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WATER JET PUMPS FOR REACTORS

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SYNOPSIS: In boiling water reactors water circulation can be maintained by using the feeding water as driving flow in jet pumps. The flow ratio of driven water/driving water may be 2 - 4.

A theoretical calculation shows that best efficiencies are received when the pressure rise in mixing chamber and diffuser is 87% of the possible pressure rise without losses and when the whole momentum at the entrance is exploited for pressure rise. Best efficiencies are 35% at flow ratio 2, decreasing to 26% at flow ratio 4.

Tests made at about 30°C and 210°C show small differences in momentum efficiency, indicating that the friction losses are low. We can presume that the velocity distribution is very non-uniform with low velocity at the perifery.

ABRÉGÉ: Dans les piles à eau bouillante une circulation peut être maintenu en employant de l'eau d'alimentation comme le flux actif dans les pompes à jet. La proportion du flux d'eau actionnée/d'eau actionnante peut être 2 - 4.

Un calculation théorique a indique que les meilleures efficacités sont recues quand l'augmentation de pression dans la chambre de mélange et dans le diffiseur est 87% d'une possible augmentation de pression sans perte et quand toute la quantité de mouvement à l'admission est exploitée pour une augmentation de pression. Les meilleures efficacités sont 35% à la proportion du flux 2, diminuant à 26% à la proportion du flux 4.

Des essais faits à 30°C et 210°C ont indiqués des différences petits d'efficacité de la quantité de mouvement, indiquant que les pertes de friction sont faibles. Nous pouvons supposer que la distribution de vitesse est trés non-uniforme avec la faible vitesse à la périphérie.

1. INTRODUCTION

Calculations and tests on water jet pumps for reactors have been made as outlined in the synopsis. Best efficiencies are 35 and 26% at flow ratios 2 and 4 respectively.

2. NOMENCLATURE

η	density
q	volume flow of water
w	velocity of water
I	momentum
A	area
p_1	pressure drop of driving water
p_2	pressure rise of driven water

Indicies:

1 driving water

2 driven water

$x = \frac{q_2}{q_1}$ (flow ratio)

$y = \frac{w_2}{w_1}$ at entrance (velocity ratio)

$z = \frac{p_2}{p_1}$ (pressure ratio)

η_i = momentum efficiency

$\eta = x \cdot z$ total efficiency

p_M pressure rise in mixing chamber

p_D pressure rise in diffuser

$p_T = p_M + p_D$ at $\eta_i = 100\%$

p_R real pressure rise

3. THEORY

In order to investigate the possibility of improving the received results we shall define the momentum efficiency η_i.

Momentum of driving water $I_1 = \rho \cdot q_1 \cdot w_1$

Momentum of driven water $I_2 = \rho \cdot q_2 \cdot w_2$

Total momentum $I = I_1 + I_2 = \rho q_1 w_1 + \rho q_2 w_2 = \rho q_1 w_1 \left(1 + \frac{q_2}{q_1} \cdot \frac{w_2}{w_1}\right)$

We put $x = \frac{q_2}{q_1}$ $y = \frac{w_2}{w_1}$

$$I = \rho q_1 w_1 \ (1 + xy) \qquad (1)$$

Area of driving water $A_1 = \frac{q_1}{w_1}$

Area of driven water $A_2 = \frac{q_2}{w_2}$

Total area $A = A_1 + A_2 = \frac{q_1}{w_1} + \frac{q_2}{w_2} = \frac{q_1}{w_1}\left(1 + \frac{q_2}{q_1} \cdot \frac{w_1}{w_2}\right)$

$$A = \frac{q_1}{w_1}\left(1 + \frac{x}{y}\right) \qquad (2)$$

Total flow $q = q_1 + q_2 = q_1 \ (1 + x)$

The biggest pr

without losses is ach

value w.

$w = \frac{q}{A} = \frac{q_1}{\frac{q_1}{w_1}}$

Momentum = ρ

Momentum dro

$\Delta I = \rho q_1 w_1 \ (1 +$

Pressure rise

$p_M = \frac{\Delta I}{A} =$

In the diffuser

1:2 we get a pressur

$p_D = \frac{15}{32} \cdot$

Total pressur

$p_T = p_M + p_D$

$p_T = \rho w_1^2$

This pressure

$\eta_i = 100\%$.

