waterloopkundig laboratorium
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Calibration Khafagi Venturi QV 303 and QV 308

Discharge characteristics for free flow and submerged flow

Calibration report

M 2136

November 1985

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1. Introduction

The Government Institute for Sewage and Waste Water Treatment (RIZA) requested the Delft Hydraulics Laboratory to calibrate the Khafagi Venturi's QV 303 and QV 308 for free flow and to determine the modular limit for the Khafagi Venturi QV 303. The assignment was granted May 9, 1985.
The purpose of the calibration was to check the discharge relations given by the Manufacturer Endress + Hauser in [5].
Endress + Hauser BV Holland lent both Venturi flumes.

The present experiments have been carried out at the Wageningen Branch of the Delft Hydraulics Laboratory, and were conducted by Mr. W. Boiten who also compiled this report.

2. Description of the Khafagi Venturi (Fig. 1 and Photopage I)

The Khafagi Venturi is a rectangular throated flume without bottom contraction and with a throat contraction s = b/B = 0.4 where:

b throat width (m)

B width of the rectangular approach channel (m).

The entrance transition is curved with R = 1.82 B and its length L_1 = B.
The throat section is short, its length x = 0.1 B.
The downstream expansion has a degree of 1:8 which is favourable for the recovery of head. The length of this section L_2 = 2.4 B.
The total length of a Khafagi Venturi becomes L = 3.5 B provided the width of the downstream channel also equals B.
Figure 1 gives the general lay-out of the flume.
The head measurement section is located at a distance Y = B upstream of the entrance transition.
The length of uniform approach channel shall be at least Y = 10 B upstream of the entrance transition according to [6].
Photopage I shows a Khafagi Venturi QV 310 in the water purification plant Velzen (The Netherlands).

3. Types of flow

The name Venturi is somewhat confusing because it is common use to reserve this term for flumes with submerged flow only.
Dr. Khafagi develloped his flume in 1942, just to create the critical depth in the throat section.
Observing the flow profile in the Khafagi Venturi one can distinguish:

- acceleration of the subcritical flow in the reach between the head-measurement section and the throat section resulting in a draw down of the flow profile;
- in the throat section critical flow occurs: $v_c = (g.y_c)^{0.5}$ where:
  y_c critical depth $y_c \approx (2/3)\ H_1$;
- downstream of the throat section the acceleration is continued. Now the flow is supercritical $v > v_c$;
- at a certain distance beyond the throat section the subcritical flow in the downstream channel encounters the supercritical flow, so creating a hydraulic jump.

Essentially three types of flow are possible depending on the submergence ratio $S = 100\ h_2/h_1$ or depending on the location of the hydraulic jump which is governed by the submergence ratio:

- free flow, the hydraulic jump is downstream of the critical section (in the throat);
- modular limit, the hydraulic jump coincides with the critical section;
- submerged flow, the downstream water level is too high to allow critical flow in the throat section.

The Khafagi Venturi has been designed to discharge under free flow conditions, which will be made possible for losses of energy head $\Delta H \geq 0.2\ H_1$ where

H_1 energy head upstream of the flume;
H_2 energy head downstream of the flume;
ΔH loss of energy head $\Delta H = H_1 - H_2$.

4. Discharge equation

Critical depth theory, augmented by experimental data is used to deduce the basic equations through flumes.
For the flow through a streamlined rectangular contraction the discharge equation reads according to the International Standard ISO 4359 [8]:

$$Q = (\frac{2}{3})^{3/2}.(g)^{1/2}.b.m.f.h_1^{1.50} \quad (1)$$

where:

Q discharge (m^3/s)

g gravitational acceleration $g = 9.81\ m/s^2$

b throat width (m)

m combined discharge coefficient (-)

f flow reduction factor for submerged flow
(for free flow f = 1)

h_1 measured head (m)

The combined coefficient $m = C_D.C_V$ where:

C_D characteristic discharge coefficient (-)

C_V approach velocity coefficient (-).

Since there is no reason to analyse m in C_D and C_V, the target of the present study is to express m as a function of h_1/b.
In general it may be expected $m = f(h_1/b, Re)$, where:

Re Reynolds number in the head measurement section $Re = (v.h_1)/\nu$

v mean velocity in the head measurement section (m/s)

ν kinematic viscosity $\nu = 1.05 * 10^{-6}$ (m^2/s)

Only for low Reynolds numbers the coefficient m is dependent on Re. As soon as this is the case, scale effects are introduced. In that case the head-discharge relations of geometrically similar flumes can not be scaled up. One of the goals of this study has been to investigate the presence of scale effects, which may occur for low discharges in flumes with a small throat width.

5. Discharge relations given by Endress + Hauser (Figure 2)

Endress + Hauser France gives in "Canal Khafagi-Venturi QV", [5] head-discharge relations for nine Khafagi Venturi's QV 302 ... QV 316.
The general equation reads:

$$Q = 1.744\ b.h_1^{1.50} + 0.091\ h_1^{2.50} \quad (2)$$

Substitution of equation (2) into equation (1) gives for free flow conditions the following expression for the combined discharge coefficient:

$$m = 1.023 + 0.0534\ h_1/b \qquad (3)$$

In the same report head-discharge relations are presented in tables and curves. From these data the coefficient m has also been derived.
Figure 2 shows m as a function of h_1/b.
For the flumes 0.120 m < b < 0.640 m and for $h_1/b > 0.10$ a linear relation has been derived:

$$m = 1.0216 + 0.0535\ h_1/b \qquad (4)$$

which is almost the same as (3).
Equation (4) is reserved for comparison with the results of the present study.

6. Calibration of the Khafagi Venturi's QV 303 and QV 308

6.1 Free flow with the QV 303 (Table I and Figure 3)

Figure 1 gives the dimensions of the flume. The width b = 0.1206 m.
The model was made of polypropylen and installed in a rectangular channel B = 0.30 m.
The length of the approach channel was Y = 4.20 m. The head was measured at Y = 1.00 m upstream from the entrance transition.
Discharges were measured volumetrically and by a calibrated V-notch thin plate weir, having accuracies of about 0.5% of the actual discharge.
Heads were measured with a pointgauge having an accuracy of 0.2 mm.
During the experiments the downstream water level was kept sufficiently low to ensure free flow through the flume (hydraulic jump downstream of the throat).
Table I gives the results of 30 measurements Q-h_1.

- The discharge coefficient m has been calculated using equation (1).
- Reynolds number has been calculated for the head measurement section.
- X_m expresses the deviation between Endress + Hauser's coefficient m (equation 4) and the measured m-value. For $h_1/b > 0.4$ the deviation $X_m < 2\%$.

Figure 3 gives the discharge coefficient m as a function of h_1/b.

6.2 Submerged flow with the QV 303 (Table II, figures 4, 5 and 6, photopages II)

The channel section downstream of the flume had a length Y = 5.00 m.
The downstream waterlevel was measured at Y = 4.20 m.
At the end of this channel the waterlevel was controlled by small stoplogs.
For nine different discharges submerged flow measurements were taken.
Table II gives the results $Q-h_1-h_2$ and the position Y of the hydraulic jump with respect to the end of the throat section (beginning of the downstream expansion).

- Q_E is the discharge calculated with equation (1) and based on the drowned head h_1;
- the flow reduction factor is defined as $f = Q_o/Q_E$;
- the submergence ratio is defined as $S = 100\ h_2/h_1$ (%).

Figure 4 shows the results of submerged flow measurements. Apparently the flow reduction factor is a function of the submergence ratio S and the parameter h_1/b.
Figure 5 illustrates the position of the hydraulic jump related to the submergence ratio. This relation is independent on the discharge (or on the parameter h_1/b).
Figure 6 gives the modular limit for the flume QV 303.

- the first graph relates the modular limit to the parameters h_1/b and Y/b.
  Conclusion: At full capacity $h_1 = 2b$ the hydraulic jump should be located at Y = 1.4 b downstream of the throat section to ensure the modular limit.
- the second graph relates the modular limit to the parameters h_1/b and S.
  Conclusion: At full capacity $h_1 = 2b$ the modular limit is $S_1 = 80\%$.

6.3 Free flow with the QV 308 (table III, figures 7 and 8, photopage III)

Figure 1 gives the dimensions of the flume. The width b = 0.32 m.
The model was made of polypropylen and installed in a rectangular channel B = 0.80 m.
The length of the approach channel was Y = 6.80 m. The heads were measured at three locations Y = 2.00 m, Y = 0.80 m and Y = 0.47 m upstream from the entrance transition.
Discharges were measured volumetrically or by an electro-magnetic flowmeter, having accuracies of about 0.5% of the actual discharge.

Table III gives the results of 28 measurements $Q-h_1$.

- The discharge coefficient m has been calculated using equation (1) and based on the head measured at Y = 0.80 m;
- The differences in head at the three locations Y are negligible;
- For $h_1/b \geqslant 0.25$ the deviations $X_m < 2\%$.

Figure 7 gives the discharge coefficient m as a function of h_1/b.

For a high discharge $h_1/b = 1.72$ the surface draw-down in the flume has been observed.

Figure 8 shows the flow profile.

- the draw-down starts at Y = 0.40 m upstream of the flume. Measurement of head closer to the flume are leading to the deviation:

  $$X_h = \frac{h_Y - h_{0.80}}{h_{0.80}} 100 \ (\%)$$

  This deviation is for $h_1/b = 1.72$ as follows:

location of head measurement	deviation X_h
Y = 0.30 m	-0.2 %
Y = 0.15 m	-0.5 %
Y = 0	-1.0 %

- The critical section is located just beyond the throat.

7. Comparison of results with earlier studies

The results of the present calibration will be compared with the following two different sources:

a) Hydraulische berechnung von Venturikanälen typ Khafagi E.T.H. Zürich, 1976 [9].

b) Bauart-prüfung des Venturikanals typ Khafagi Venturi Univ. Stuttgart, 1982 [7].

Barczewski [1] recommended a general equation, which can be converted in

$$Q = (\tfrac{2}{3})^{3/2}.(g)^{1/2}.b.m.h_1^{1.50} \quad \text{with} \quad m = 1.021 + 0.0527\ h_1/b.$$

This is almost the same coefficient as presented by [7] and adapted in [5]. The available information papers of Endress + Hauser adapted their head-discharge relations from [9] and later from [7] as follows:

original source	location of head measurement	modular limit	Endress + Hauser information papers
ETH Zürich [9]	$Y = 0.15$	$S = 75\%$	[3] and [4]
Univ. Stuttgart [7]	$Y = 1$ to $2B$	$S = 70\%$	[5] and [6]

The head-discharge relations of both studies [9] and [7] are compared with the present calibration, carried out by Delft Hydraulics Laboratory (DHL), for the Khafagi Venturi QV 308.

head h_1 (m)	h_1/b	discharge (m^3/s) according to			deviations $X_Q = \frac{Q - Q_{DHL}}{Q_{DHL}} 100$ (%)	
		Zürich [9]	Stuttgart [7]	DHL*	Zürich [9]	Stuttgart [7]
0.12	0.38	23.1	23.62	23.36	-1.1	1.1
0.24	0.75	65.7	68.11	67.59	-2.8	0.8
0.36	1.12	121.1	127.49	126.85	-4.5	0.5
0.48	1.50	187.5	199.91	199.40	-6.0	0.3
0.60	1.88	263.6	284.46	284.51	-7.3	0.0

* The DHL discharges have been calculated based upon the relation $m - h_1/b$ presented in figure 3.

8. Conclusions and recommendations (fig. 9...11 and table IV)

Conclusions

1. The recommended discharge coefficient $m = f(h_1/b)$ for the Khafagi Venturi's QV 303 and QV 308 is presented in figure 9.
   The lower limit in the h_1/b range is based on $h_{min} = 0.05$ m, which is recommended for long throated Venturi flumes [8]. The upper limit $h_1/b = 2$.
   Both flumes are geometrically similar. From the curves in figure 9 it can be concluded that small scaling effects are present for low discharges.
   Table IV gives the head-discharge relations for QV 303 and QV 308, based on the present calibration.
2. Comparison of the present calibration of the Khafagi Venturi QV 308 with earlier studies learns:
   a) the deviation with the Zürich-data [9] is about $X_Q = -8\%$ for the maximum discharge ($h_1/b = 2$).

b) there is a fair agreement with the Stuttgart data [7] which have been adapted by Endress + Hauser in their information papers [5] and [6].

