REACTION TYPE HOT WATER TURBINE

Ryozo Nishioka
Yoshifumi Kato

Fuji Electric Co.,Ltd.
1-1 Tanabeshinden, Kawasaki-ku, Kawasaki, 210 Japan

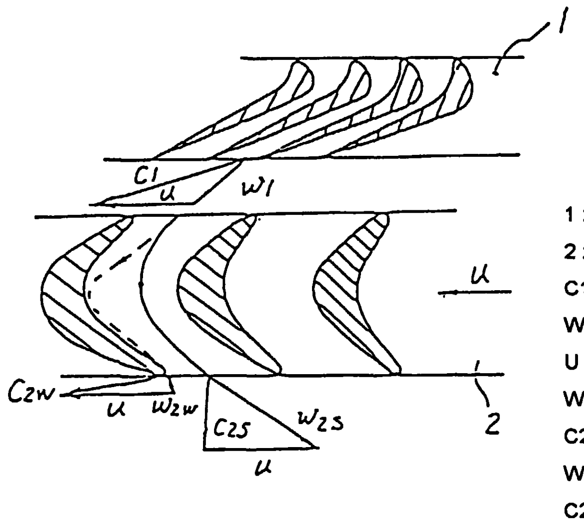
ABSTRACT

Most geothermal resources in the world are liquid dominated and this tendency will be more remarkable in the future. To extract electric power from such geothermal resources flash cycles, single or double, have been hitherto adopted.

In the case of a single flash cycle steam and hot water mixture from geothermal well is first treated in steam separator and herein separated steam is then expanded in steam turbine for power generation. In this case effective energy, contained in hot water from separator, is not utilized.

In the case of a double flash cycle, adopted to utilize the effective energy of hot water from separator, a further possibility for utilizing the energy, so far consumed on the occasion of flashing and expanding of the hot water inside low pressure flasher, still remains. Several types of called total flow turbines have been tried and tested, but any type has not been practically realized as yet.

Geothermal hot water features its low pressure (lower than 10atg), large mass flow, and much impurity content. Our company developed a new efficient and re-liable hot water turbine of high reaction type, suitable for such geothermal hot water. The following presents a information about the principle and features of hot water turbines of high reaction type, the summarized test results with a scale model hot water turbine and the conceptual design of a full-scale hot water turbine of high reaction type.



1 : Nozzles
2 : Moving blades
C1 : Nozzle outlet velocity
W1 : Moving blade inlet relative velocity
U : Moving blades peripheral speed
W2s : Steam relative velocity at moving blade outlet
C2s Steam velocity at moving blade outlet
W2w : Water relative velocity at moving blade outlet
C2w : Water velocity at moving blade outlet

Figure 1

PRINCIPLE AND FEATURES OF HOT WATER TURBINES OF HIGH REACTION TYPE

1. Problems with hot water turbines of impulse type

Figure 1 shows a blade arrangement of hot water turbines of impulse type. Hot water is fully expanded and flashed through the nozzles. Accelerated hot water and steam mixture flows into the moving blades. Inside the moving blades the flow direction of the mixture is changed and thus the speed energy of the mixture is converted into power on the moving blade disc. For instance, hot water and steam mixture after the adiabatic expansion of saturated hot water of 5atg consists of hot water, occupying its 91% mass, and steam, occupying its 99.4% volume. For this reason the flow pass area of the moving blades is decided depending on the volume flow of the steam part. Inside the nozzles hot water is unable to be accelerated to the steam velocity because of the large difference between the densities of the water and steam. At the nozzle outlet the velocity of hot water becomes lower than the steam velocity, due to slipping of hot water droplets in steam flow. Therefore the velocity triangle of hot water at the moving blade inlet is different from that of steam and an additional flow loss is possibly caused at the moving blade inlet due to the collision of hot water against the moving blades.