The real pres

p_2 + the depression

We put $\frac{p_2}{p_1} =$

$p_R = p_2 +$

The driving w

difference in mixin

The biggest pressure rise in the mixing chamber with constant area and without losses is achieved if the water velocity equalizes to a constant mean value w.

$$w = \frac{q}{A} = \frac{q_1 (1 + x)}{\frac{q_1}{w_1} (1 + \frac{x}{y})} = w_1 \frac{1 + x}{1 + \frac{x}{y}} \qquad (3)$$

$$\text{Momentum} = \rho \cdot q \cdot w = \rho \cdot q_1 (1 + x) \cdot w_1 \frac{1 + x}{1 + \frac{x}{y}} = \rho q_1 w_1 \frac{(1 + x)^2}{1 + \frac{x}{y}}$$

Momentum drop in mixing chamber ΔI

$$\Delta I = \rho q_1 w_1 (1 + xy) - \rho q_1 w_1 \frac{(1 + x)^2}{1 + \frac{x}{y}} = \rho q_1 w_1 \left[1 + xy - \frac{(1 + x)^2}{1 + \frac{x}{y}}\right]$$

Pressure rise in mixing chamber $= p_M = \frac{\Delta I}{A}$

$$p_M = \frac{\Delta I}{A} = \frac{\rho q_1 w_1 \left[1 + xy - \frac{(1 + x)^2}{1 + \frac{x}{y}}\right]}{\frac{q_1}{w_1} (1 + \frac{x}{y})} = \rho w_1^2 \left[\frac{1 + xy}{1 + \frac{x}{y}} - \left(\frac{1 + x}{1 + \frac{x}{y}}\right)^2\right] \qquad (4)$$

In the diffuser we assume a efficiency of 100%, with the diameter ratio 1:2 we get a pressure rise $p_D = \frac{15}{16} \cdot \frac{\rho w^2}{2}$

$$p_D = \frac{15}{32} \cdot \rho w^2 = \frac{15}{32} \rho w_1^2 \left(\frac{1 + x}{1 + \frac{x}{y}}\right)^2 \qquad (5)$$

Total pressure rise in mixing chamber and diffuser $= p_T$.

$$p_T = p_M + p_D = \rho w_1^2 \left[\frac{1 + xy}{1 + \frac{x}{y}} - \left(\frac{1 + x}{1 + \frac{x}{y}}\right)^2\right] + \rho w_1^2 \cdot \frac{15}{32} \left(\frac{1 + x}{1 + \frac{x}{y}}\right)^2$$

$$p_T = \rho w_1^2 \left[\frac{1 + xy}{1 + \frac{x}{y}} - \frac{17}{32} \left(\frac{1 + x}{1 + \frac{x}{y}}\right)^2\right] \qquad (6)$$

This pressure rise p_T would be achieved with the momentum efficiency $\eta_i = 100\%$.

The real pressure rise p_R is equal to the pressure rise for driven water p_2 + the depression $\frac{\rho w_2^2}{2}$ at the beginning of mixing chamber.

We put $\frac{p_2}{p_1} = z$

$$p_R = p_2 + \frac{\rho w_2^2}{2} = p_1 z + \frac{\rho w_1^2}{2} \cdot y^2 \qquad (7)$$

The driving water is accelerated by the pressure drop p_1 + the pressure difference in mixing chamber and diffuser equal to p_R.

$$\frac{\rho w_1^2}{2} = p_1 + p_R = p_1 + p_1 z + \frac{\rho w_1^2}{2} y^2$$

$$\frac{\rho w_1^2}{2}(1 - y^2) = p_1 (1 + z)$$

$$p_1 = \frac{\rho w_1^2}{2} \cdot \frac{1 - y^2}{1 + z}$$

$$p_R = \frac{\rho w_1^2}{2} \frac{1 - y^2}{1 + z} \cdot z + \frac{\rho w_1^2}{2} \cdot y^2 = \frac{\rho w_1^2}{2} \frac{z + y^2}{1 + z}$$

We now define $\eta_i = \frac{p_R}{p_T}$ or $\eta_i \cdot p_T = p_R$

$$\eta_i \cdot \rho w_1^2 \left[\frac{1 + xy}{1 + \frac{x}{y}} - \frac{17}{32}\left(\frac{1 + x}{1 + \frac{x}{y}}\right)^2\right] = \frac{\rho w_1^2}{2} \cdot \frac{z + y^2}{1 + z}$$

$$\eta_i \left[\frac{1 + xy}{1 + \frac{x}{y}} - \frac{17}{32}\left(\frac{1 + x}{1 + \frac{x}{y}}\right)^2\right] = \frac{z + y^2}{2(1 + z)} \tag{8}$$

From eq. 8 we can easily derive that the total efficiency $\eta = x \cdot z$ is

$$\eta = x \frac{2\eta_i \left[\frac{1 + xy}{1 + \frac{x}{y}} - \frac{17}{32}\left(\frac{1 + x}{1 + \frac{x}{y}}\right)^2\right] - y^2}{1 - 2\eta_i \left[1 + \frac{xy}{1 + \frac{x}{y}} - \frac{17}{32}\left(\frac{1 + x}{1 + \frac{x}{y}}\right)^2\right]} \tag{9}$$

4. TEST ASSEMBLY

The test assembly is shown in fig. 1. The jet pump consists of entrance to mixing chamber (1), mixing chamber (2), diffuser (3). The driving water flows through a pump (4), a flow meter (5) and the jet nozzle (6). The driven water flows through a electrical heater (7), a valve (8), a flow meter (9) to a chamber (10).