3. The modular limit has been determined in the present calibration for the Khafagi Venturi QV 303.
   Figure 10 relates the modular limit to the submergence ratio and also to the position of the hydraulic jump. For the maximum discharge ($h_1/b = 2$) the modular limit is S = 80%, which is better than in earlier studies:
   - E.T.H. Zürich, 1976 [9] S = 75%
   - Univ. Stuttgart, 1982 [7] S = 70%.
4. Submerged flow can be estimated when both waterlevels h_1 and h_2 are measured. The latter one should be measured sufficiently far downstream of the turbulent area in the throat.
   The discharge equation is

$$Q = (\frac{2}{3})^{3/2} . (g)^{1/2} . b.m.f.h_1^{1.50}$$

   where f is the drowned flow reduction factor (-).
   Figure 11 gives this factor f as a function of the submergence ratio S and the parameter h_1/b.
   The modular limit S_1 as well as the drowned flow reduction factor f are expected to be applicable to all Khafagi Venturi's QV 303...QV 316.

Recommendations

1. The general requirements for the construction and the installation of the Khafagi Venturi and the measurement of head can be adapted from the International Standard for long throated flumes [8].
   The location of the head measurement section shall be at Y = 1B upstream of the entrance transition.
2. Further calibration shall be necessary to determine scaling effects for the other Khafagi Venturi's.
   It is recommended to extend the present study with the calibration of the Khafagi Venturi's QV 302 and QV 305. From the results of the Venturi's QV 302, QV 303, QV 305 and QV 308 the scale effects for the whole family of Khafagi Venturi's QV 302...QV 316 can be estimated.
   Standardization of the Khafagi Venturi by the International Organization of Standardization might then be considered.

Notations

b	throat width	m
B	width of approach channel	m
C_D	characteristic discharge coefficient	-
C_V	coefficient of approach velocity	-
f	drowned flow reduction factor	-
g	gravitational acceleration	m/s^2
h_1	upstream gauged head	m
h_2	downstream gauged head	m
H_1	upstream energy head	m
H_2	downstream energy head	m
L	length of flume section	m
m	discharge coefficient $m = C_D . C_V$	-
Q	discharge	m^3/s
Q_E	discharge calculated from drowned h_1	m^3/s
R	radius entrance transition	m
Re	Reynold number $Re = v.h/\nu$	-
s	throat contraction $s = b/B = 0.4$	-
S	submergence ratio $S = 100\ h_2/h_1$	%
S_1	modular limit	-
v	flow velocity	m/s
v_c	velocity in critical section	m/s
x	throat length $x = 0.1\ B$	m
X_m	deviation in m	%
y_c	critical depth	m
Y	length	m
ΔH	loss of energy head	m
ν	kinematic viscosity	m^2/s

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$b = 0.1206\ m \qquad m = Q/(\frac{2}{3})^{3/2}.(g)^{1/2}.b.h_1^{1.50} \qquad m_{EH} = 1.0216 + 0.0535 \frac{h_1}{b}$

measurements			calculations			comparison with m_{EH}	
no.	Q (10^{-3} m^3/s)	h_1 (m)	m (-)	h_1/b (-)	$Re = \frac{v.h_1}{\nu}$ (-)	m_{EH} (-)	$X_m = 100 \frac{m_{EH} - m}{m}$ (%)
1	0.514 *	0.0208	0.8333	0.172	1600	1.0308	23.7
2	0.661 *	0.0236	0.8867	0.196	2100	1.0321	16.4
3	0.732	0.0246	0.9226	0.204	2300	1.0325	11.9
4	0.827 *	0.0262	0.9484	0.217	2600	1.0332	8.9
5	0.961	0.0280	0.9975	0.232	3100	1.0340	3.7
6	1.039 *	0.0294	1.0024	0.244	3300	1.0346	3.2
7	1.151 *	0.0316	0.9965	0.262	3600	1.0356	3.9
8	1.381 *	0.0356	0.9999	0.295	4400	1.0374	3.8
9	1.748 *	0.0412	1.0165	0.342	5500	1.0399	2.3
10	2.093 *	0.0463	1.0217	0.384	6600	1.0421	2.0
11	2.693 *	0.0546	1.0265	0.453	8600	1.0458	1.9
12	3.418 (s)	0.0641	1.0243	0.532	10800	1.0500	2.5
13	4.054 *	0.0715	1.0312	0.593	12900	1.0533	2.0
14	4.886 (s)	0.0806	1.0384	0.668	15500	1.0574	1.8
15	6.020 *	0.0923	1.0441	0.765	19100	1.0625	1.8
16	7.146 (s)	0.1030	1.0513	0.854	22700	1.0673	1.5
17	8.392 *	0.1141	1.0589	0.946	26600	1.0722	1.3
18	9.811 (s)	0.1260	1.0668	1.045	31200	1.0775	1.0
19	11.507 *	0.1393	1.0764	1.155	36500	1.0834	0.7
20	12.980 (s)	0.1509	1.0769	1.251	41200	1.0885	1.1
21	15.385 *	0.1676	1.0905	1.390	48800	1.0959	0.5
22	17.251 (s)	0.1801	1.0977	1.493	54800	1.1015	0.3
23	19.049 *	0.1920	1.1012	1.592	60500	1.1068	0.5
24	20.922 (s)	0.2032	1.1108	1.685	66400	1.1117	0.1
25	22.925 *	0.2157	1.1129	1.789	72800	1.1173	0.4
26	24.685 (s)	0.2259	1.1181	1.873	78400	1.1218	0.3
27	26.961 *	0.2387	1.1243	1.979	85600	1.1275	0.3
28	30.726 *	0.2584	1.1376	2.143	97500	1.1362	-0.0
29	31.153	0.2615	1.1330	2.168	98900	1.1376	0.4
30	31.279	0.2616	1.1369	2.169	99300	1.1376	0.1

results are presented in figure 3

* volumetric calibration
(s) also submerged flow $\qquad \nu = 1.05 * 10^{-6}\ m^2/s$

Results of free flow measurements, QV 303

TABLE I

Run: 109

b = 0.1206 m

B = 0.300 m

$Q_E = (\frac{2}{3})^{3/2} . (g)^{1/2} . b.m.h_1^{1.50}$

Q_o is calculated discharge for h_2 low

S is the submergence ratio

m is taken from figure 3

measurements						calculations				
		gauged head		position hydr. jump					f =	S =
no.	Q (10^{-3} m^3/s)	h_1 (m)	h_2 (m)	Y (m)	Y/b (-)	h_1/b (-)	m (-)	Q_E (10^{-3} m^3/s)	Q_o/Q_E	$100 \frac{h_2}{h_1}$ (%)
29	31.153	0.2615		1		2.168	1.1357	31.228	-	< 0
		0.2615	0.1930	0.28	2.32	2.168	1.1357	31.228	1.000	73.8
		0.2623	0.2033	0.20	1.66	2.175	1.1363	31.388	0.995	77.5
		0.2629	0.2080	0.17	1.41	2.180	1.1366	31.504	0.991	79.1
		0.2636	0.2135	0.14	1.16	2.186	1.1368	31.635	0.987	81.0
26	24.685	0.2259	0.1376			1.873	1.1196	24.718	-	60.9
		0.2259	0.1636	0.31	2.57	1.873	1.1196	24.718	1.000	72.4
		0.2266	0.1780	0.17	1.41	1.879	1.1199	24.839	0.995	78.6
		0.2275	0.1850	0.14	1.16	1.886	1.1204	24.999	0.989	81.3
		0.2302	0.1951	0.09	0.75	1.909	1.1216	25.472	0.970	84.8
		0.2339	0.2047	0.07	0.58	1.939	1.1233	26.128	0.946	87.5
		0.2368	0.2112	0.06	0.50	1.964	1.1248	26.651	0.927	89.2
		0.2416	0.2210			2.003	1.1271	27.522	0.898	91.5
		0.2459	0.2279	0.04	0.33	2.039	1.1290	28.308	0.873	92.7
		0.2491	0.2333	0.04	0.33	2.066	1.1305	28.900	0.855	93.7
		0.2592	0.2480	0.03	0.25	2.149	1.1349	30.795	0.803	95.7
		0.2634	0.2530			2.184	1.1369	31.602	0.782	96.1
18	9.811	0.1260	0.0790			1.045	1.0653	9.797	-	62.7
		0.1260	0.0985	0.20	1.66	1.045	1.0653	9.797	1.000	78.2
		0.1264	0.1092	0.09	0.75	1.048	1.0654	9.845	0.995	86.4
		0.1280	0.1146	0.06	0.50	1.061	1.0665	10.043	0.976	89.5
		0.1291	0.1184	0.05	0.41	1.070	1.0671	10.178	0.963	91.7
		0.1344	0.1280	-	-	1.114	1.0702	10.843	0.904	95.2
		0.1388	0.1338	u.s.		1.151	1.0728	11.407	0.859	96.4
		0.1458	0.1421	u.s.		1.209	1.0768	12.327	0.795	97.5
14	4.886	0.0806	0.0449			0.668	1.0382	4.885	-	55.7
		0.0806	0.0645	0.20	1.66	0.668	1.0382	4.885	1.000	80.0
		0.0814	0.0742	0.06	0.50	0.675	1.0389	4.961	0.985	91.2
		0.0834	0.0781	u.s.		0.692	1.0402	5.152	0.948	93.6
		0.0848	0.0802	u.s.		0.703	1.0410	5.286	0.924	94.6
		0.0877	0.0844	u.s.		0.727	1.0425	5.567	0.877	96.2
		0.0927	0.0903	u.s.		0.769	1.0454	6.067	0.805	97.4
22	17.251	0.1801	0.1156			1.493	1.0956	17.218	-	
		0.1803	0.1278	0.40	3.32	1.495	1.0958	17.250	0.998	70.9
		0.1803	0.1350	0.26	2.16	1.495	1.0958	17.250	0.998	74.9
		0.1803	0.1448	0.17	1.41	1.495	1.0958	17.250	0.998	80.3
		0.1812	0.1490	0.13	1.08	1.502	1.0964	17.389	0.990	82.2
		0.1822	0.1553	0.10	0.83	1.511	1.0969	17.541	0.982	85.2
		0.1835	0.1601	0.08	0.66	1.522	1.0976	17.741	0.971	87.2
		0.1858	0.1658	0.06	0.50	1.541	1.0988	18.095	0.952	89.2
		0.1875	0.1700	0.05	0.41	1.555	1.0997	18.359	0.938	90.7
		0.1924	0.1793	0.04	0.33	1.595	1.1021	19.125	0.900	93.2
		0.2019	0.1941	0.04	0.33	1.674	1.1073	20.656	0.834	96.1

measurements						calculations				
		gauged head		position hydr. jump					f =	S =
no.	Q (10^{-3} m^3/s)	h_1 (m)	h_2 (m)	Y (m)	Y/b (-)	h_1/b (-)	m (-)	Q_E (10^{-3} m^3/s)	Q_o/Q_E	$100 \frac{h_2}{h_1}$ (%)
24	20.922	0.2032	0.1346	0.54	4.47	1.685	1.1079	20.867	-	66.2
		0.2034	0.1519	0.28	2.32	1.687	1.1080	20.900	0.998	74.7
		0.2047	0.1688	0.12	1.00	1.697	1.1087	21.114	0.988	82.5
		0.2054	0.1727	-	-	1.703	1.1092	21.232	0.983	84.1
		0.2072	0.1786	0.10	0.83	1.718	1.1100	21.527	0.969	86.2
		0.2089	0.1827	0.08	0.66	1.732	1.1110	21.812	0.957	87.5
		0.2134	0.1932	0.06	0.50	1.769	1.1130	22.561	0.925	90.5
		0.2183	0.2022	0.05	0.41	1.810	1.1158	23.401	0.892	92.6
		0.2281	0.2173	0.03	0.25	1.891	1.1206	25.102	0.831	95.3
		0.2435	0.2372	u.s.	-	2.019	1.1280	27.870	0.749	97.4
12	3.418	0.0641	0.0374	-	-	0.532	1.0285	3.432	-	58.3
		0.0653	0.0599	0.07	0.58	0.541	1.0290	3.531	0.972	91.7
		0.0666	0.0625	0.06	0.50	0.552	1.0300	3.640	0.943	93.8
		0.0696	0.0666	u.s.	-	0.577	1.0316	3.895	0.881	95.7
20	12.980	0.1509	0.1007	0.50	4.14	1.251	1.0798	13.015	-	66.7
		0.1509	0.1183	0.21	1.74	1.251	1.0798	13.015	1.000	78.4
		0.1515	0.1287	-	-	1.256	1.0800	13.095	0.994	85.0
		0.1524	0.1329	-	-	1.264	1.0805	13.218	0.985	87.2
		0.1542	0.1385	0.07	0.58	1.279	1.0814	13.477	0.966	89.8
		0.1557	0.1423	0.07	0.58	1.291	1.0825	13.675	0.952	91.4
		0.1614	0.1530	0.05	0.41	1.338	1.0854	14.472	0.899	94.8
		0.1710	0.1661	-	-	1.418	1.0909	15.862	0.821	97.1
16	7.146	0.1030	0.0758	0.31	2.57	0.854	1.0517	7.149	-	73.6
		0.1031	0.0858	0.14	1.16	0.855	1.0517	7.159	1.000	83.2
		0.1039	0.0923	0.08	0.66	0.862	1.0523	7.247	0.986	88.8
		0.1047	0.0958	0.06	0.50	0.868	1.0528	7.334	0.975	91.5
		0.1074	0.1012	u.s.	-	0.891	1.0545	7.632	0.937	94.2
		0.1168	0.1136	u.s.	-	0.968	1.0600	8.700	0.822	97.3