Inside the moving blade hot water is unable to turn along the moving blade flow passage having a small radius of curvature as steam does and for the most part reaches on the pressure side surfaces of the moving blade profiles and forms thin liquid layers over the profile - surfaces.(Figure 1) As the result the velocity triangle of hot water at the outlet of the moving blades is quite different from that of steam and the efficient energy conversion cannot be performed at the moving blade row of impulse type.

2. Principle and features of high reaction type

Figure 2 presents a blade arrangement of hot water turbines of high reaction type. The flow passage area of the nozzles narrows along the passage route. The difference between the pressures at the inlet and outlet of the nozzles is decided so small that hot water is not thermodynamically expanded and flashed but only accelerated by the head drop from the pressure before the nozzles to that after the nozzles. Therefore there is no fear of a considerable difference between the velocities of hot water and steam at the outlet of the nozzles. The moving blades has a straight planner profile and this flow passage area widens from the inlet to the outlet by means of increasing the blade height along the blade passage. During flowing through the blade passage hot water is expanded, flashed and accelerated without any turning its flow direction. By the reaction of hot water and steam mixture leaving the moving blade a highly efficient power conversion on the moving blade row can be realized. As above mentioned the nozzle pressure drop is very small and therefore the temperature of hot water remains unchanged after the nozzle, while hot water, having a fairly high relative speed already at the moving blade inlet, is continuously accelerated through the blade passage. There is no fear for depositing or scaling over both nozzle and blade passage surfaces by impurities contained in geothermal hot water.

The features of our hot water turbines of high reaction type are as follows.

- axial flow high reaction type
- nozzle passage narrows along flow direction
- small nozzle pressure drop and uniform hot water velocity distribution at nozzle outlet
- moving blades have a straight planer profile and blade passage widens along flow direction with increasing blade height toward the exit
- hot water is expanded, flashed, and accelerated through straight blade passage without turning flow direction
- highly efficient power conversion, robust construction, long durability and high reliability

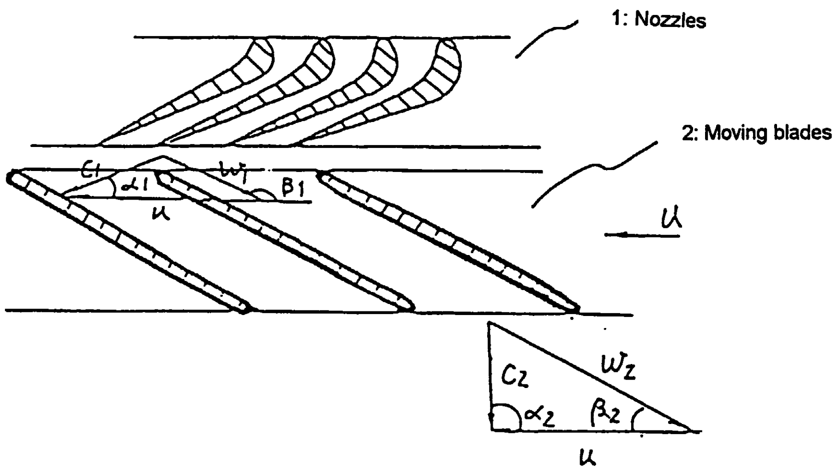


Figure 2

TEST FACILITY

1. Specification of model hot water turbine

hot water pressure	; 2.7 ata (saturated)
backpressure	; 1.033 ata
hot water flow	; 50 t/h
rotating speed	; 1800 rpm
pitch diameter	; 530 mm
nozzle height	; 2.6 mm
moving blade height	; 4 mm (inlet)/ 95 mm (outlet)

Figure 3 shows the cross-sectional view of the model hot water turbine.