The mixing chamber entrance (1) and the jet nozzles (6) are shaped as cônes with the angles 90° and 45° respectively according to the experiences of Mueller [1]. Jet nozzles with the diameters 36, 30, 27, 24 and 21 mm have been tested. The nozzles are connected to a movable tube. Before every test this tube is moved so that the best efficiency is received.

When planning the tests, momentum calculations were made. It seemed to be advantageous to perform the beginning of the mixing chamber as a cone with decreasing diameter. Two beginning parts of the mixing chamber were made, one conical with diameter decreasing from 81 to 75 mm and the length 110 mm, one cylindrical with the diameter 75 mm. To this beginning parts the following parts of different lengths with diameter 75 mm were connected.

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5. EXPERIMEN

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Two diffusers were tested, one with angle 3.5° and one with 4.5°, the diameter increasing from 75 to 150 mm. The mixing chamber parts and the diffusers were connected with stuffing boxes in order to get a convenient set-up.

In order to study the pressure rise in mixing chamber and diffuser a great number of pressure taps T_1 ---- T_{13} was connected. The pressure rise p_2 for driven water was measured between point T14 and T13 at the end of the diffuser. The pressure drop p_1 for driving water was measured between T15 and T13. The dynamic pressure in the tube at T15 was added.

When recording a curve with different flow ratios the valve (8) was turned in different positions. All tests were made with cold water, about 30°C, and hot water, about 210°C.

5. EXPERIMENTAL RESULTS

The experimental results are brought together in table 1. The points with the best efficiency η are shown with the corresponding values of $x = \frac{q_2}{q_1}$, $y = \frac{w_2}{w_1}$ and $z = \frac{p_2}{p_1}$ with hot and cold water. The values of η_i are also calculated.

The first test was made with nozzle 30 mm and diffuser angle 4.5° in order to investigate if the mixing chamber beginning with a conical part with decreasing diameter is better than a cylindrical mixing chamber. The first tests gave somewhat better results for conical mixing chamber. However, the pressure measurements along the mixing chamber indicated that this difference was depending on a contraction at the edge between the driven water entrance and the mixing chamber. This edge was rounded, the efficiences increased and the differences between conical and cylindrical mixing chamber were very small.

The same result was received with diffuser angle 3.5° (test No. 10-13). No important improvement may be obtained with conical mixing chamber. Therefore it was decided that the following tests would be made with cylindrical mixing chamber.

These tests with nozzle 30 mm (ratio nozzle diameter/mixing chamber diameter = 0.4) have obtained the following results. Best efficiency is received at $q_2/q_1 = 2.0 - 2.2$. Best efficiency about 35% for hot water and 33% for cold water. Length of mixing chamber in the order 420 - 570 mm, corresponding ratio length/diameter of mixing chamber = 5.5 - 7.5. The ratio $w_2/w_1 = 0.32 - 0.35$.

There is no significant difference between the diffuser angle 3.5° and 4.5°.

The best values of the momentum efficiency η_i are about 87% for hot water and somewhat lower for cold water. This seems to be a high value. By searching the optimal values of the different parameters it is possible that the best efficiency may be increased. However, depending on the high value of η_i it is probable that the improvement of η cannot be more than 1 or 2%. Therefore it was decided to end the tests with jet diameter 30 mm.

Test No. 14 - 16 were made with jet diameter 27 mm. These tests gave η_i about 87% and η about 34% for hot water. There is no significant difference between mixing chamber length 420 and 570 mm.

Test No. 17 - 19 were made with jet diameter 24 mm. With chamber length 570 mm η_i was about 87% and η about 26%. With chamber length 420 the result was lower. This shows that with decreasing jet diameter the optimal mixing chamber length increases. Probably an increase of the mixing chamber length will increase the efficiency.

Test No. 20 and 21 with jet diameter 21 mm and mixing diameter length 570 mm only gave η_i about 84% and η about 27.5%. Here it seems to be quite certain that an increase of the mixing chamber length will increase the efficiency.