. u.s. = unstable position

. results are presented in figure 4

Results of submerged flow measurements QV 303, Run 109

TABLE II

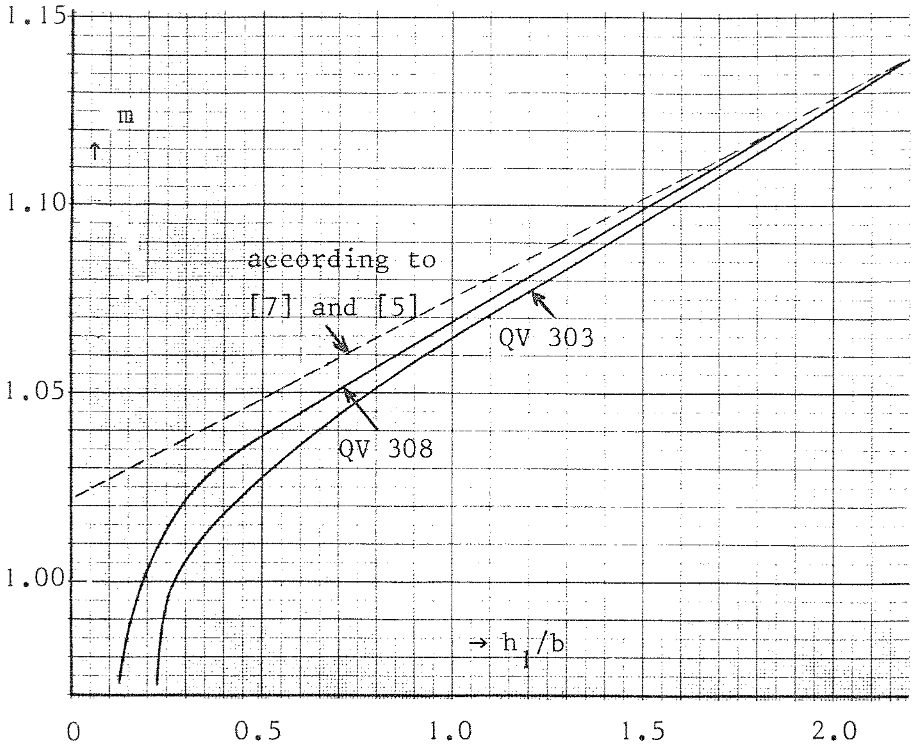
$b = 0.3200$ m $\quad m = Q/(\frac{2}{3})^{3/2}.(g)^{1/2}.b.h_1^{150} \quad m_{EH} = 1.0216 + 0.0535 \frac{h_1}{b}$

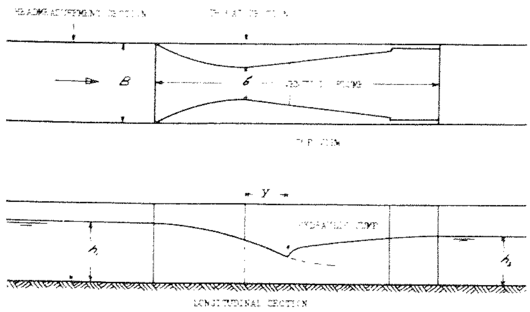
measurements					calculations			comparison with m_{EH}	
no.	Q $(10^{-3}\ m^3/s)$	heads h_1(m) at Y = 2.00 m	0.80 m	0.47 m	m (-)	head at X=0.80 m h_1/b (-)	Re = $\frac{v.h_1}{\nu}$ (-)	m_{EH}	X_m (%)
1	3.389 *	0.0350	0.0349	0.0347	0.9527	0.109	4000	1.0274	7.8
2	4.742 *	0.0431	0.0429	0.0426	0.9781	0.134	5600	1.0288	5.2
3	6.061 *	0.0504	0.0501	0.0500	0.9906	0.157	7200	1.0300	4.0
4	7.394 *	0.0570	0.0567	0.0566	1.0038	0.177	8800	1.0311	2.7
5	8.707 *	0.0634	0.0632	0.0630	1.0044	0.198	10400	1.0322	2.8
6	10.032 *	0.0694	0.0693	0.0691	1.0079	0.217	11900	1.0332	2.5
7	11.306 *	0.0752	0.0750	0.0748	1.0089	0.234	13500	1.0341	2.5
8	12.609 *	0.0806	0.0804	0.0802	1.0137	0.251	15000	1.0350	2.1
9	17.049 *	0.0979	0.0977	0.0974	1.0233	0.304	20300	1.0379	1.4
10	22.505 *	0.1171	0.1170	0.1168	1.0307	0.365	26800	1.0412	1.0
11	27.683 *	0.1342	0.1341	0.1339	1.0332	0.418	33000	1.0440	1.0
12	33.177 *	0.1510	0.1509	0.1508	1.0374	0.471	39500	1.0468	0.9
13	38.421 *	0.1663	0.1662	0.1659	1.0393	0.519	45700	1.0494	1.0
14	43.637	0.1807	0.1805	0.1805	1.0430	0.564	51900	1.0518	0.8
15	50.793	0.1991	0.1989	0.1989	1.0495	0.622	60500	1.0549	0.5
16	62.822	0.2292	0.2291	0.2289	1.0500	0.716	74800	1.0599	0.9
17	74.895	0.2563	0.2562	0.2561	1.0585	0.801	89200	1.0644	0.6
18	89.379	0.2884	0.2883	0.2882	1.0583	0.901	106400	1.0698	1.1
19	105.591	0.3205	0.3206	0.3203	1.0661	1.002	125700	1.0752	0.9
20	122.443	0.3525	0.3526	0.3524	1.0719	1.102	145800	1.0806	0.8
21	141.279	0.3850	0.3851	0.3852	1.0835	1.203	168200	1.0860	0.2
22	162.973	0.4226	0.4230	0.4229	1.0858	1.322	194000	1.0923	0.6
23	186.545	0.4597	0.4600	0.4599	1.0959	1.438	222000	1.0985	0.2
24	206.917	0.4903	0.4906	0.4904	1.1036	1.533	246300	1.1036	0.0
25	221.636	0.5127	0.5131	0.5130	1.1053	1.603	263900	1.1074	0.2
26	227.852	0.5223	0.5227	0.5224	1.1051	1.633	271300	1.1090	0.4
27	241.175	-	0.5405	0.5407	1.1124	1.689	287100	1.1120	-0.0
28	248.204	-	0.5502	0.5501	1.1147	1.719	295500	1.1136	-0.1
29									
30					results are presented in figure 7				

* volumetric calibration $\quad \nu = 1.05 * 10^{-6}\ m^2/s$

Results of free flow measurements QV 308

TABLE III





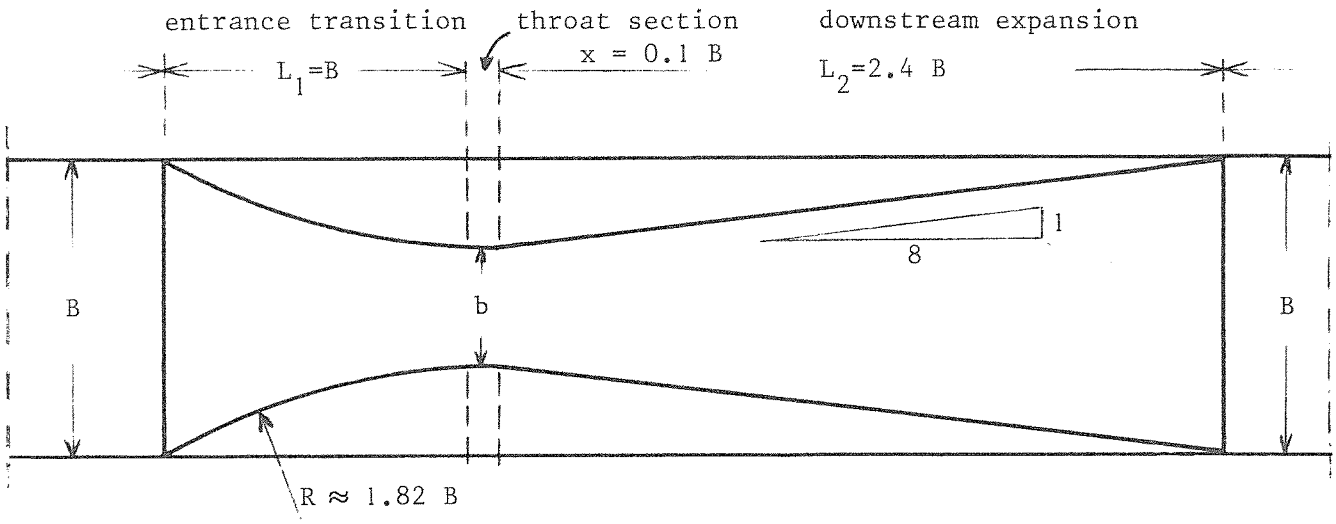
$$Q = \left(\frac{2}{3}\right)^{3/2} \cdot (g)^{1/2} \cdot b \cdot m \cdot h_1^{1.50}$$

QV 303	$Q = \left(\frac{2}{3}\right)^{3/2} \cdot (g)^{1/2} \cdot 0.12 \cdot h_1^{1.50}$	
h_1 (m)	m (-)	Q (10^{-3} m^3/s)
0.05	1.020	2.33
0.06	1.028	3.09
0.07	1.035	3.92
0.08	1.041	4.63
0.09	1.048	5.79
0.10	1.054	6.82
0.11	1.059	7.90
0.12	1.065	9.06
0.13	1.070	10.26
0.14	1.075	11.52
0.15	1.080	12.83
0.16	1.085	14.21
0.17	1.090	15.63
0.18	1.096	17.12
0.19	1.101	18.66
0.20	1.106	20.24
0.21	1.111	21.88
0.22	1.116	23.56
0.23	1.121	25.30
0.24	1.127	27.11