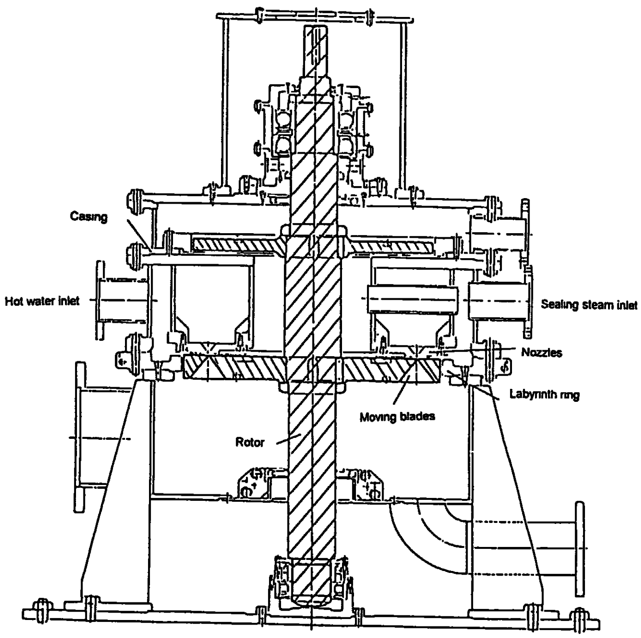


Figure 3 Cross Section of Model Turbine

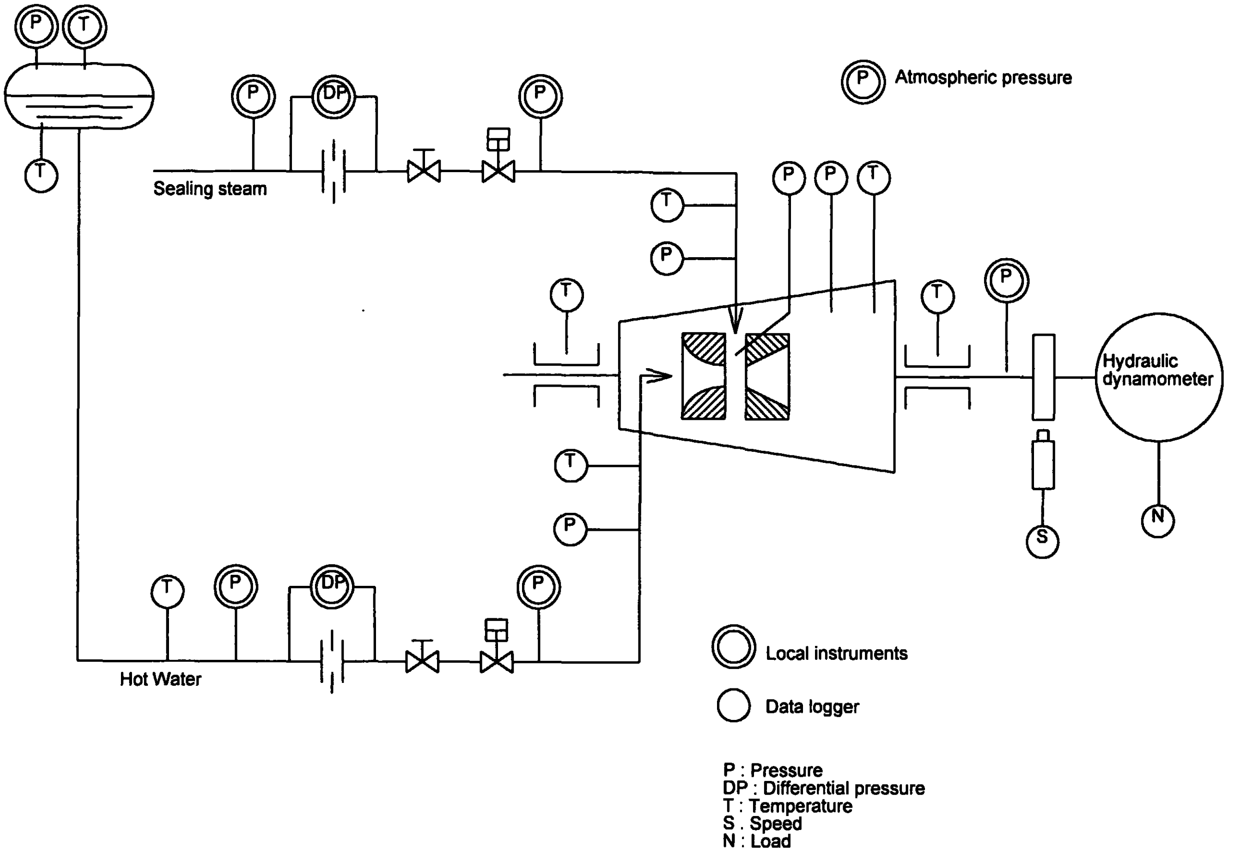


Figure 4 Testing and Instrumentation Diagram

2. Test circuit and instrumentation

Figure 4 illustrates the piping system and measuring positions for testing.

In the feed water tank of the dearator of the boiler for steam turbine factory testing saturated hot water was first accumulated and load testings of hot water were carried out by its flowing-down. Sealing steam was led from the heating steam line in the factory. The shaft torque was measured by a hydraulic dynamometer.

TEST RESULTS

1. Measured data

75 load tests were carried out under different test conditions, of which 13 tests were selected as representative and evaluated. Measuring results for its 13 tests are summarized in Table 1.

2. output and total efficiency

Figure 5 is a diagram illustrating the relation between measured outputs (Ne) of the model hot water turbine and measured pressures (P1) after the nozzles, before the moving blade row. The output Ne increases linearly relating to the pressure P1.

Figure 5 Output (Ne) vs Nozzle Outlet Pressure (P1)

