Aqua Drive System

- A Technical Guide

Japan Fluid Power Association

Triple water mills, a national registered monument
Back cover: *Fukuroda-no-taki*, Ibaragi Prefecture, Japan.

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Chapter 1　Overview of Aqua Drive System

1.1 What is the aqua drive system?

Fluid power technology using water as its pressure medium was already utilized at the end of the 18th century. It was mainly to transmit a large power. However, the water hydraulic technology at the time had problems, such as low efficiency due to leakage, deterioration of materials due to wear, friction, and rust. All these were blamed on low viscosity of water. Not to mention, nothing was done to treat and maintain the working water.

Later, various kinds of water-based working fluids, of which rust-prevention, corrosion resistance, and lubricating properties having been improved by adding additives to the water, have begun to be used for press and mining machines. The major advantage offered by these water-based working fluids is flame resistance; therefore, they have been well applied to iron manufacture facilities where the danger of fire was the most concern. A water hydraulic drive system today is often recognized just as "water hydraulics" in a broader sense, which generally includes water-based working fluids.

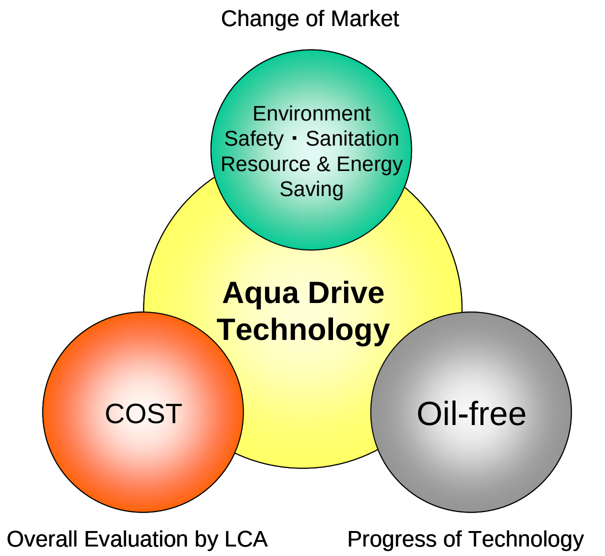


Fig. 1.1　Three elements supporting aqua drive technology

The “aqua drive system (**ADS**)”, different from the water hydraulic driving technology described above, solely uses tap water or pure water for its system working fluid.

(1) The basic policy is “oil-free”.

- The aqua drive system is consisted of components without lubricating oil, working oil, and mechanical oil.
- The driving characteristics of the aqua drive system are equivalent to those of the conventional driving technologies, such as by electricity, oil hydraulics and pneumatics.

(2) Life Cycle Assessment (LCA), is the core concept to evaluate the viability of the system.

- Resource and energy saving
- Environmental conservation, cleanness required for the environmentally sustainable manufacturing processes, safety in hygiene.
- Overall cost performance including, not only the initial cost but also service, maintenance and management, etc.

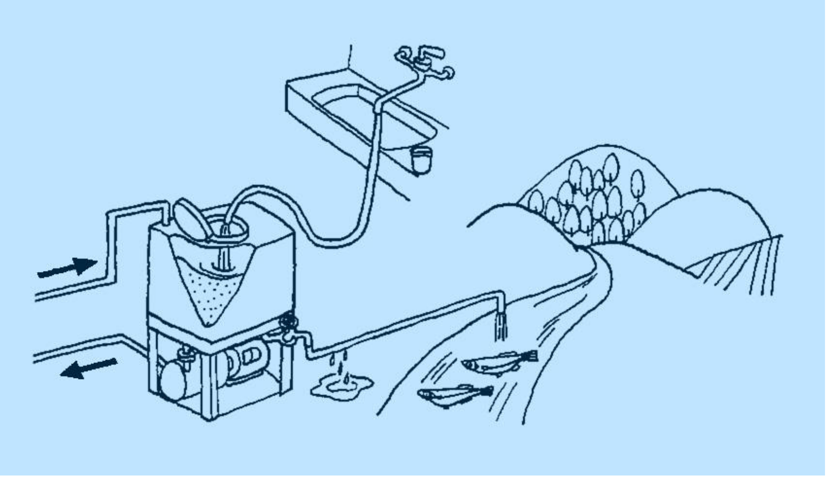
(3) Backup by “high technology”