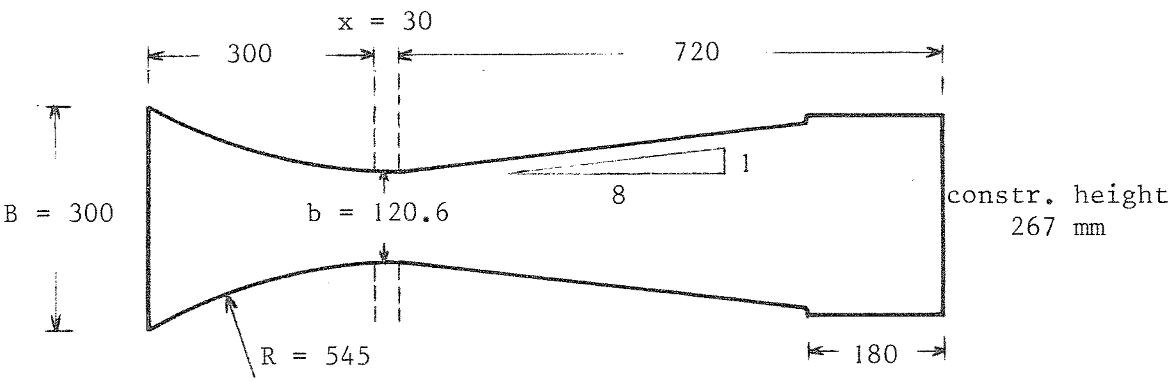
QV 308	$Q = \left(\frac{2}{3}\right)^{3/2} \cdot (g)^{1/2} \cdot 0.32 \cdot h_1^{1.50}$	
h_1 (m)	m (-)	Q (10^{-3} m^3/s)
0.05	0.993	6.06
0.06	1.000	8.02
0.07	1.007	10.18
0.08	1.014	12.52
0.09	1.019	15.01
0.10	1.023	17.65
0.12	1.030	23.36
0.14	1.034	29.55
0.16	1.039	36.28
0.18	1.042	43.42
0.20	1.046	51.04
0.25	1.056	72.02
0.30	1.065	95.48
0.35	1.074	121.33
0.40	1.084	149.62
0.45	1.093	180.02
0.50	1.103	212.76
0.55	1.112	247.47
0.60	1.122	284.51
0.64	1.128	315.10

Recommended head-discharge relations QV 303 and QV 308

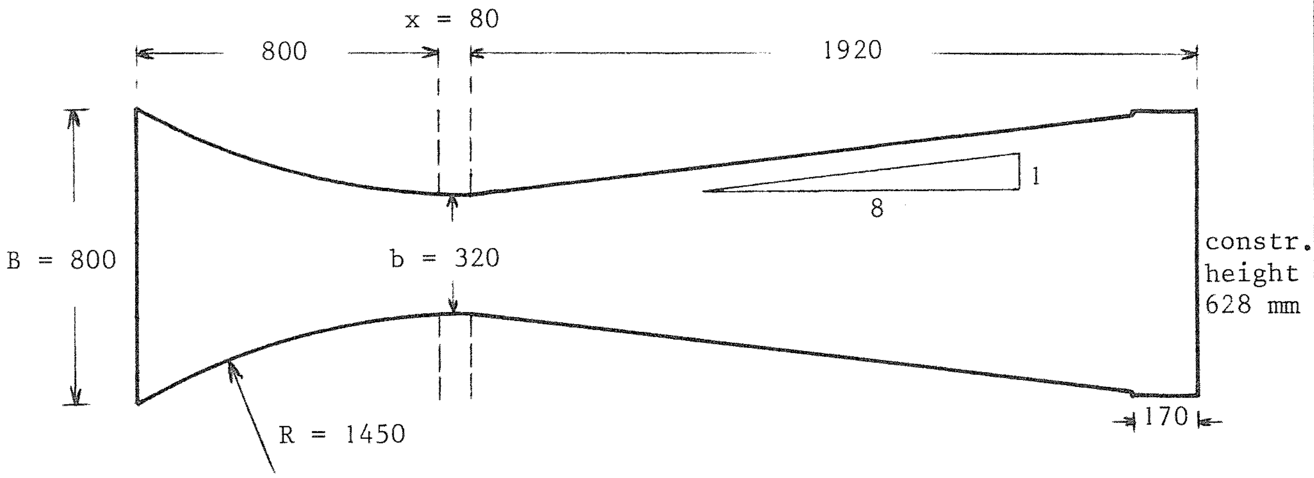
TABLE IV



GENERAL LAY-OUT KHAFAGI VENTURI



KHAFAGI VENTURI QV 303



KHAFAGI VENTURI QV 308

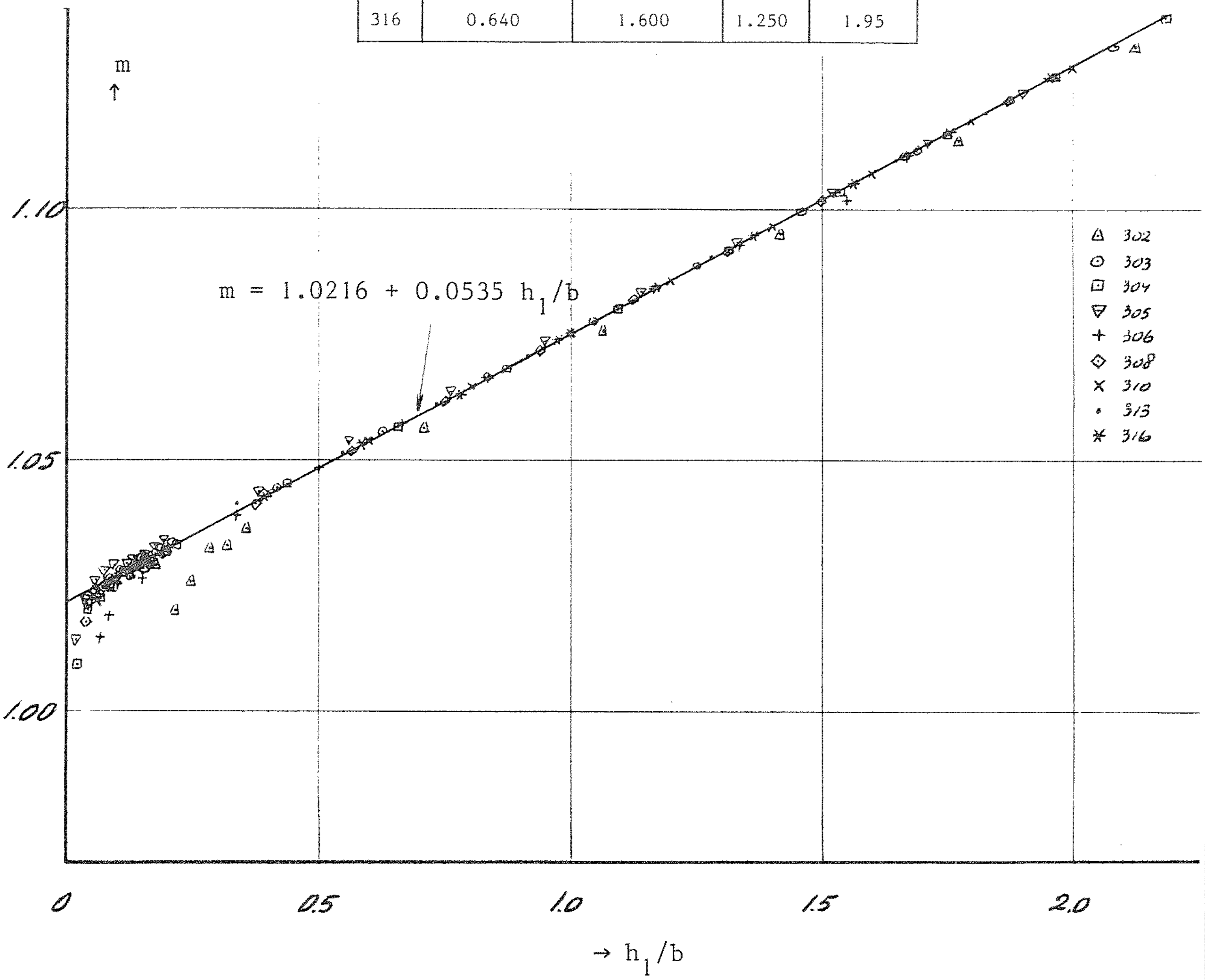
material: PVC

dimensions in millimeters

Dimensions of the Khafagi Venturi's QV 303 and QV 308		A4
DELFT HYDRAULICS LABORATORY	M2136	FIG. 1

Khafagi Venturi's

no.	throat width b (m)	canal width B (m)	$h_1$max (m)	$h_1$max/b
302	0.048	0.120	0.170	3.54
303	0.120	0.300	0.250	2.08
304	0.160	0.400	0.350	2.19
305	0.200	0.500	0.380	1.90
306	0.240	0.600	0.400	1.67
308	0.320	0.800	0.600	1.88
310	0.400	1.000	0.800	2.00
313	0.520	1.300	0.950	1.83
316	0.640	1.600	1.250	1.95



. In the report "Canal Khafagi-Venturi QV" [5], adapted from [7], head-discharge relations are presented in tables and in curves for 8 Khafagi-Venturi's, of which the throat varies 0.048 m < b < 0.640 m.

. From these data the discharge coefficient $m = Q/(\frac{2}{3})^{3/2}.(g)^{1/2}.b.h_1^{1.50}$ has been derived. The figure shows $m = f(h_1/b)$.

. For the flumes 0.120 m < b < 0.640 m and for h/b > 0.1 a linear relation has been derived $m = 1.0216 + 0.0535\ h_1/b$.

Discharge coefficient m as a function of h/b derived from Endress + Hauser's curves

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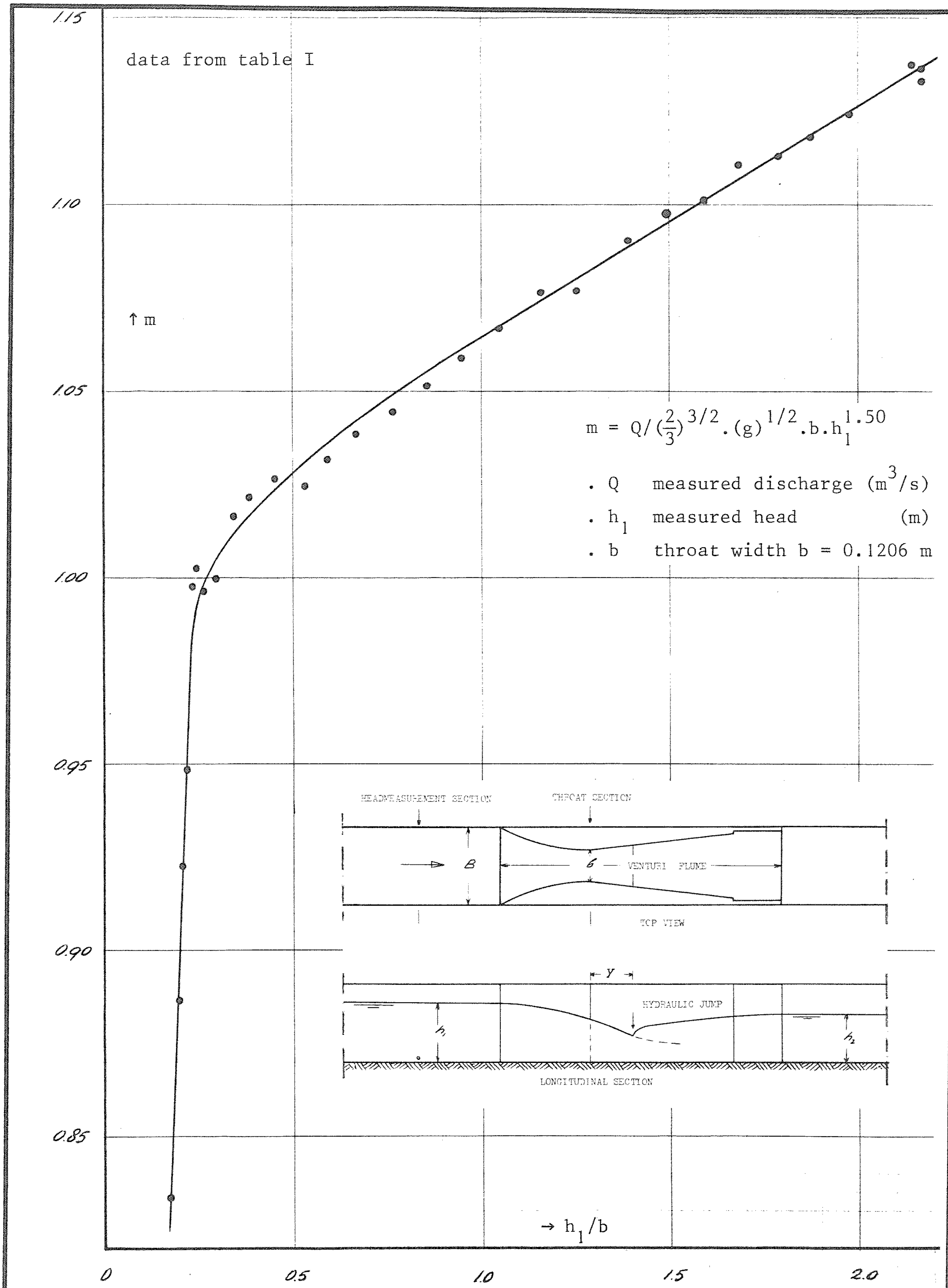
FIG. 2