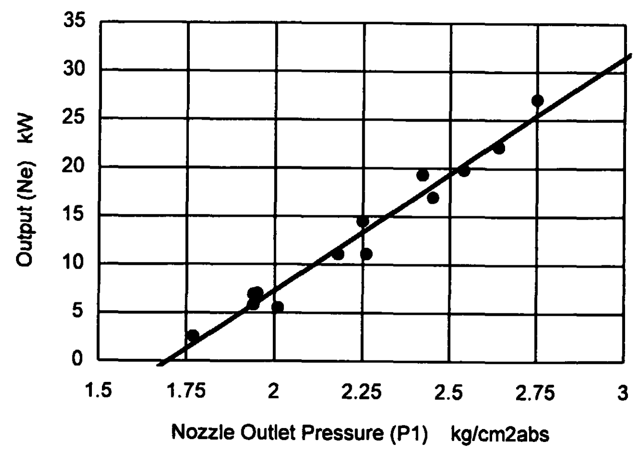


Table 1 Measured Results

Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Output Ne (kW)	22.16	14.51	5.84	7.03	5.56	19.3	19.8	17	11.1	2.58	11.1	27.1	6.96
Rotating speed n (rpm)	1782	1805	1758	1746	1760	1819	1762	1776	1775	1754	1712	1729	1848
Hot water quantity Gw (t/h)	46	48.4	38.1	23.1	39	42.5	31	23.5	11.4	61.4	55.3	44.1	47.9
Hot water inlet pressure Po (kg/cm2abs)	2.96	2.61	2.2	2.02	2.51	2.7	2.67	2.54	2.27	2.98	2.85	3.05	2.54
saturated temperature Tos (deg.C)	132.5	128.3	122.7	120	126.9	129.3	129	127.3	123.7	132.7	131.2	133.5	127.3
Hot water inlet temperature To (deg.C)	123.3	123.3	111.9	110.8	127.6	127.2	125.3	125.1	125	130.7	130.1	128.2	128.2
saturated pressure Pos (kg/cm2abs)	2.25	2.25	1.56	1.5	2.56	2.53	2.39	2.37	2.37	2.81	2.76	2.61	2.61
Nozzle outlet pressure P1 (kg/cm2abs)	2.64	2.25	1.94	1.95	2.01	2.42	2.54	2.45	2.26	1.77	2.18	2.75	1.94
Nozzle pressure drop) Pn (kg/cm2abs)	0.32	0.36	0.26	0.07	0.5	0.28	0.13	0.09	0.01	1.21	0.67	0.3	0.6
Backpressure P2 (kg/cm2abs)	1.135	1.094	1.072	1.062	1.071	1.091	1.081	1.071	1.061	1.065	1.095	1.105	1.071
Sealing steam supply pressure (kg/cm2abs)	2.7	2.28			2.01	2.45	2.59	2.5	2.32	1.79	2.2	2.77	1.94
Sealing steam supply temperature (deg.C)	129.6	124.4	119.8	120	135.3	127.1	136.3	136.1	136.3	116.9	121.7	130.9	136.8
Sealing steam quantity (t/h)	3.91	3.18	2.997	3.49	2.2	3.47	4.32	4.36	4.4	0.7	2.21	3.76	1.89
Labyrinth steam quantity (t/h)	2.58	2.14	1.77	1.79	1.85	2.34	2.49	2.39	2.17	1.55	2.05	2.71	1.76
Assist steam quantity Ga (t/h)	1.33	1.04	1.227	1.7	0.35	1.13	1.83	1.97	2.23	-0.85	0.16	1.05	0.13

Table 2 Test results of total efficiency

Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Hot water inlet temperature To (deg.C)	123.3	123.3	111.9	110.8	127.6	127.2	125.3	125.1	125	130.7	130.1	128.2	128.2
saturated pressure Pos (kg/cm2abs)	2.25	2.25	1.56	1.5	2.56	2.53	2 39	2.37	2.37	2.81	2 76	2.61	2.61
Backpressure P2 (kg/cm2abs)	1.135	1.094	1.072	1.062	1.071	1.091	1.081	1.071	1.061	1.065	1.095	1.105	1.071
Adiabatic heat drop) How (kcal/Kg)	0.582	0.644	0.171	0.144	0.949	0.887	0.784	0.782	0.799	1.188	1.083	0.932	0.994
Hot water quantity Gw (t/h)	45	48.4	38.1	23.1	39	42.5	31	23.5	11.4	61.4	55.3	44.1	47.9
Hot water adiabatic work Now (kW)	30.5	36.3	7.6	3.9	43.0	43.8	28.3	21.4	10.6	84.8	69.6	47.8	55.4
Hot water velocity ratio U/Cow	0.55	0.61	0.65	0.65	0.64	0.59	0.55	0.57	0.60	0.70	0.59	0.52	0.69
Nozzle outlet pressure P1 (kg/cm2abs)	2.64	2.25	1.94	1.95	2.01	2.42	2.54	2.45	2.26	1.77	2.18	2.75	1.94
saturated temperature T1s (deg.C)	128.6	123.4	118.7	118.8	119.8	125.7	127.3	126.1	123.5	115.8	122.4	129.9	118.7
Backpressure P2 (kg/cm2abs)	1 135	1.094	1.072	1.062	1.071	1.091	1.081	1.071	1.061	1.065	1.095	1.105	1.071
Adiabatic heat drop) Hoa (kcal/Kg)	34.498	29.378	24.163	24.704	25.608	32.458	34.826	33.678	30.751	20.649	28.052	37.185	24.163
Assist steam quantity Ga (t/h)	1.33	1.04	1.23	1.7	0.35	1.13	1.83	1.87	2.24	-0.85	0.17	1.05	0.13
Assist steam adiabatic work Noa (kW)	53.4	35.5	34.6	48.8	10.4	42.6	74.1	73.2	80.1	-20.4	5.5	45.4	3.7
Assist steam velocity ratio U/Coa	0.092	0.101	0.108	0.106	0.105	0.097	0.091	0.093	0.097	0.117	0.098	0.086	0.114
Total adiabtic work No=Now+Noa (kW)	83.8	71.8	42.1	52.7	53.5	86.5	102.4	94.6	90.7	64.4	75.2	93.2	60.8
Measured output Ne (kW)	22.2	14.5	5.84	7.03	5.56	19.3	19.8	17	11.1	2.58	11.1	27.1	6.96
Total efficiency 0t	0.265	0.202	0.139	0.133	0.104	0.223	0.193	0.180	0.122	0.040	0.148	0.291	0.114