However, the best efficiences received by Mueller [1] are a little higher than those in these experiments. According to the dimensions of the Mueller equipment the flow ratio $x = \frac{q_2}{q_1}$ seems to be lower than 2. To get a comparison test No. 22 and 23 were made with jet diameter 36 mm. Without searching for optimum parameters the efficiency $\eta = 36\%$ and $\eta_i = 85\%$ was obtained at flow ratio $x = \frac{q_2}{q_1} = 1.6$. The mixing chamber length is 320 mm or ratio length/diameter = 4.3. Therefore we can assume that these measurements are comparable with Mueller's.

As a summary of table 1 we can assume that with sufficiently many tests we should get a momentum efficiency $\eta_i = 87\%$ independent of the ratio jet diameter/mixing chamber diameter. This seems to be unexpected. It could be expected that with decreasing ratio jet diameter/mixing chamber diameter η_i would decrease.

However, depending on the complicated connection between η_i and η (eq. 9), the total efficiency η decreases with decreasing ratio jet diameter/mixing chamber diameter. This seems to be depending on the fact that at best efficiency the ratio $y = w_2/w_1$ is also decreasing.

Therefore it is interesting to investigate how the momentum efficiency varies with the driven mass flow. As examples the tests 23, 13, 15, 18 and 20 are shown in diagram 1 - 5. Curves for pressure ratio p_2/p_1 efficiency η and momentum efficiency η_i are drawn as functions of mass flow ratio q_2/q_1 for cold and hot water.

The curves p_2/p_1 are approximately straight lines and therefore the efficiency curves η approximately are parables. The curves η_i begin with embarassing high values at $q_2/q_1 = 0$, then fall steeply and perhaps rise a little at highest flow ratio.

The very high values of η_i at low flow ratios require a special explanation. When the expression for η_i was derived we assumed that the velocity w_2 is uniform at the entrance. At $q_2 = 0$ this implies that the water around the driving jet would be stagnant. This naturally is impossible. Near the jet water is flowing into the mixing chamber and it returns near the perifery. This flow gives an addition to the momentum which is not accounted for in the calculation.

Furthermore some nozzles, which divide the water in several jets, have

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6. DISCUSSIO

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been tested. These give much lower efficiency than the single-jet nozzle.

5.1 What is happening in the mixing chamber

Some pressure taps are placed along the mixing chamber in order to investigate the pressure rise. In diagram 6 the pressures along the mixing chamber are shown for cold water at tests 7, 15, 18, 20 and 23. These tests are made in the neighbourhood of the maximum efficiency. Pressure zero is the pressure of driven water at point T14 (fig. 1).

In the first 60 mm of the mixing chamber we get a very big pressure rise. However, if we for test 7 calculate the pressure at the beginning of the mixing chamber assuming a constant velocity the pressure would be -8.5 meters of H_2O. The measured pressure is -12.2 m of H_2O depending on higher velocity at the perifery. After 60 mm the pressure is -8 m of H_2O which means that the pressure rise only is slightly more than what would be obtained by equalization of the velocity of the driven water.

For the jets 21, 24, 27 and 30 mm the pressure curves are similar. For the jet 36 mm the pressure rise is less.

5.2 What is happening in the diffuser

Seven pressure taps are placed along the diffuser, dividing it into six parts. The pressure rises in these six parts are measured in the neighbourhood of the maximum efficiency. Table 2 shows measured pressure rises for test No. 23, 7, 15, 18 and 20 for cold water. As a comparison the pressure rises with uniform velocity distribution and diffuser efficiency 100% are calculated. In part 1 the measured pressure rises are considerably lower than the pressure rises at $\eta =$ $= 100\%$. Of the other 25 points the measured pressure rises are higher than the pressure rises at $\eta = 100\%$ in 21 points.

In a common diffuser the efficiency of the several parts decreases depending on an increasing nonuniformity of the velocity distribution. In the jet pump the diffuser seems to work in completely opposite manner. In the first part the efficiency is obviously low, in the following parts the efficiency is commonly more than 100%. This shows that in the first part the velocity distribution is growing more uneven, in the following parts it is equalizing.

It is intricate to explain this phenomena, but the high diffuser efficiences - 100% at jet 36 mm to 87% at jet 21 mm - indicate that the velocity distribution is very uneven at the beginning of the diffuser. It seems probable that the change from the mixing chamber with constant diameter to the diffuser with the angle 3.5° or 4.5° is too sudden. It seems probable that a jet pump with a mixing chamber with constant area, a diffuser with a very little angle, perhaps 2°, and then a diffuser with 3.5° or 4.5° would give a higher total efficiency.

6. DISCUSSION OF EXPERIMENTAL RESULTS

When comparing the values of η_i in table 1, we see that the differences between hot and cold water are very low. Commonly the difference is between 0 and 2%. Yet the ratio of kinematic viscosity at 30°C and 210°C is 5.2:1. Therefore it is probable that a relatively little part of the momentum losses depends on friction losses.