Results of free flow measurements QV 303

A4

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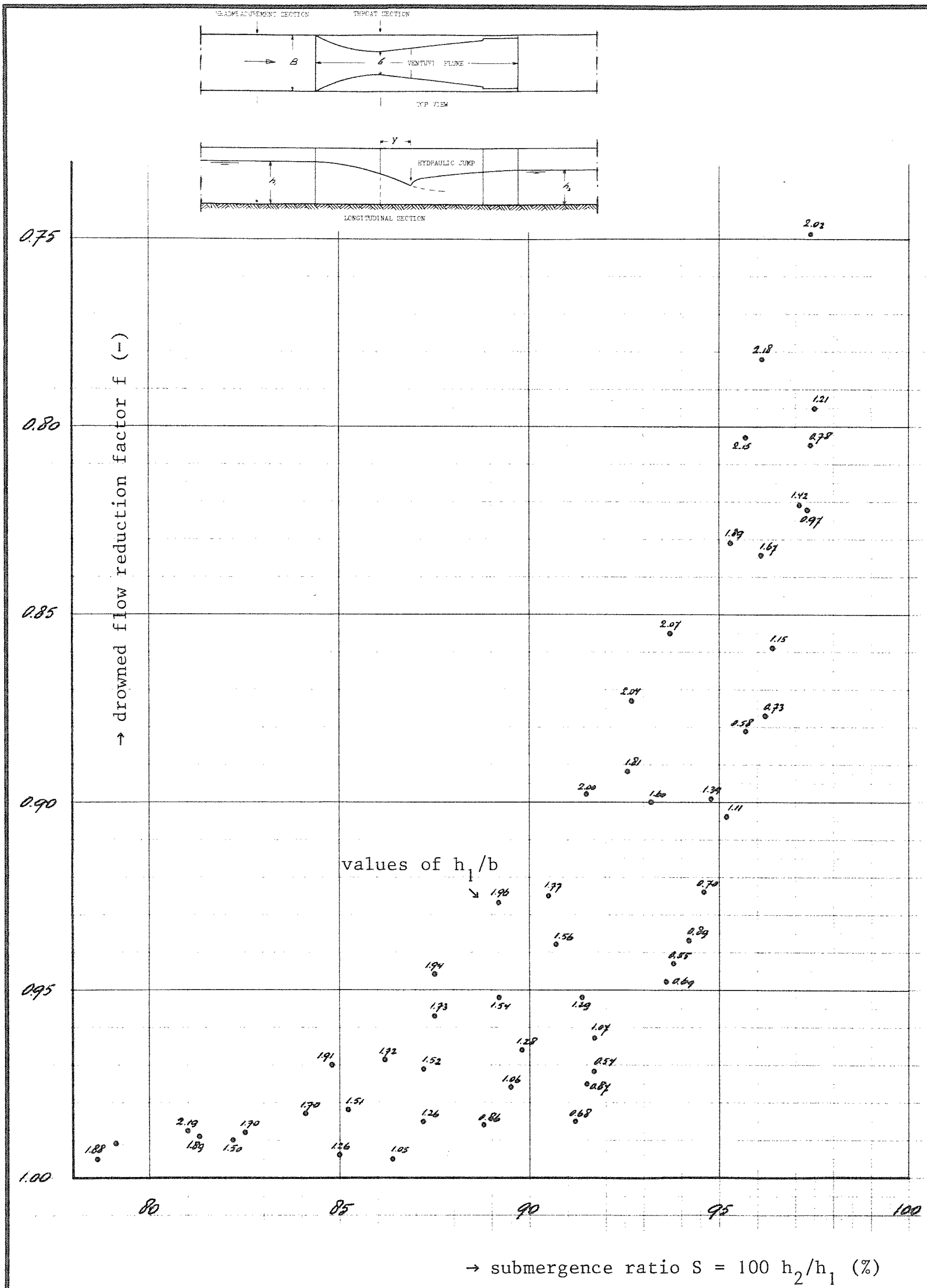
FIG. 3



data from table II

Results of submerged flow measurements QV 303

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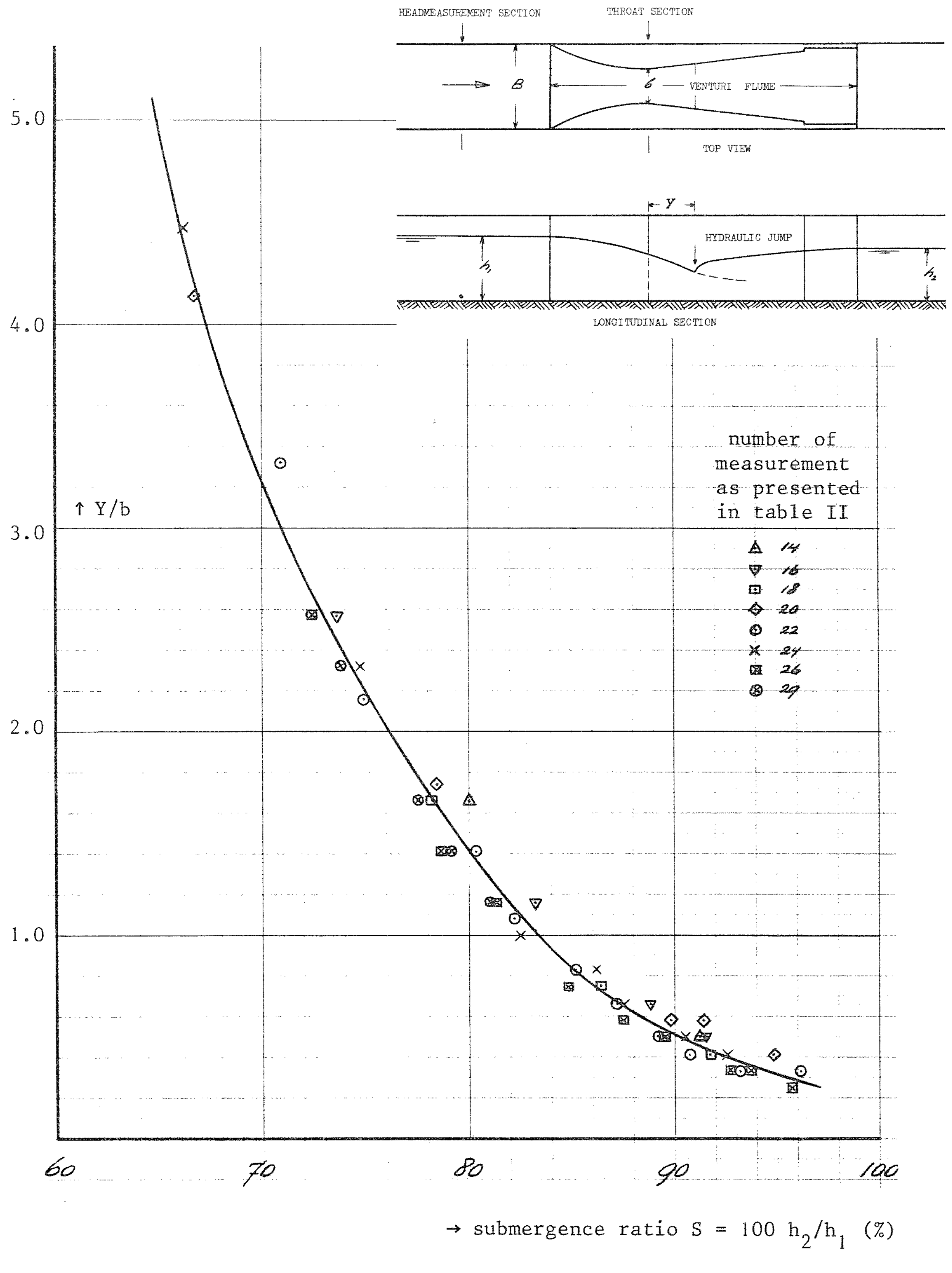
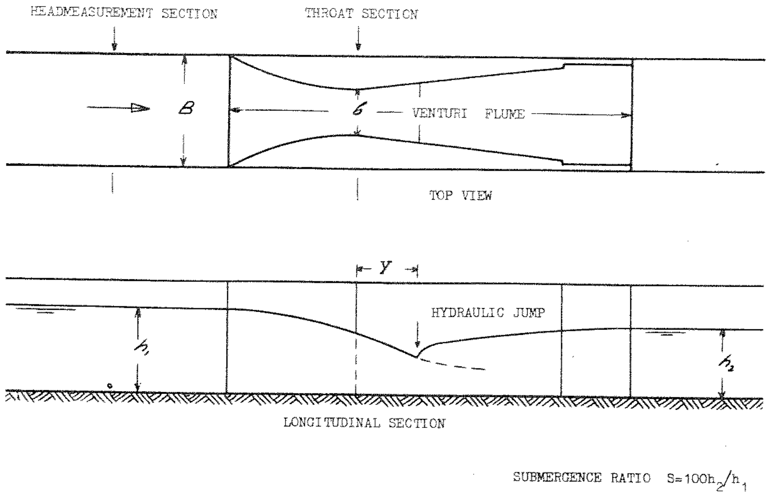
FIG. 4



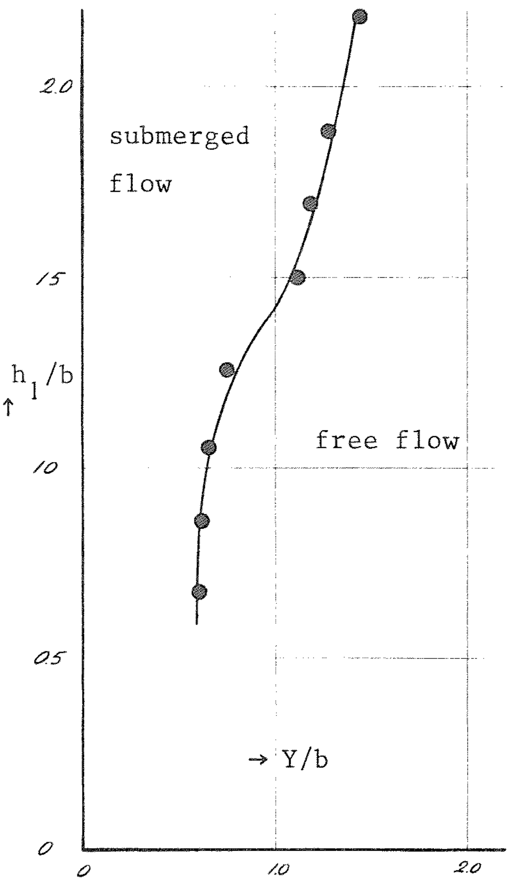
Position of hydraulic jump related to submergence ratio, QV 303

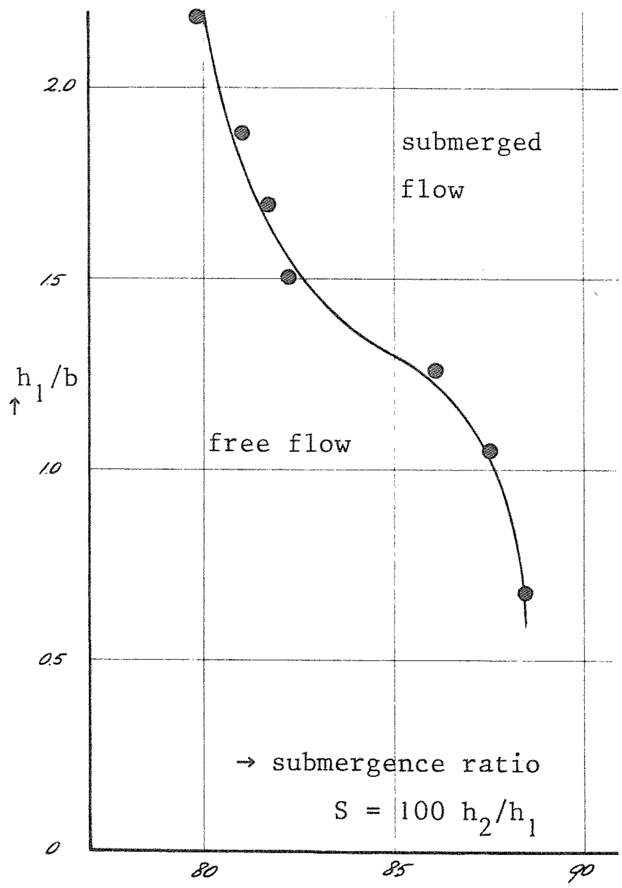
		A4
DELFT HYDRAULICS LABORATORY	M2136	FIG. 5



The modular limit is defined as the submergence ratio for which the deviation between submerged flow, calculated with the free flow head-discharge relation, and the real flow is 1%.