Table 3 Circumferential work and efficiency

Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Hot water quantity Gbw (t/h)	45.0	48.4	38.1	23.1	38.4	42.5	31.0	23.5	11.4	59.6	54.5	44.1	47.0
Steam quantity Gbs (t/h)	1.33	1.04	1.23	1.7	0.94	1.13	1.83	1.87	2.24	0.9032	0.9980	1.05	1.0123
Peripherical speed U (m/sec)	50	50	50	50	50	50	50	50	50	50	50	50	50
Nozzle outlet velocity C1w (m/sec)	7.38	7.81	6.62	3.43	9.20	6.89	4.70	3.91	1.30	14.35	10.67	7.27	10.08
Nozzle outlet angle "1 deg	19	19	19	19	19	19	19	19	19	19	19	19	19
Moving blade outlet angle $2 deg	165	165	165	165	165	165	165	165	165	165	165	165	165
Hot water heat drop) How (kcal/kg)	0.905	0.647	0.428	0.449	0.484	0.792	0.913	0.852	0.704	0.312	0.586	1.046	0.430
Steam heat drop) Hos (kcal/kg)	34.480	29.451	24.127	24.704	25.608	32.458	34.790	33.678	30.751	20.649	28.052	37.036	24.163
Moving blade velocity factor Nb	0.725	0.7	0.65	0.675	0.625	0.75	0.75	0.775	0.7	0.6	0.625	0.775	0.65
Hot water circumferencial work Nubw (kW)	15.61	10.26	1.65	1.17	2.63	13.98	11.22	8.47	2.02	0.55	7.00	21.02	3.55
Steam cicumferencial work Nubs (kW)	6.05	4.15	3.99	5.86	3.01	5.17	8.70	9.07	9.16	2.42	3.38	5.37	3.29
Total circum ferencial work Nu (kW)	21.66	14.41	5.64	7.03	5.64	19.15	19.92	17.54	11.18	2.97	10.38	26.39	6.84
Measured output Ne (kW)	22.2	14.5	5.84	7.03	5.56	19.3	19.8	17	11.1	2.58	11.1	27.1	6.96
Nub/Ne	0.98	0.99	0.97	1.00	1.01	0.99	1.01	1.03	1.01	1.15	0.94	0.97	0.98
Hot water circumferencial efficiency 0ubw=Nubw/Nobw	0.329	0.281	0.087	0.097	0.121	0.357	0.340	0.363	0.216	0.025	0.188	0.391	0.151
Steam circumferencial efficiency 0ubs=Nubs/Nobs	0.113	0.116	0.115	0.119	0.107	0.121	0.117	0.123	0.114	0.111	0.103	0.118	0.115

Table 2 shows the calculated total efficiencies (ηt) of the model hot water turbine based on measured results.

The total efficiency is defined as following.

$$\eta t = Ne / (Now + Nos)$$

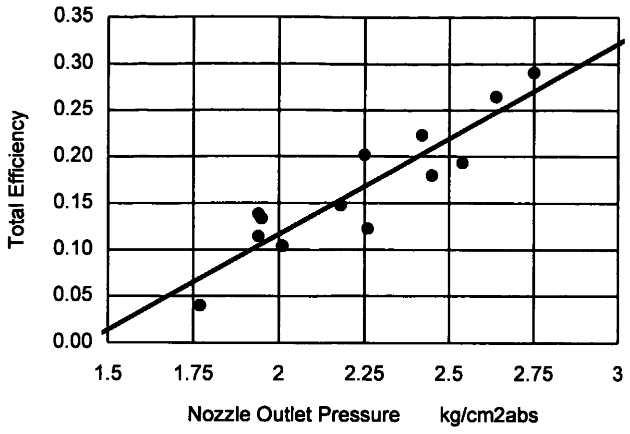
,where Ne ; model turbine output on shaft
Now; adiabatic work of hot water
Nos; adiabatic work of assistant steam

Assistant steam is a part of sealing steam and supplied into the moving blades not through the nozzle but directly.

