar pump deliver 25 l/min at an elevation head of 7 m.

A5.3 Starting behaviour of the pump

The exact Voltage needed to start the pump was determined for different current-values.
The watercolumn against which the pump had to start was only 2 m.
It was found that the pump starts at Vdc ≈ 102 V (or more).
Immediately after starting the Voltage Vdc dropped to 98 V, which value then remained constant, independent of changes in current.
It was impossible to make the pump start if the Voltage over the inverter Vdc was only 101 V.
The value of Idc had no influence on the starting behaviour.

A5.4 Efficiency

The hydraulic power output and the efficiency of the pump-inverter combination are determined.
The hydraulic power is Phydr = q . ρ . g . H
The efficincy is : η = Phydr/Pel . 100%
The power input: Pel = Vdc . Idc

So the efficiency is: $\eta = \frac{q.\rho.g.H}{Vdc.Idc} . 100\%$

The results are in fig. 12.

From this figure it can be seen that the efficiency reaches a maximum value at a certain flow. This is caused by the hydraulic efficiency of the pump, which reaches a maximum for a certain rotation speed.

$$\eta = \frac{\text{Hydraulic power output}}{\text{electric power input}} = \frac{P_{hydr}}{P_{dc}} \cdot 100\%$$

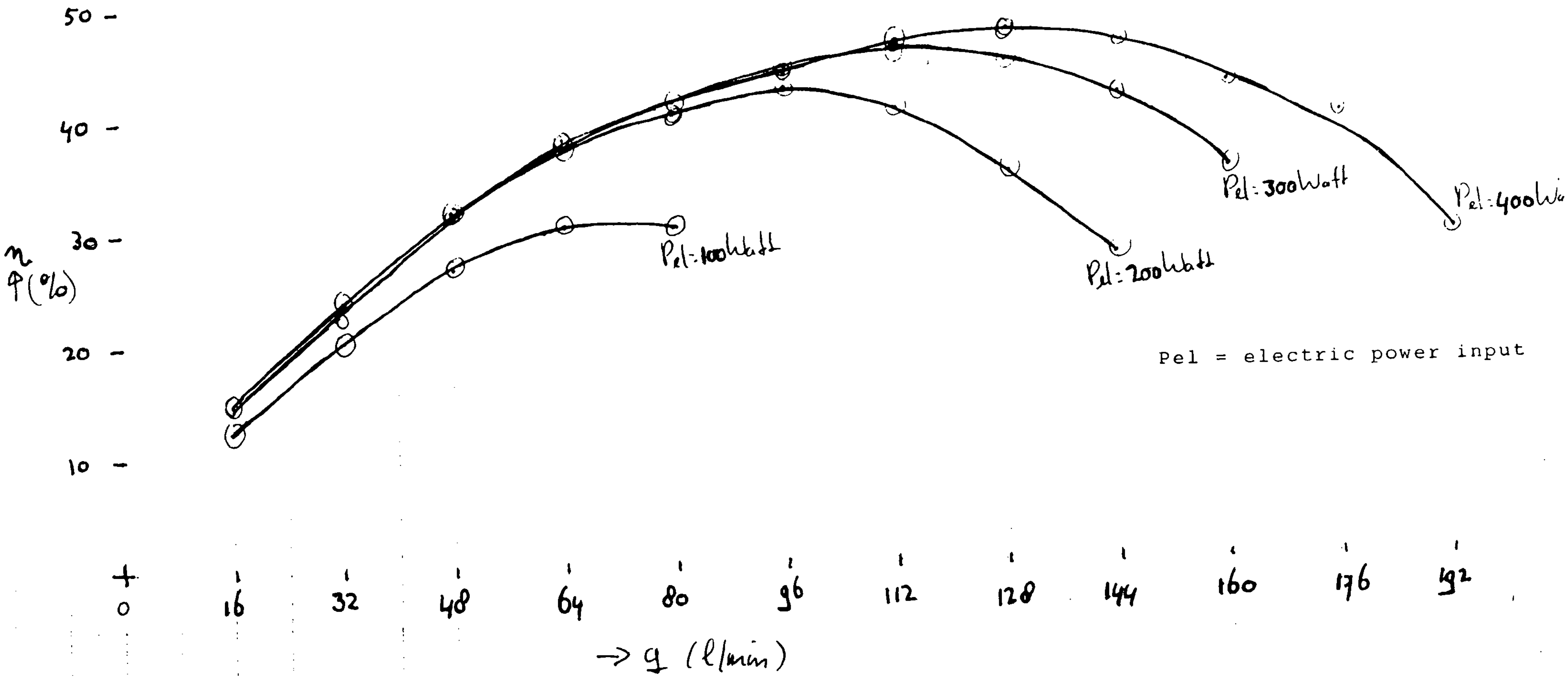


fig 12 Efficiency of the pump-inverter combination as a function of the flow

pump 1, inverter 1

A5.5 Efficiency of the inverter

The efficiency of the inverter is the power output compared to the power input, or:

$$\eta = \frac{Pac}{Pdc} \cdot 100\%$$

Pdc is the power input, direct current.
Pdc = Vdc . Idc
Vdc and Idc were measured with a dc voltmeter and a dc current-meter, both Unigor A43.

Pac is the power output, three phase alternating current
Pac = Vac . Iac . cos φ . 3 , for three phase current.
Pac can be determined by measuring Vac, Iac and the phase-angle φ , but as there was no phase angle meter available Pac had to be measured direct, using a Wattmeter.