$S < S_1$ free flow
$S > S_1$ submerged flow





Modular limit QV 303

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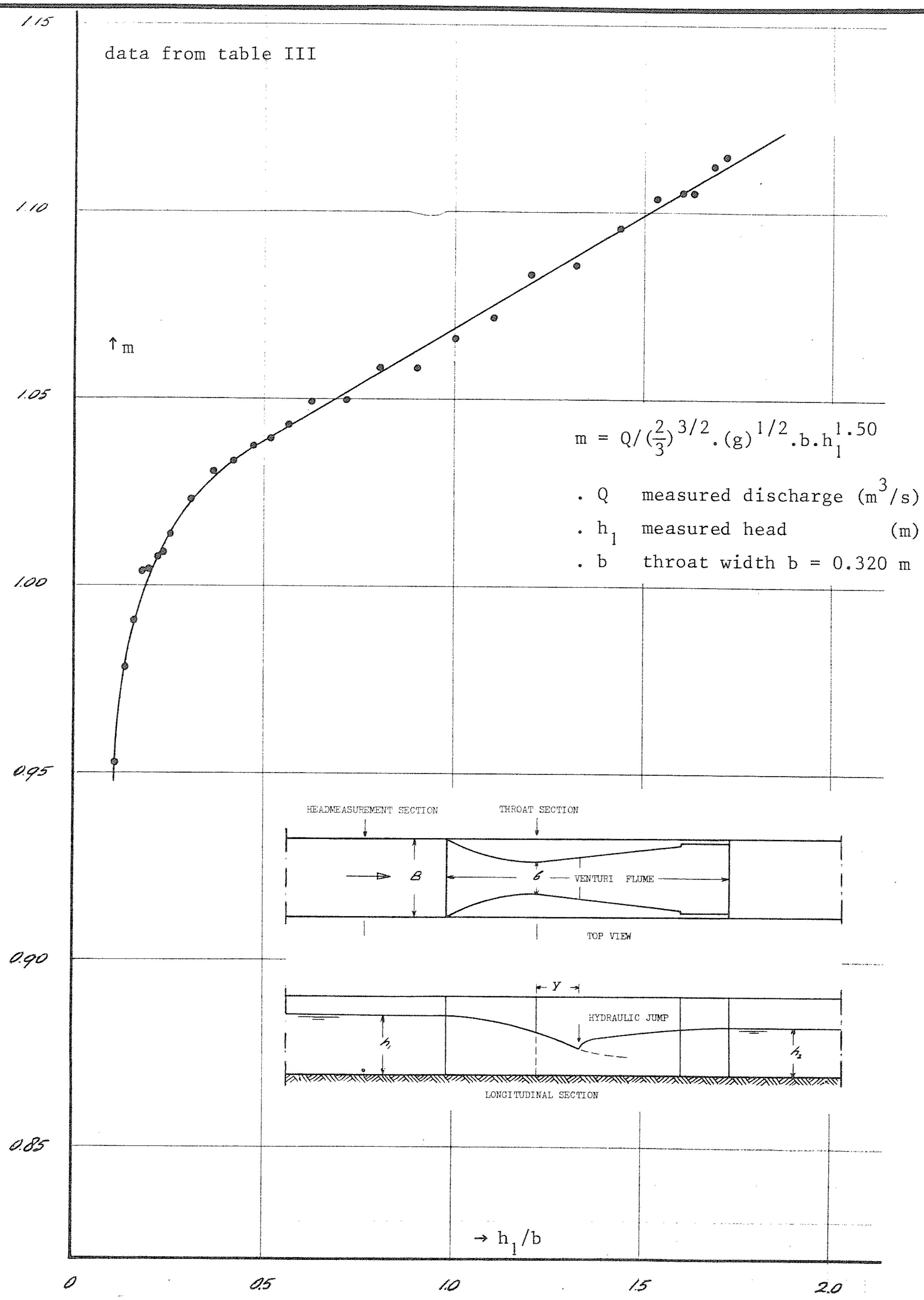
FIG. 6



Results of free flow measurements QV 308

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FIG. 7

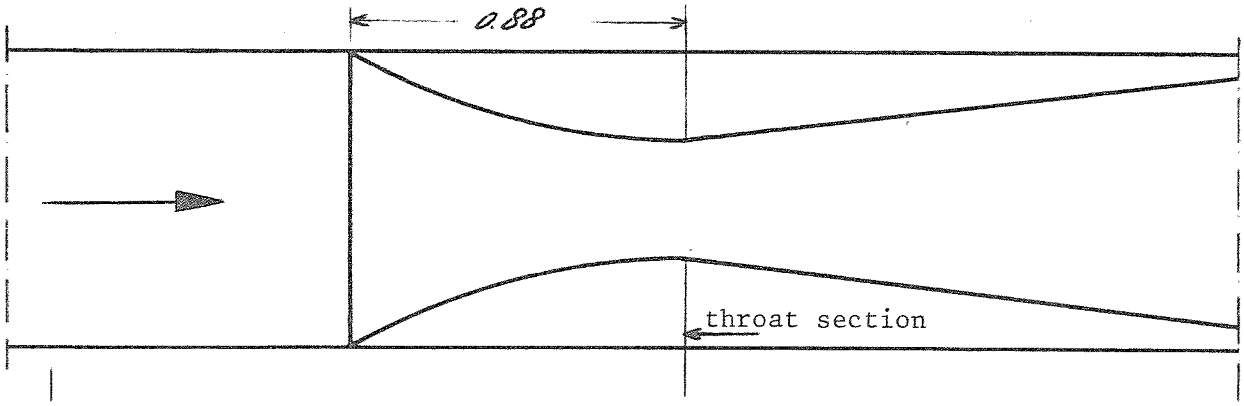
Location pointgauge related to front Khafagi Y (m)	measured head h (m)
+0.80	0.5502
+0.60	0.5502
+0.50	0.5499
+0.40	0.5500
+0.30	0.5489
+0.20	0.5484
+0.08	0.5464
+0.01	0.5441
-0.10	0.5426
-0.13	0.5402
-0.20	0.5368
-0.475	0.5020
-0.575	0.4852
-0.675	0.4607
-0.755	0.4337
-1.045	0.3253
-1.175	0.2689
-1.375	0.2231
-1.57	0.1863
-1.73	0.1677

Determination of the critical section, measurement no. 28

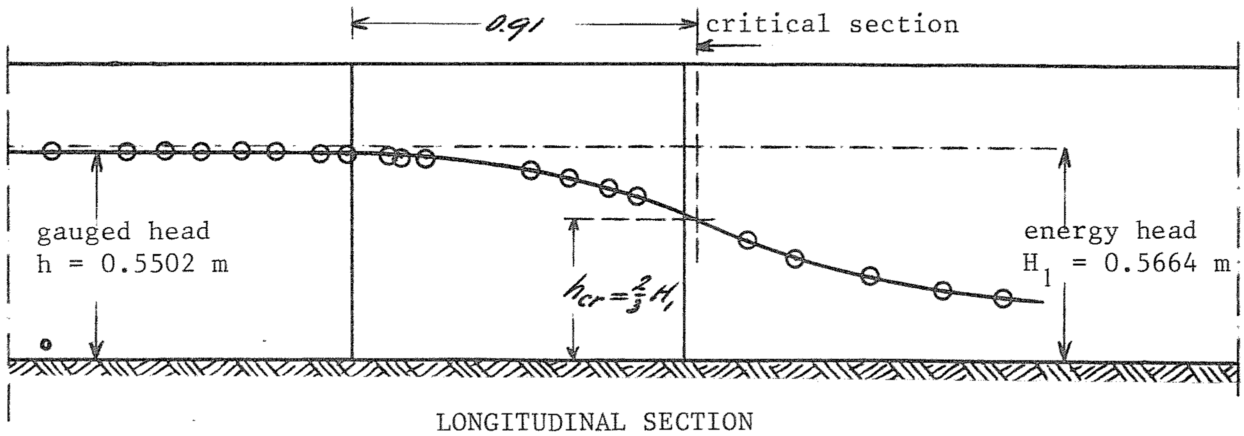
head h_1 = 0.5502 m
canal width B = 0.800 m
} $A = h_1 * B = 0.4402\ m^2$
$Q = 0.248204\ m^3/s$

mean velocity $\bar{v} = Q/A = 0.564$ m/s
velocity head $v^2/2g = 0.0162$ m
gauged head h_1 = 0.5502 m
energy head H = 0.5664 m
critical depth $h_c = \frac{2}{3} H_1 = 0.3776$ m

The critical section is located at Y = 0.91 m which is 0.03 m downstream of the throat section.



TOP VIEW



LONGITUDINAL SECTION

Surface draw-down in the Khafagi Venturi
QV 308

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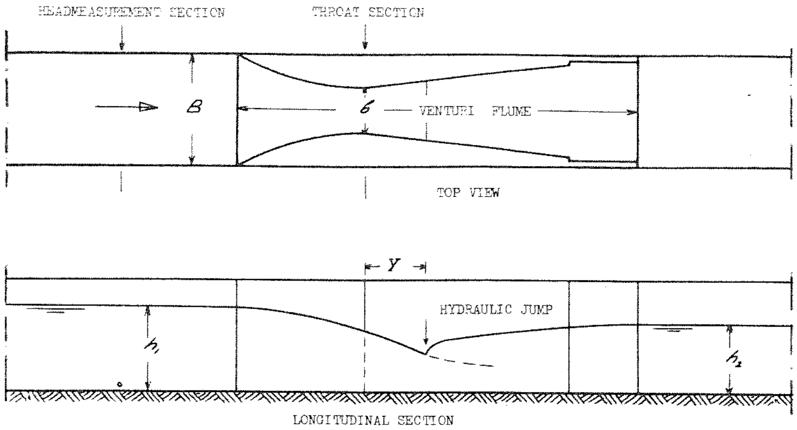
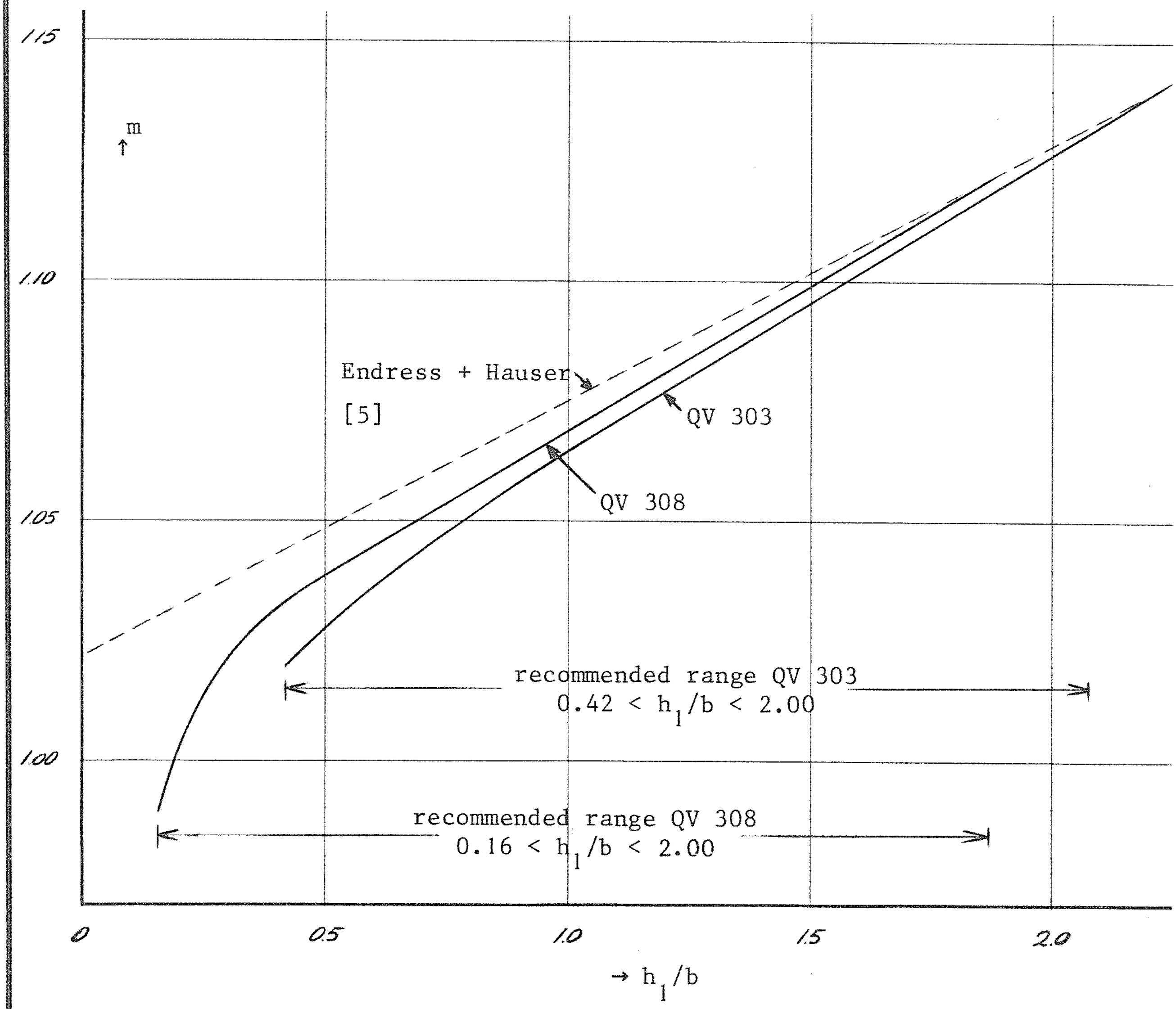
FIG. 8