The reason for the total efficiency ηt of a fairly low levels comes from the very low circumferential efficiency of assistant steam because of its very low velocity ratio (about 0.1). In order to get the proper efficiency of hot water it is needed, that the circumferential work of hot water is evaluated independently from that of assistant steam. (mentioned later on)

Figure 6 shows the relation of the total efficiency ηt to the nozzle outlet pressure P1. ηt increases linearly with P1.

Figure 6 Total Efficiency vs Nozzle Outlet Pressure

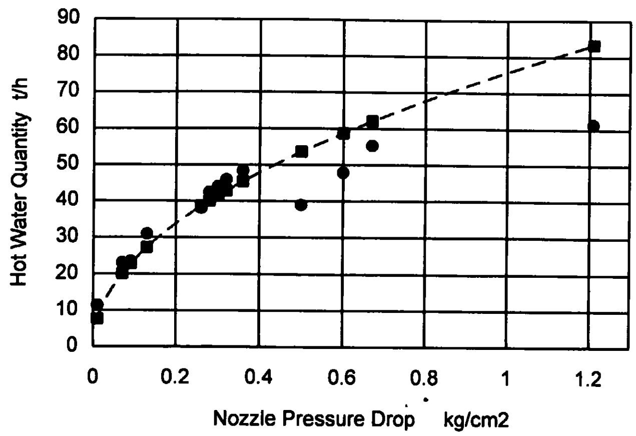


From Figure 5 and 6 it can be said, that the nozzle outlet pressure P1 plays an important roll on the hot water turbine performance.

3. Flow characteristics through the nozzle

Figure 7 shows the relation of the hot water quantity Gw to the nozzle pressure drop ΔPn. In the range of smaller ΔPn than about 0.5 ata the relation coincides fairly good with the curve calculated under an assumption, that hot water is only hydraulically accelerated with a velocity factor 0.9 depending on the nozzle head drop, while in the range of larger ΔPn than about 0.5 ata Gw falls under the calculated curve and this could mean the beginning of hot water flashing inside the nozzles.

Figure 7 Hot Water Quantity vs Nozzle Pressure Drop



4. Moving blade velocity factor, circumferential work and efficiency

Table 3 shows results of moving blade velocity factor ϕb, circumferential works Nuw, Nus and circumferential efficiencies ηuw, ηus respectively, calculated from the flow characteristics of hot water and steam through the nozzles and moving blades.

Figure 8 and 9 show respectively the moving blade velocity factor ϕb, the efficiencies ηuw, ηus of hot water and steam relating to the nozzle outlet pressure P1. The moving blade velocity factor ϕb, the circumferential efficiencies ηuw, ηus of hot water and steam increases linearly with P1. The circumferencial efficiencies ηuw of hot water comes near to 40%. The circumferencial efficiencies ηus of steam remains always on a low level of about 11% because of its small velocity ratio as already mentioned.