The powermeter used was a single-phase Feedback EW 604 Wattmeter. It was connected as in figure 13. The total (three phase) powe. output of the inverter is three times the reading of the single-phase Watt-meter. Also see annex 7.

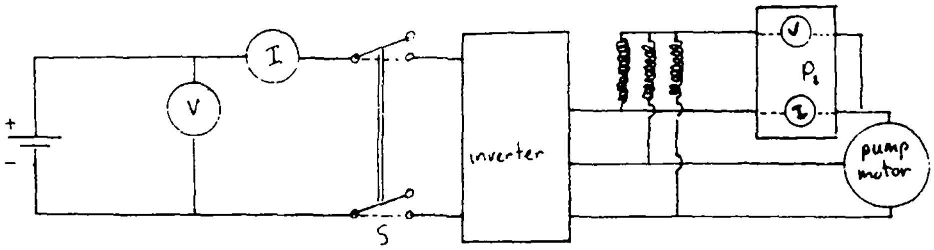


fig. 13 AC-power measurements, electric circuit

The results are:
Pdc = 392 W
Pac = 90 . 3 = 360 W
Then the efficiency is: η = 360/392 . 100 = 92%.
After the electric circuit was optimized (shorter cables, better connectors, etc.) the following results were found for different power inputs.

Table 6

Efficiency of the inverter for different values of the input power and the flow..

power input	flow q (l/min):	150	115	72	34
Pdc = Vdc . Idc	Pac(W)	410	415	410	
Pdc = 420 W	η (%)	98	99	98	
Pdc = 392 W	Pac(W)	380	380	380	400
	η (%)	97	97	97	102
Pdc = 196 W	Pac(W)	200	200	200	215
	η (%)	100	100	100	109

The electric efficiency of the inverter is very high, it gets higher with decreasing power and with decreasing flow. Both , decreasing power and flow, mean that the pump rotates slower, meaning that the output frequency of the inverter gets lower. It seems also that the efficiency of the inverter increases with decreasing frequency of the AC output. But as the efficiency exceeds 100% for low power and low flow it is also possible that the powermeter is not working well for low frequencies, or that it is overall a little bit optimistic. No further investigations have been done to find the cause of this somewhat high results, because it was clear that they were only a little bit too high as could be seen from the efficiency of the combination pump-inverter.

A5.6 Frequency and phase-angle

The frequency of the AC current was determined as a function of the electric power. An oscilloscope was used to measure the wavelength, and so to calculate the frequency. Also the phase-angle was determined. The results are:

Power input: Vdc = 98 V. Idc = 2 A. Pdc = 196 W.
Power output: Pac = 180 W.
Frequency f= 29 cycles/sec, phase-angle $\varphi = 55^{o}$

Power input: Vdc = 98 V. Idc = 4 A. Pdc = 392 W.
Pac = 360 W.
Frequency: f = 41 cycles/sec, phase angle $\varphi = 45^{o}$.