The conical mixing chamber caused an improvement by decreasing the maximum velocity of driven water in the entrance. But that improvement is concentrated just to the beginning of the mixing chamber. An optimal conical mixing chamber must be much shorter than 110 mm. It was no point in making more tests with this long conical part.

The tests show no pronounced difference between the diffuser angles 3.5° and 4.5°. It is probable that with more narrow steps of the mixing chamber length the best values of η and η_i would increase and a difference between the angles 3.5° and 4.5° would arise. However, the Mueller [1] experiments show that the efficiency curve as function of the mixing chamber length is very flat around the maximum value.

Literature:

1. N.H.G. Mueller. Water jet pump. J. of the Hydraulics Division. "Proceedings of the American Society of Civil Engineers", Vol. 90, 8Y-HY3 (1964).

Table 2. Pressure rise in diffuser

Test No.	Nozzle mm	Diffuser	η_D	Part of diffuser		Test with cold water 1	2	3	4	5	6
23	36	3.5°	1.01	Pressure rise	at η_D=100%	5.61	2.73	1.45	0.84	0.53	0.28
				meters of H_2O	Measured	.9	3.25	1.55	0.95	0.55	0.45
7	30	4.5°	0.995	- " -	η_D=100%	6.61	3.22	1.7	0.98	0.63	0.33
					Measured	5.9	3.35	1.7	1.25	0.75	0.45
15	27	3.5°	0.944	- " -	η_D=100%	5.12	2.49	1.3[illegible]	0.76	0.48	0.26
					Measured	3.65	3.0	1.4	0.8	0.6	0.4
18	24	3.5°	0.894	- " -	η_D=100%	4.83	2.35	1.24	0.72	0.46	0.24
					Measured	3.2	2.7	1.3	0.7	0.5	0.4
20	21	3.5°	0.869	- " -	η_D=100%	3.67	1.8	0.95	0.55	0.35	0.18
					Measured	2.3	2.1	0.85	0.55	0.4	0.3

Table 1. Summary of tests

Test No.	Nozzle mm	Diffuser	Mixing chamber Con=conical Cyl =cylindrical R=rounded edge		Length mm	Best efficiency at							
								Hot			Cold		
						q_2/q_1	w_2/w_1	p_2/p_1	η	η_i	p_2/p_1	η	η_i
1	30	4.5°	Con		320	1.85	0.293	0.166	0.307	0.830	0.158	0.292	0.809
2	30	4.5°	Con		420	2.1	0.332	0.158	0.332	0.847	0.157	0.330	0.845
3	30	4.5°	Con		570	2.0	0.316	0.165	0.330	0.850	0.160	0.320	0.837
4	30	4.5°	Con		770	2.0	0.316	0.158	0.316	0.832	0.154	0.308	0.822
5	30	4.5°	Cyl		420	2.0	0.316	0.164	0.328	0.847	0.160	0.320	0.837
6	30	4.5°	Cyl		570	1.8	0.285	0.180	0.324	0.858	0.158	0.284	0.801
7	30	4.5°	Cyl	R	420	2.0	0.316	0.165	0.33	0.850	0.156	0.312	0.827
8	30	4.5°	Cyl	R	570	2.0	0.316	0.162	0.324	0.842	0.160	0.320	0.837
9	30	4.5°	Con	R	570	2.2	0.348	0.159	0.35	0.865			
						2.0	0.316				0.160	0.320	0.837
10	30	3.5°	Con	R	420	2.1	0.332	0.167	0.351	0.869	0.157	0.330	0.845
11	30	3.5°	Con	R	570	2.1	0.332	0.158	0.332	0.847	0.152	0.319	0.833
12	30	3.5°	Cyl	R	320	1.9	0.301	0.162	0.308	0.827	0.162	0.308	0.827
13	30	3.5°	Cyl	R	470	2.2	0.348	0.159	0.350	0.865	0.150	0.33	0.844
14	27	3.5°	Cyl	R	420	2.5	0.310	0.136	0.340	0.876	0.130	0.325	0.858
15	27	3.5°	Cyl	R	570	2.7	0.355	0.127	0.343	0.872	0.120	0.324	0.852
16	27	4.5°	Cyl	R	570	2.4	0.298	0.140	0.336	0.876	0.132	0.317	0.852
17	24	3.5°	Cyl	R	420	2.8	0.261	0.102	0.286	0.840	0.099	0.277	0.827
18	24	3.5°	Cyl	R	570	2.8	0.261	0.110	0.308	0.873	0.107	0.300	0.861
19	24	4.5°	Cyl	R	570	2.8	0.261	0.110	0.308	0.873	0.106	0.297	0.857
20	21	3.5°	Cyl	R	570	3.7	0.264	0.074	0.274	0.840	0.074	0.274	0.840
21	21	4.5°	Cyl	R	570	3.5	0.250	0.079	0.276	0.849	0.078	0.273	0.844
22	36	3.5°	Cyl	R	320	1.6	0.386	0.225	0.360	0.853	0.225	0.360	0.853
23	36	3.5°	Cyl	R	420	1.55	0.373	0.230	0.356	0.851	0.230	0.356	0.851