Figure 8 Moving Blade Vlocity Factor vs Hot Water Heat Drop

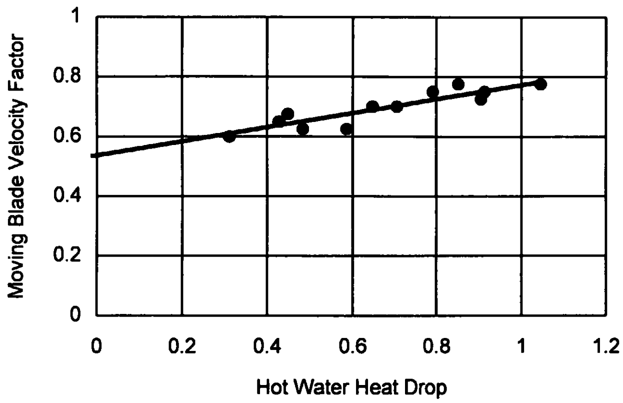
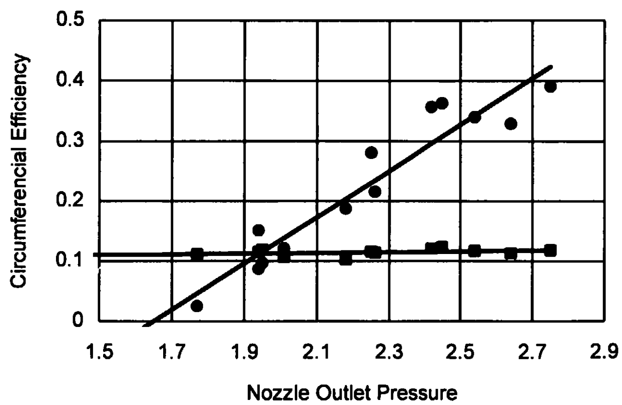


Figure 9 Cirumferencial Efficiency vs Nozzle Outlet Pressure



5. conclusion from the model test

The test results with the model hot water turbine suggested a possibility to realize hot water turbines having a such high level of efficiency as 40%.

A further performance improvement can be expected under considering next points based on the test results.

- selecting the nozzle outlet pressure as high as possible (high degree of reaction)
- fitting moving blade throat area to nozzle throat area to minimize assistant steam quantity
- improving profiles of nozzles and moving blades
- optimizing nozzle outlet angle $\alpha 1$ and velocity ratio U/Co

RELIABILITY TEST AT A GEOTHERMAL FIELD

A test operation with the model hot water turbine was carried out at a Japanese geothermal field during 2 months. The total operational hours amounted to 1000 hours. This field test operation confirmed the operational reliability fo the model turbine as followings.

- without any trouble to go to unit tripping
- low operational noise
- easy operationability
- no depositing and scaling on the flow channel surfaces inside the nozzles and moving blades
- no sign by any corrosion or erosion on turbine parts

EXAMPLE OF A CONCEPTUAL DESIGN FOR A FULL SCALE HOT WATER TURBINE

A conceptual design for a full scale hot water turbine was carried out for a Japanese planned geothermal power plant of a double flash type. The hot water turbine is arranged between the 1st flasher-steam separator -and 2nd one and used to utilize the effective energy of hot water flowing from the 1st flasher to the 2nd one. Table 4 shows the specification, main dimensions and the performance of the hot water turbine.

Figure 10 is the sectional view of the hot water turbine.

Hot water inlet pressure	ata	5.4
Inlet temperature	° C	154
Backpressure	ata	1.47
Adiabatic heat drop	kcal/kg	2.48
Hot water quantity	t/h	851
Sealing steam quantity	t/h	2.4
Number of stages		1
Number of flows		2
Pitch diameter	mm	1000
Rotating speed	rpm	1200
Peripheral speed	m/s	62.8
Nozzle outlet height	mm	4
Moving blade outlet height	mm	150
Internal output	kW	1000
Internal efficiency	%	38

Table.4 Specification, dimension and performance of a full-scale hot water turbine

SUMMERY

The test results with the scale model hot water turbine of high reaction type confirmed the high efficiency and reliability. It can be expected to realize hot water turbine with a efficiency over 40% in the case of full scale hot water turbines.

We hope, that the principle of hot water turbines of high reaction type will be adopted in actual geothermal field and a way will be found to utilize the effective energy of geothermal hot water in the future.

Figure 10 Cross section of Hot Water Turbine