- Today’s cutting-edge fundamental technologies in the field of ceramics, engineering plastics, and the advanced surface treatment technology.
- Computer-related technologies, such as in design and analysis, as well as in control, and management.

1.2 Advantages and problems to be solved

Advantages

(1) **Availability**: the readily available tap water is the working fluid.
(2) **Easy to dispose**: The used water can be damped to the rivers and sewage without special wastewater process otherwise required.
(3) **Low management cost**: Costs for purchase and management of the fluid are low.
(4) **Low environmental impact**: Even upon an accidental leakage during the operation, the fluid is non-odorous, non-toxic, and harmless.
(5) **Superior compatibility with products**: The system is very clean and hygiene control is easy.



(6) **Fire resistance**: The system is safer to the fire. Also, in case of fire around the system, it can stand to prevent the fire from spreading. For this reason, the system is excluded from the applicable range of the Fire Defense Law. In other words, the system is superior to any other driving systems in regards to fire insurance and safety management.
(7) **Low pressure loss**: The water's low viscosity contributes to the pipe pressure loss reduction and to easy system expansion. Because of this, the user can even save power required when compared to that required for the oil hydraulic system of the same size.
(8) **Faster response**: High fluid stiffness provides faster power transmission.

Problems to be solved

(1) **Lubrication property, sealing characteristic**: Water's low viscosity deteriorates the lubrication property. Decreased efficiency by leakage from slight gaps of the system components. Decreased efficiency by increase of wear and friction on the mating faces of moving parts. Deteriorated sealing.
(2) **Cavitation prevention**: The high-saturated vapor pressure easily initiates cavitation and erosion, which cause material deterioration.
(3) **Rust-prevention**: Rust is easy to form.
(4) **Water quality maintenance**: In the working fluid, bacteria, sludge, and slime are developed. Metal compounds are deposited.

These problems unique to the "aqua drive system" can be solved through careful selection of component structure, materials and by the use of advanced designing methods with computer. Applying today's high-end technology is also beneficial for the materials and the surface treatment.