$$Q = (\frac{2}{3})^{3/2} . (g)^{1/2} . b . m . h_1^{1.50}$$



Recommended discharge coefficient for free flow

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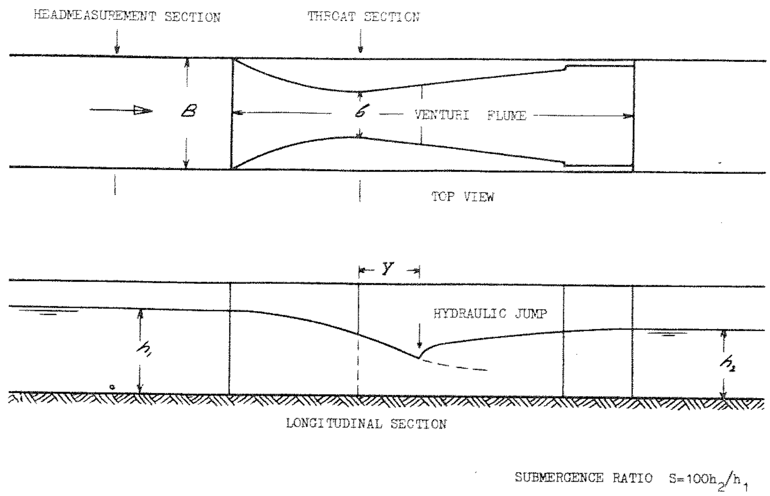
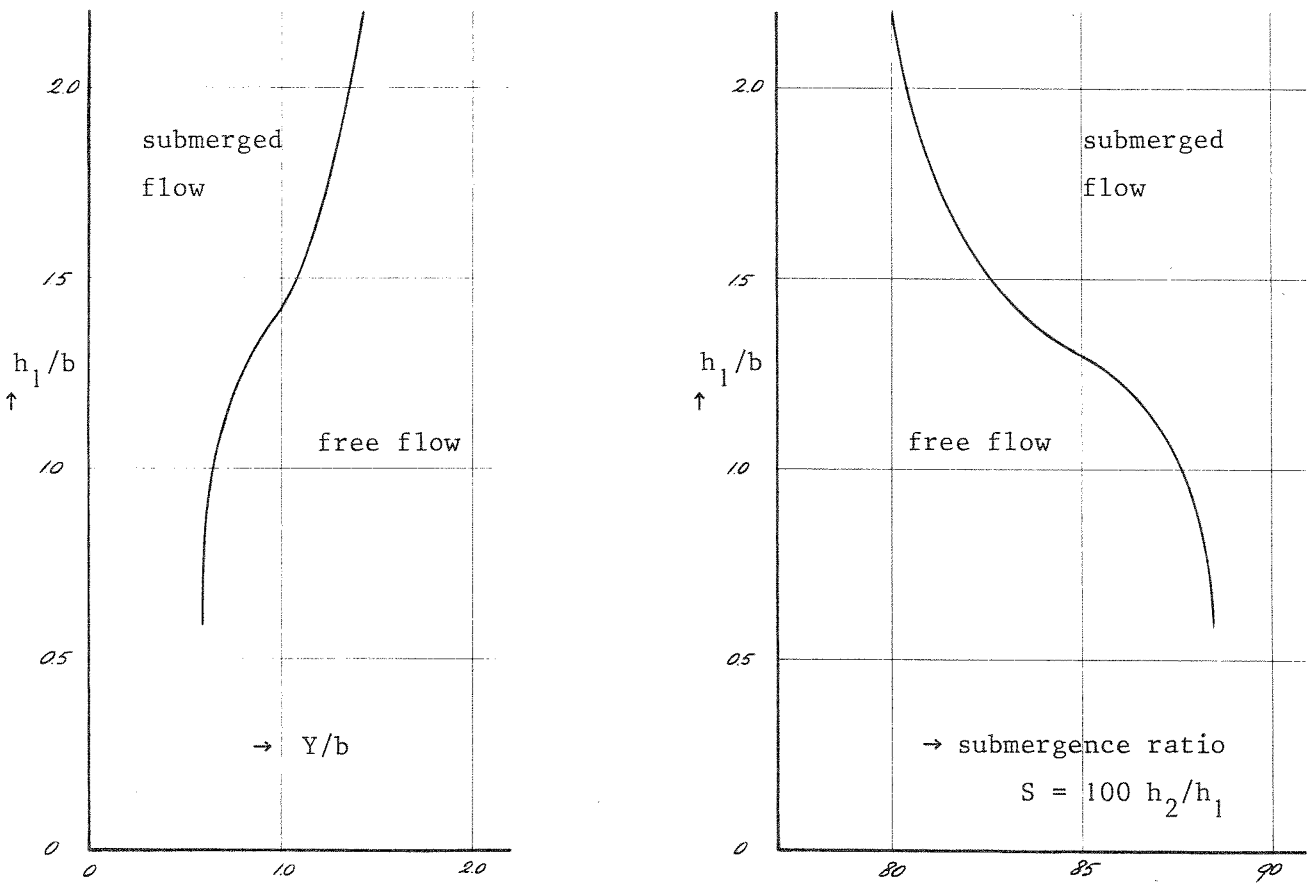
FIG. 9



The modular limit is defined as the submergence ratio for which the deviation between submerged flow, calculated with the free flow head-discharge relation, and the real flow is 1%.

$S < S_1$ free flow

$S > S_1$ submerged flow



Recommended modular limit

A4

DELFT HYDRAULICS LABORATORY

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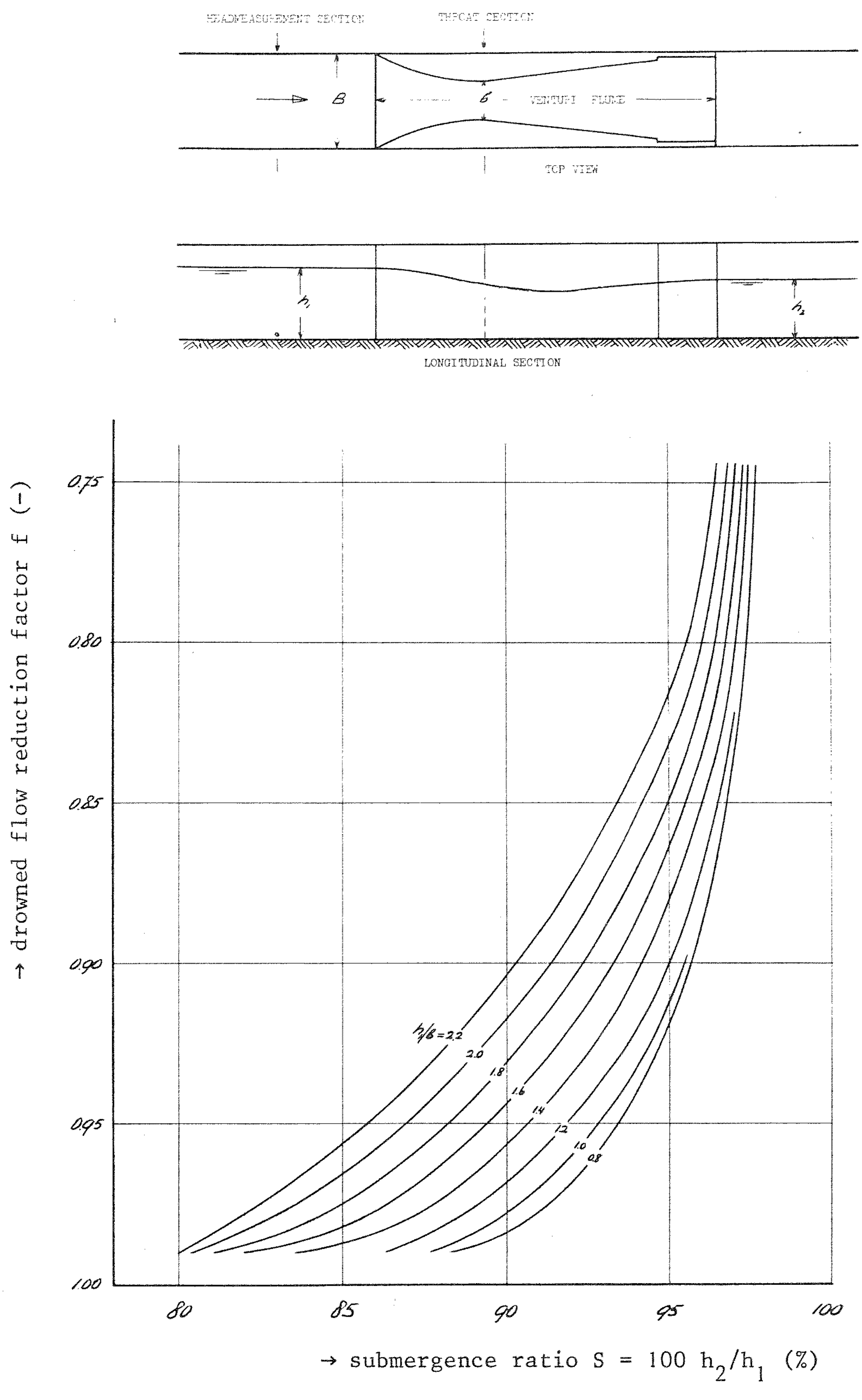
FIG. 10