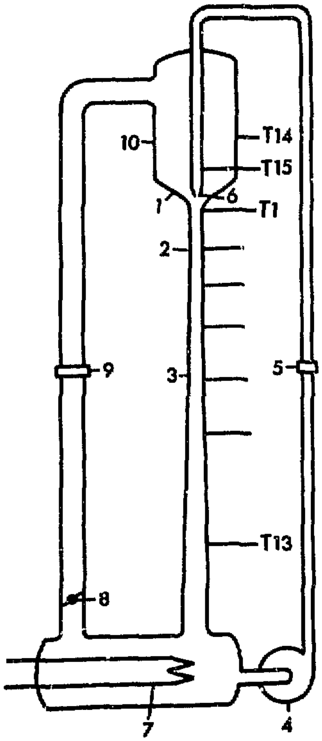


Fig. 1. Test assembly

1. Entrance
2. Mixing chamber
3. Diffuser
4. Pump
5. Flow meter
6. Nozzle
7. Heater
8. Valve
9. Flow meter
10. Chamber

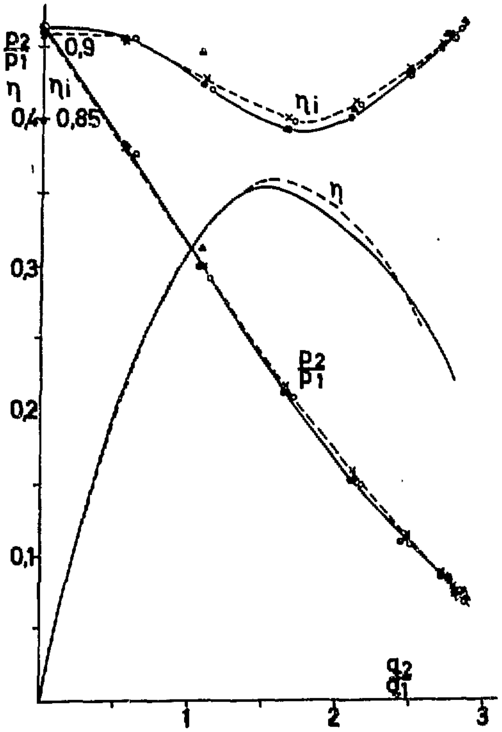


Diagram 1. - Hot --- Cold
Test 23. Nozzle 36 mm
Mixing chamber 420 mm
Diffuser 3.5°

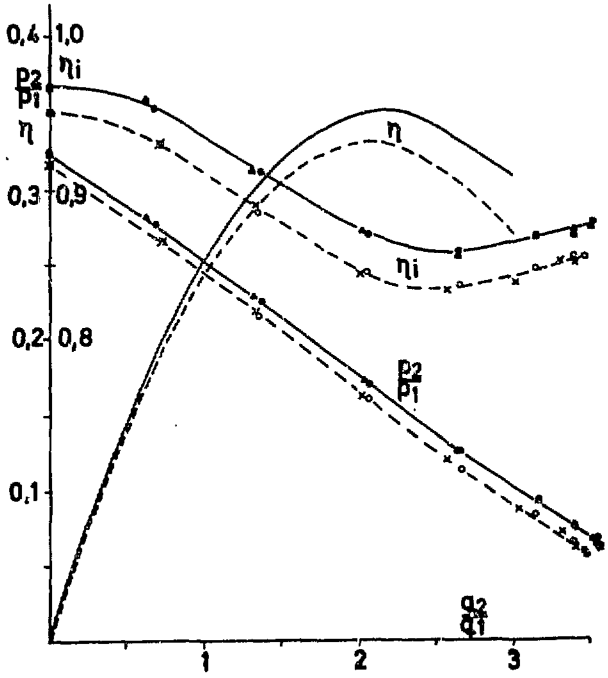
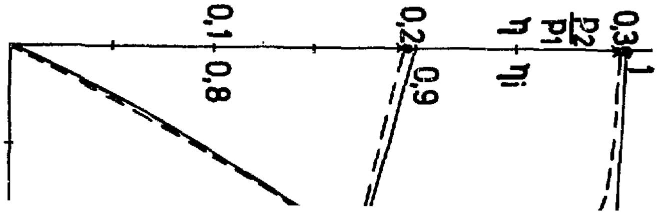