It can be seen that the frequency increases with the input power, the phase angle (the shift between Voltage and current) decreases.
The power output has also been determined for the inverter, and it can be seen that the efficiency is 92%, which is less than the result of test 5, see table 6.

A6 Results of the pumptests, 2^{nd} pumpset

For the second pump and second inverter also flow - Head characteristics have been made. It showed that the second pump performs little better than the first. The results are given in fig.14.
The second inverter does not have any influence on the output, it performs exactly in the same way as the first inverter.

The hydraulic power output of the second pump is 200 W, as can be seen in fig. 15.
As the power input was 400 W, DC, this gives an efficiency for the combination of 50%. As the inverter had no influence, compare fig.14 and fig.15, the pump must be performing better. This can be caused by small differences between the two pumps. It is also possible that this difference gives the error in the testresults, which would mean that with this set up it is not possible to measure the hydraulic performance of a pump more precise than with a 2% margin. The latter is very well possible as certain effects, such as the influence of the waterlevel in the watertank, were not known.

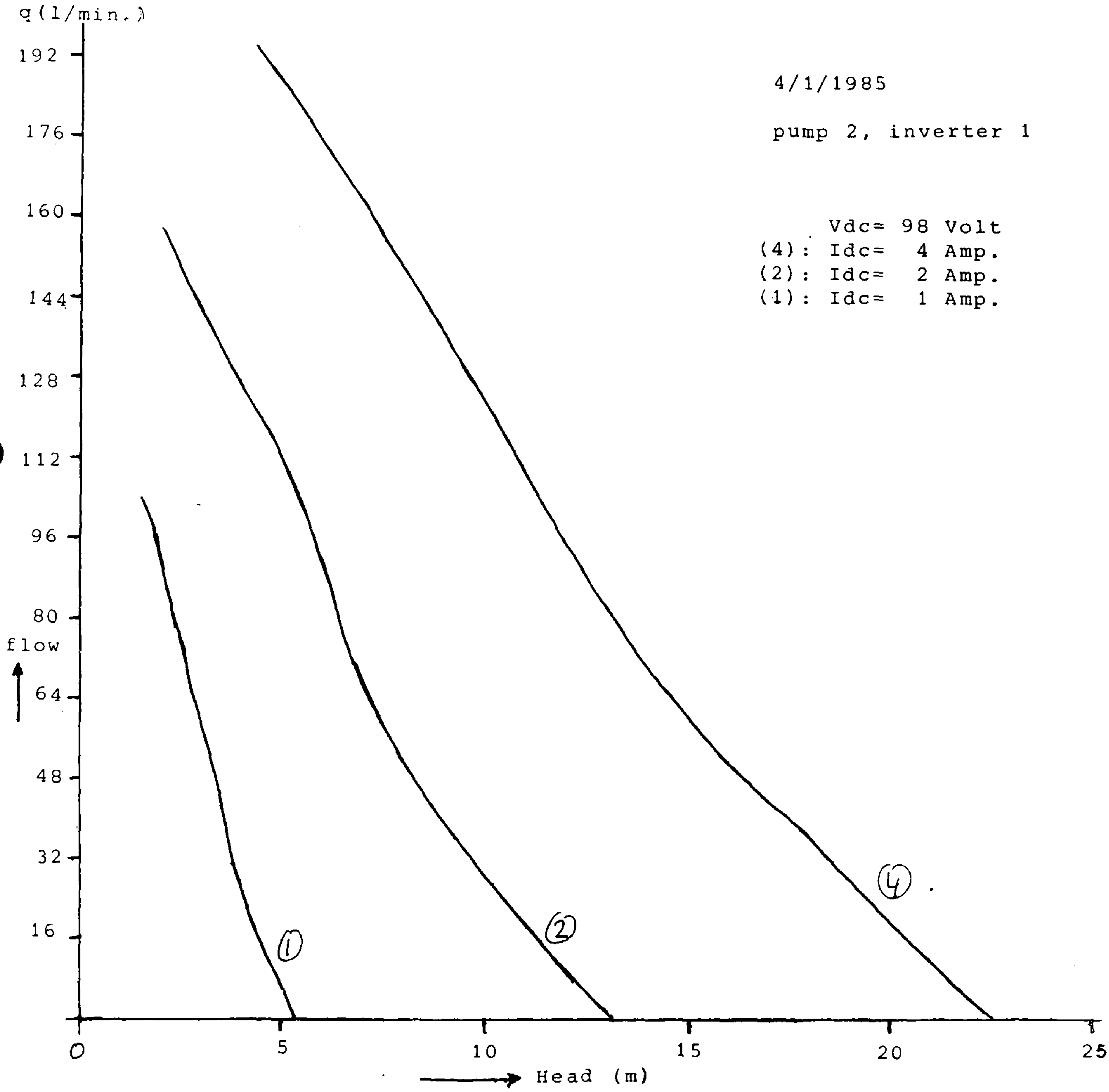


Fig. 14 q - H characteristic

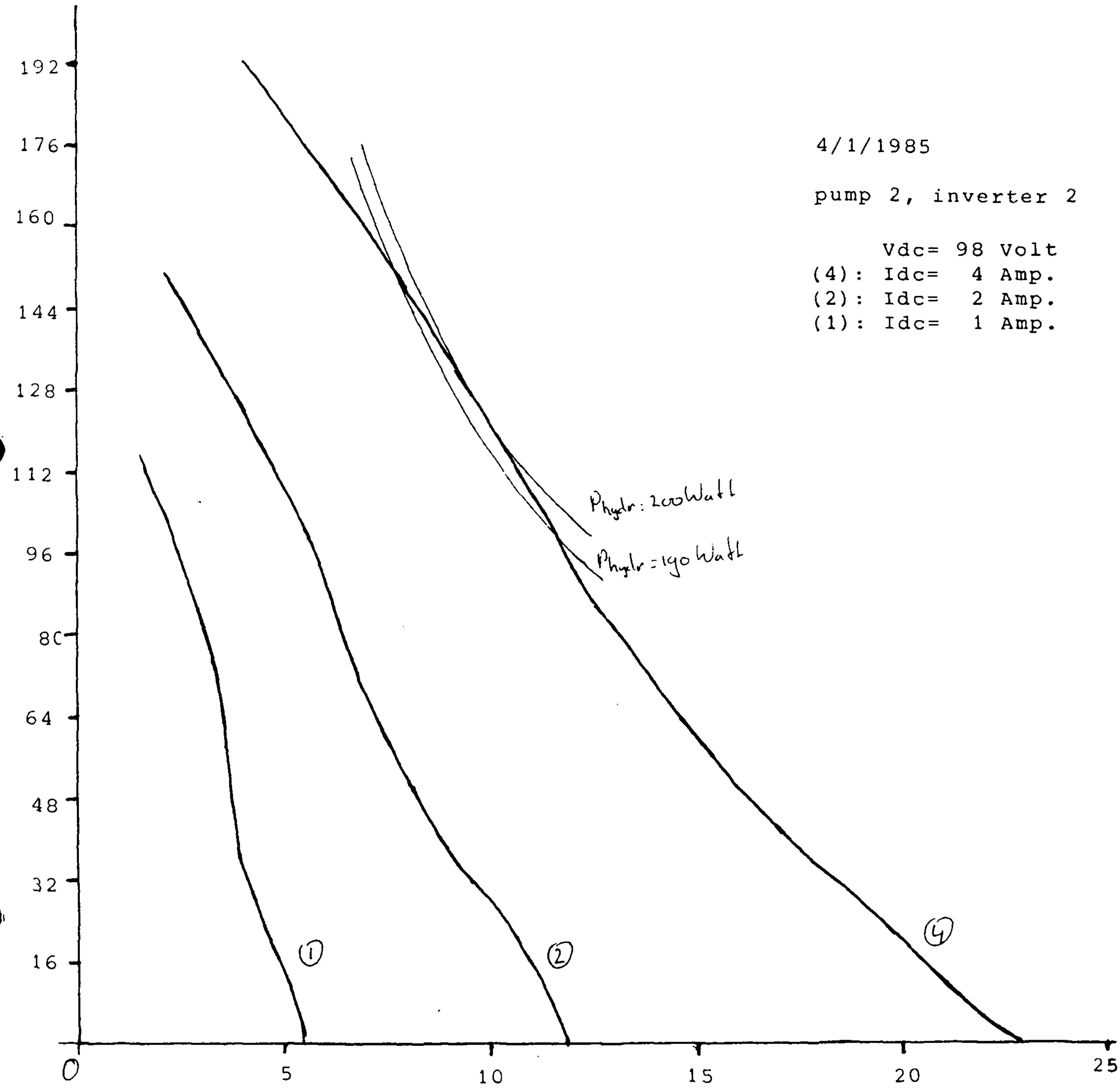


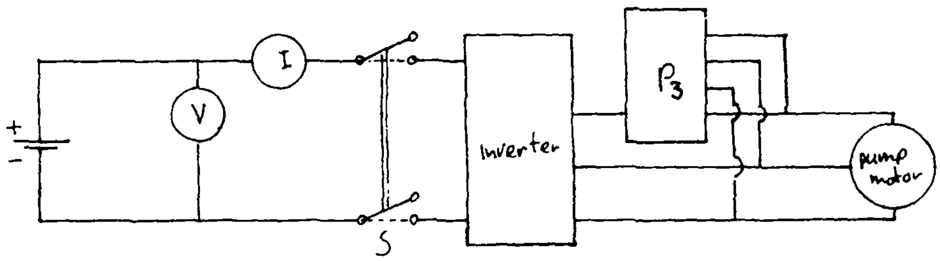
fig. 15 q - H characteristic

A7 AC-power Measurements

These measurements have been performed with two different types of power meter. Both gave problems during the tests.

A7.1 Three-phase power measurement:

A NIEAF three-phase Watt-meter was used, it was connected as in fig. 16.



P_3 = Wattmeter

Fig. 16, Three phase power measurements,

The results of the test are:

Pdc = Vdc . Idc = 98 . 4 = 392 Watts

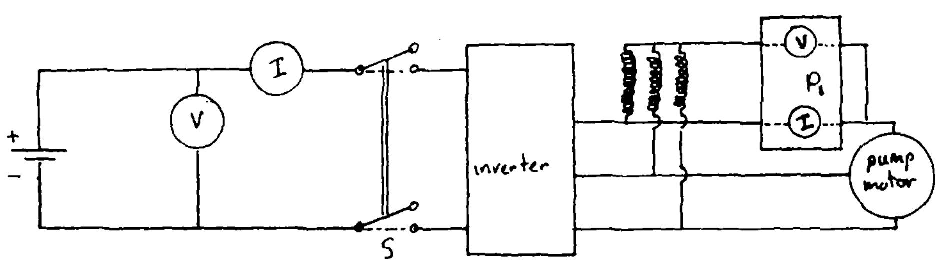
Pac ≈ 340 Watts (direct reading of the Watt-meter.

Then: η = 340/392 . 100 = 87%.

This is much less than the manufacturer gives as the efficiency of the inverter, the conclusions is that the Watt-meter might not be working well, because the pump is performing sufficiently.

A7.2 Single-phase powermeasurements.

The same NIEAF meter was used as a single-phase powermeter. The electric circuit is given in fig. 17.



P_1 = Wattmeter

Fig. 17. Single phase power measurement.

Three coils are connected to the power leads to the pumpmotor to create a neutral lead.
This neutral lead is necessary for the NIEAF meter to measure the single-phase Voltage. The impedance of the coils was very high so there would be no powerloss.
The current in one phase is measured direct.

The results are:
  Pdc = 392 W.
  Measured output: 90 Watts for one phase, so:
  Pac = 3 . 90 = 270 Watts.
Then: η = 270/392 . 100 = 69%.

This value is obviously wrong because the efficiency of the pump-inverter combination reaches 50%. It is not clear why this powermeter did not function properly, the results were not usable.