$$Q = \left(\frac{2}{3}\right)^{3/2} . (g)^{1/2} . b.m.f.h_1^{1.50}$$

Recommended drowned flow reduction factor

A4

DELFT HYDRAULICS LABORATORY

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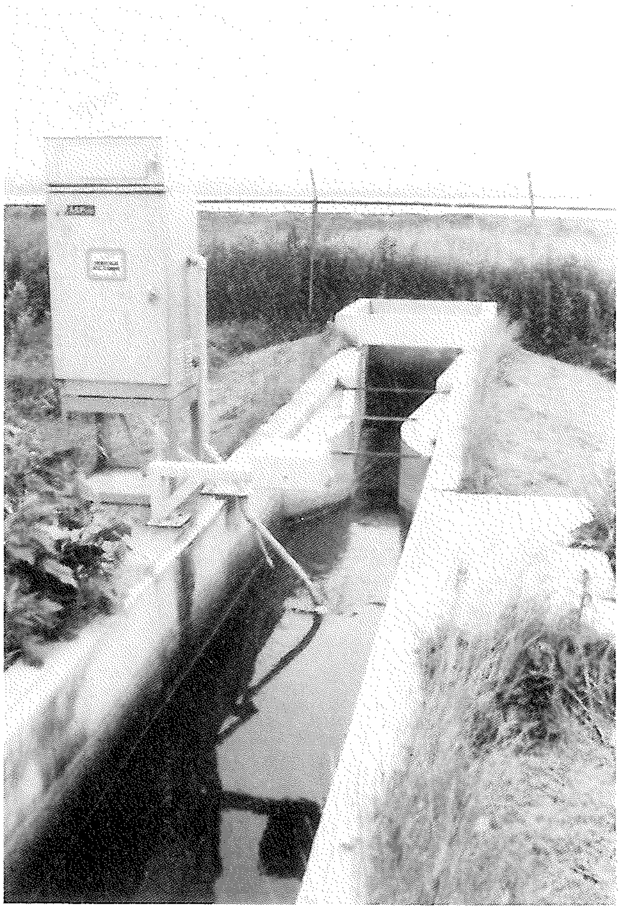
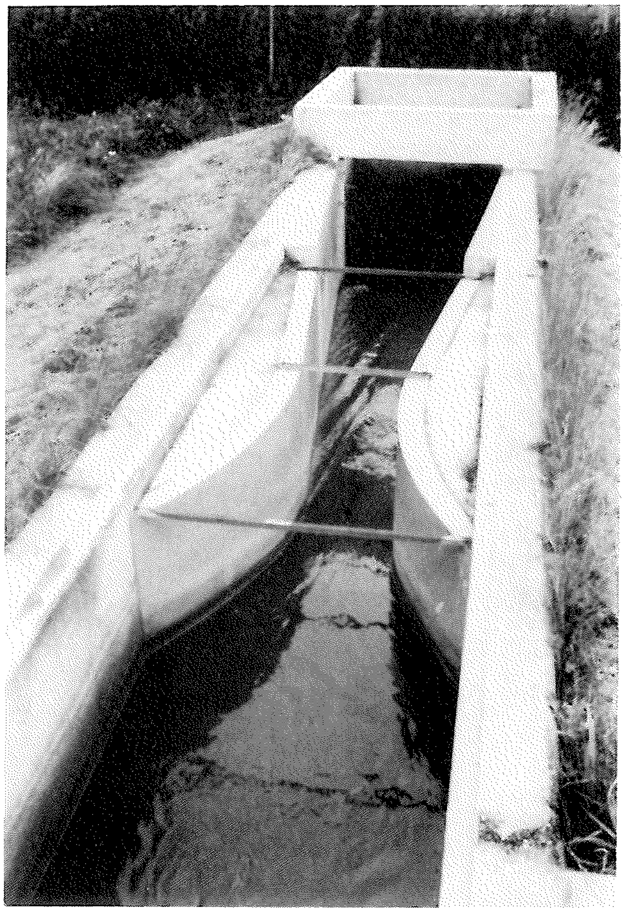
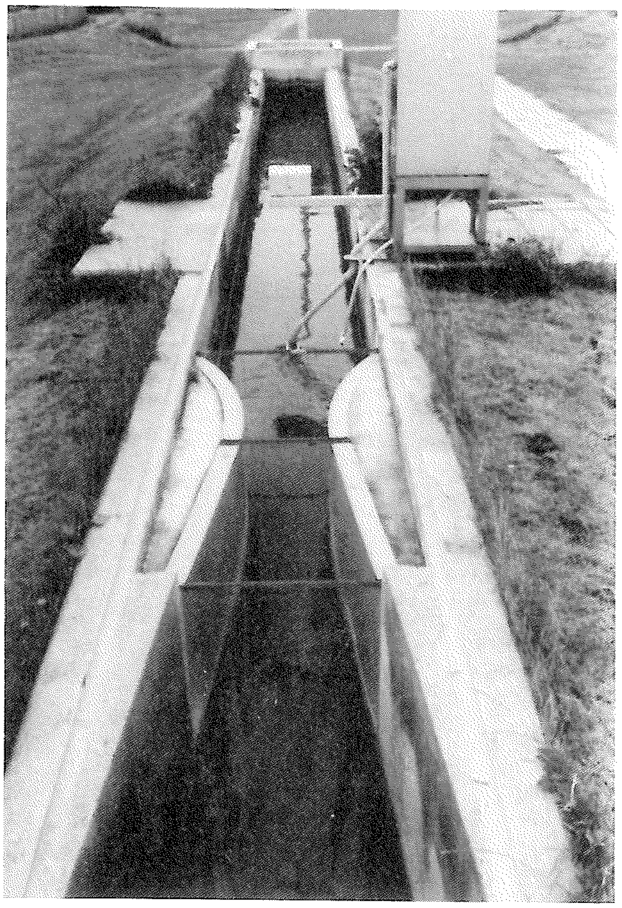
FIG. 11







Khafagi Venturi QV 310

- throat width b = 0.40 m
- canal width B = 1.00 m
- the head is measured with an ultra-sonic sensor at a distance Y = 2.05 m upstream of the flume
- maximum discharge Q = 0.55 m^3/s (head h = 0.80 m)

QV 303

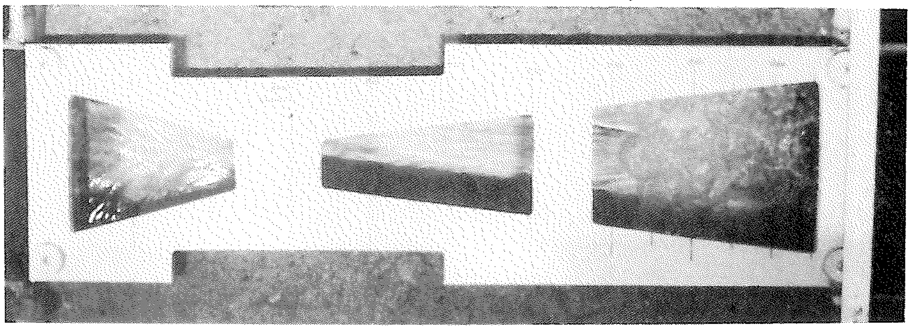
canal width B = 0.30 m

throat width b = 0.12 m

maximum discharge 29 l/s

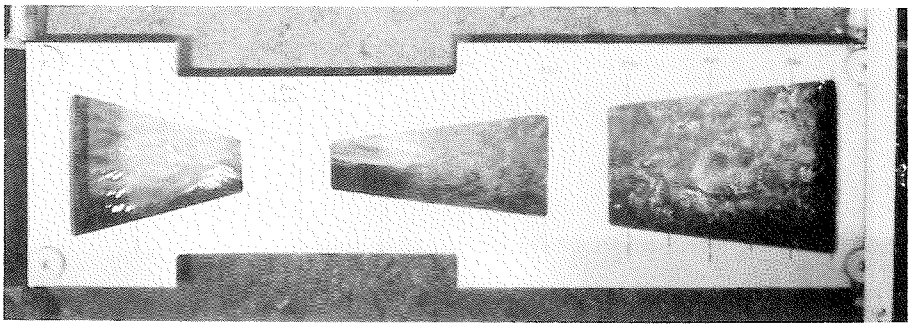
hydraulic jump at Y = 0.42 m

direction of flow →



a) FREE FLOW

hydraulic jump at Y = 0.14 m

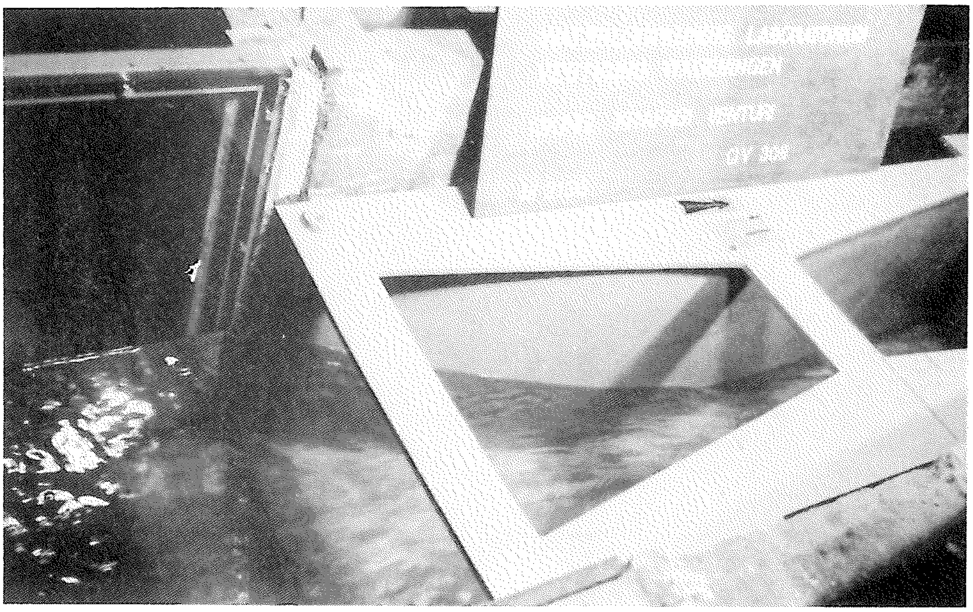


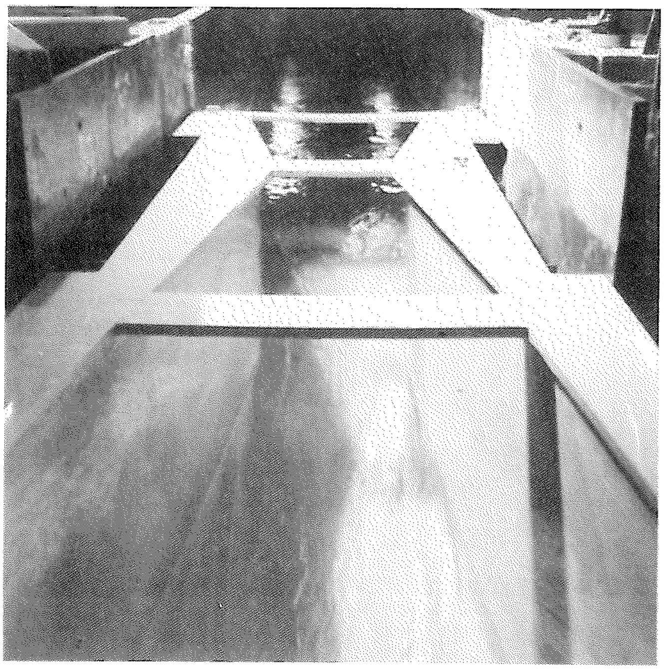
b) MODULAR LIMIT

hydraulic jump at Y = 0.02 m

c) SUBMERGED FLOW

Determination modular limit Khafagi Venturi QV 303



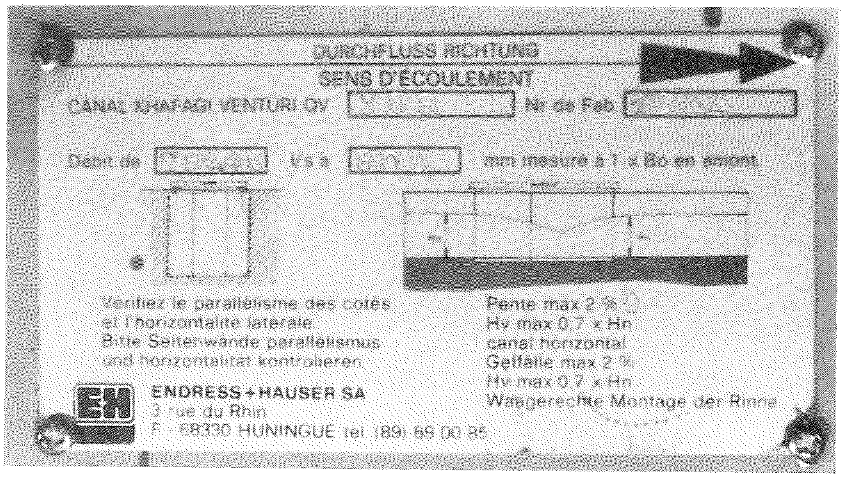


QV 308

canal width B = 0.80 m

throat width b = 0.32 m

maximum discharge 284 l/s



Calibration Khafagi Venturi QV 308 for free flow

p.o. box 177 2600 mh delft the netherlands