Diagram 2. - Hot --- Cold
Test 13. Nozzle 30 mm
Mixing chamber 420 mm
Diffuser 3.5°



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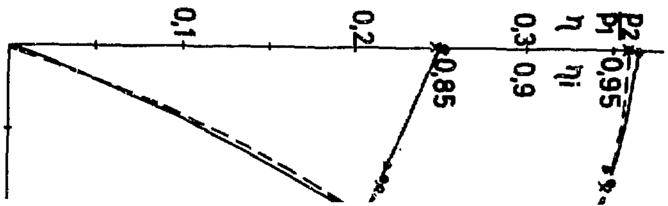
Test 18.
Mixing



Diagrar
Test 15
Mixing

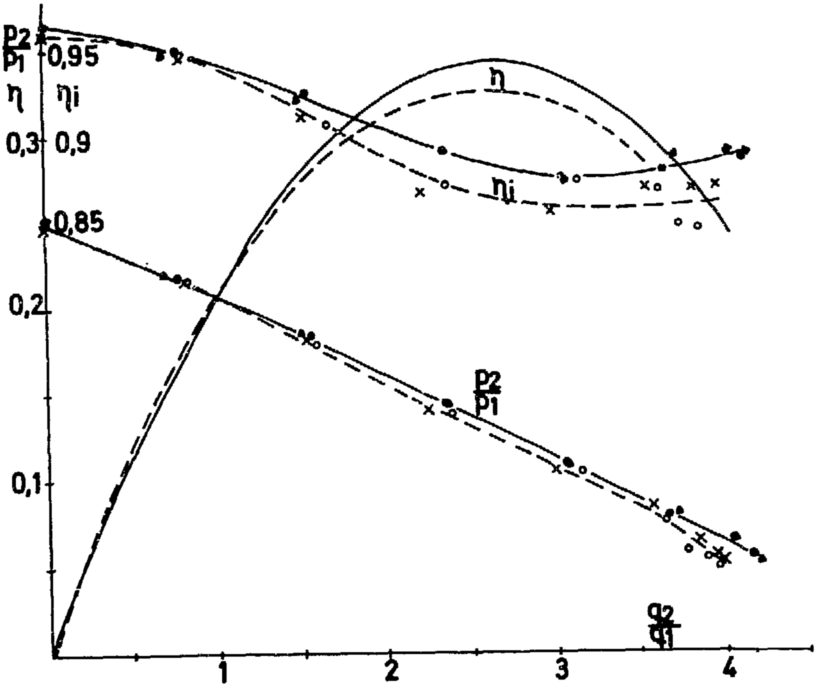


Diagram 3. - Hot --- Cold
Test 15. Nozzle 27 mm. Diffuser 3.5°
Mixing chamber 570 mm

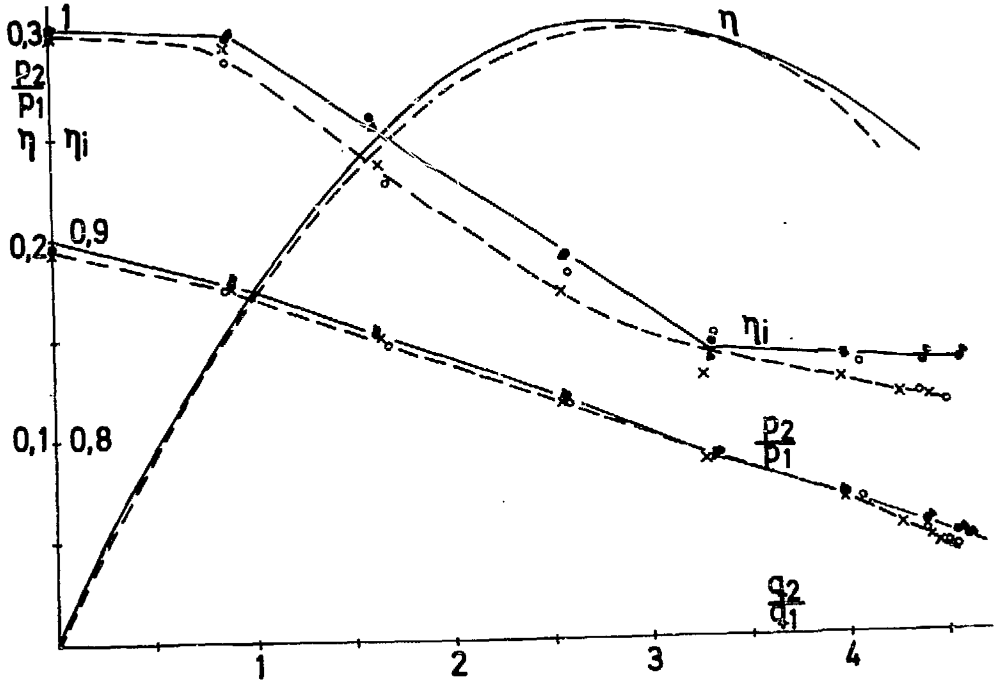


Diagram 4. - Hot --- Cold
Test 18. Nozzle 24 mm. Diffuser 3.5°
Mixing chamber 570 mm