A7.3 Single-phase power measurements, electronic Wattmeter
Another powermeter was used, the electronic Feedback EW 604. This was connected as in fig. 17.
The results of the tests with this meter were better, they are given in table 6.
There was a problem though, at low power input and waterflow the efficiency of the inverter seems to exceed 100%.
The reason for this strange phenomenon is the fact that the Grundfoss inverter does not produce a clean sinus-shaped AC-output. This disturbes the working of the Watt-meter.

The inverter produces an AC-Voltage at a high frequency, about 2.5 kHz (kCycles/sec.). This value was measured with the oscilloscope. This high frequent AC-Voltage is superposed on a slower AC, with a frequency ranging from 25 to 60 Hz.
See fig. 18

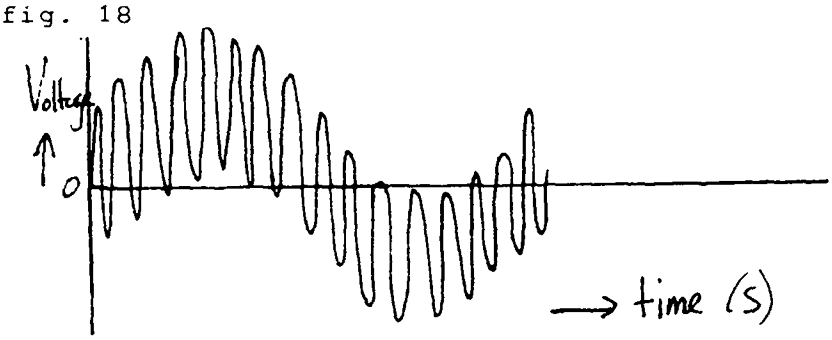


Fig. 18. Output of the inverter

The peak value of the AC-Voltage exceeded 180 V, though the mean Voltage was only 32 V.
As the maximum range of the powermeter was 10 Amp. and 100 V or 5 Amp and 200 V the powermeter was constantly indicating "overflow", both on Voltage and current range. In this case the maximum power reading of the meter never was more than 140 Watt, on a 1000 Watt scale.

The conclusion is that the Watt-meter could not cope with the high Voltage and current peaks. To reduce this effect as much as possible the power measurements were done using the 1000 Watt range,i.c. 10 A and 100 V or 5 A and 200V. The result was ofcourse that always the lower end of the scale was used, never more than 14% of full scale (1000Watts). This increases the error in the results, especially if these are multiplied by three, to calculate the three-phase power.

The error in the readings of the Wattmeter is obviously large enough to produce efficiency numbers that exceed 100%. It is possible that the error in the Watt-meter increases with increasing phase-angle ore decreasing frequency. The phase-angle increases with decreasing power (=decreasing frequency), see annex 5. This may account for the too high values of the efficiency at low power-input of the inverter (table 6). This was not further inverstigated.

The power output of the inverter can also be measured by measuring Vac, Iac and the phase-angle. As there was no phase-angle meter available the oscilloscope was used to determine the phase-angle φ . Because of the very complicated output it was not possible to make an accurate reading reading of φ , see annex 5. Because of this it was not possible to determine Pac more accurate than with a powermeter.

Equipment used:

Function:	Type, specifications:
Voltage meter	Unigor A43, multimeter
Voltage meter	H&B, digital voltmeter
Current meter	Unigor A43, multimeter
Watt meter	NIEAF 1 phase and 3 phase wattmeter
Watt meter	Feedback Electronic Wattmeter, EW 604
Pressure meter	Elan Abgleichautomat MBS 5102 Elan TF messverstärker MBS 5204 Elan Anzeige-einheit MBS 5405
Oscilloscope	HP 1200 A oscilloscope, 100 V, dual trace
X - Y recorder	Kipp BD 91 x-y-y' recorder
Flow meter	MM 50 PVC transmitter LMELA-30 monitoring instr.
DC-power supply	Delta Electronica TPS 050-5, 50V, 5A (three units)
Solarimeter	Kipp CM 5/6, 11.28 μV per W/m^2
Voltage meter	Keithley 177 microvolt, digital voltmeter

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