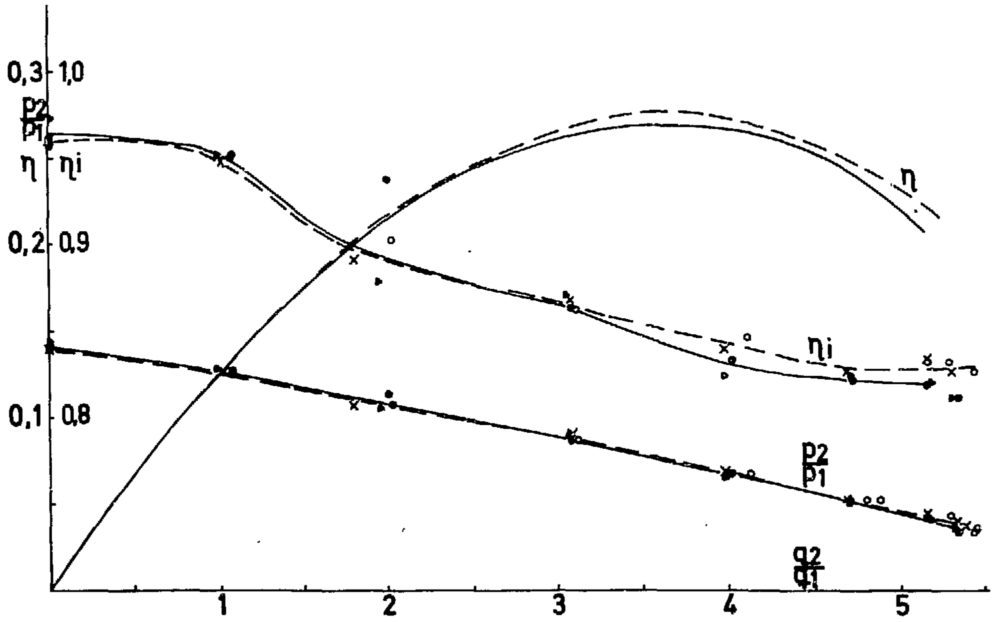


Diagram 5. - Hot --- Cold
Test 5. Nozzle 21 mm. Diffuser 3.5°
Mixing chamber 570 mm

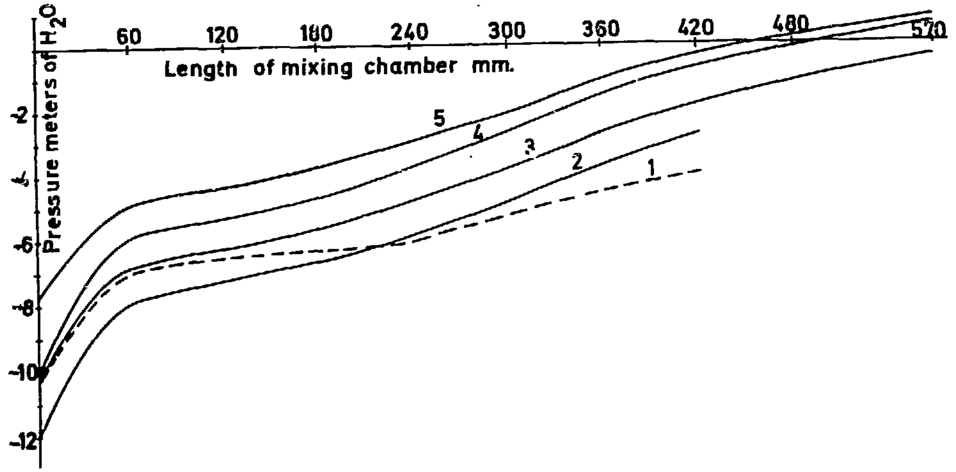


Diagram 6. Pressure rise in mixing chamber cold water.
Pressure zero = pressure before entrance.

1. Test 23. Nozzle 36 mm
2. Test 7. Nozzle 30 mm
3. Test 15. Nozzle 27 mm
4. Test 18. Nozzle 24 mm
5. Test 20. Nozzle 21 mm

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