Chapter 2 Components for Aqua Drive System

2.1 Components and accessories

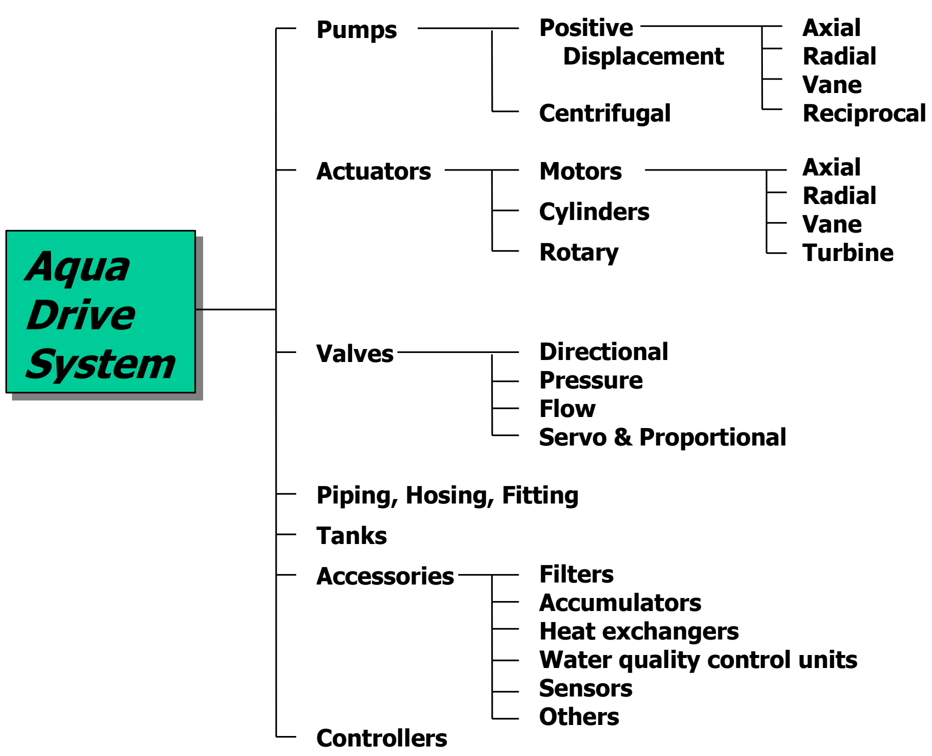


Fig. 2.1 Configuring devices and accessories of ADS

2.1.1 Pump

Structure: A water hydraulic pump used for the aqua drive system is selected either from the positive displacement or the centrifugal, according to specifications and the use of the system. For a time being, a majority of the pumps are the positive displacement in the ADS. The centrifugal pump, which has been used widely for the fluid transportation in many industrial fields, can be used for a low-pressure drive system, due to its low-pressure level compared to that of the positive displacement pump.

Displacement: The pump size should be selected such that the required flow rate and rotational speed are obtained. The flow velocity of the inlet/outlet
is preferred to be within the recommended flow velocity range of the pipe size.

Rotational speed: The rotational speed should be selected based on the following suction requirements.

- Relative location of the pump and the water surface
- Pressure of the suction port part (upper and lower limits)
- Suction pipe size and length as well as suction filter resistance, etc.
- Necessity of the boost pump
- Installation method

2.1.2 Actuator

Motor

Structure: The positive displacement and turbine types are mainly used. As the positive displacement motor, the axial piston and the radial piston motors are commercially available. The vane motor is also available for the low-pressure use.

Rotational speed: When the water hydraulic motor is used at a low rotational speed, the user should select a motor of which rotational speed is not lower than the value recommended by the manufacturer. If no appropriate motor is available, combine the motor with a reduction gear. Actuator, integrating a water lubricated type reduction gear and a water hydraulic motor, is also developed and commercially available; therefore, the user has a variety of choices according to the use.

Water hydraulic vane motor

Cylinder

Structure: Two cylinder types, the single acting and the double acting, are offered based on their motion. The user can choose the cylinder from a wide variety, such as the plunger, the single and double rods and telescope types. However, about the material and the seal system, clearly define the cylinder speed, frequency of operation and loading requirements.

Water hydraulic cylinders

Cylinder speed: The user can refer to the recommended speed range of the oil hydraulic cylinder for selecting the water hydraulic cylinder speed. The cylinder should be equipped with a seal system of which sliding resistance is minimum as possible.

Air vent: The air vent must be installed such that it can automatically vent the air; otherwise, accessible by human to vent it manually.

Buckling strength: To prevent the cylinder piston rod from being bent or buckled no matter where it is installed, the user needs to pay attention to the stroke length, the loading direction, and installation method of the cylinder.

Loading method and excessive load: When the cylinder is used where excessive or external load can be built up, the user needs to install the cylinder by a method, which takes the expected maximum load or the pressure peak into account.

Pressure amplification: The system must be equipped with a measure so that the rated pressure does not go beyond the limit because of the difference of piston areas.

2.1.3 Control valve

Overview: The water hydraulic valve is classified per functions to control the pressure, flow rate, and direction of the working fluid. The user can select various valves to satisfy the requirements due to the ADS circuit configuration. Spool type is available for the servo and proportional valves.

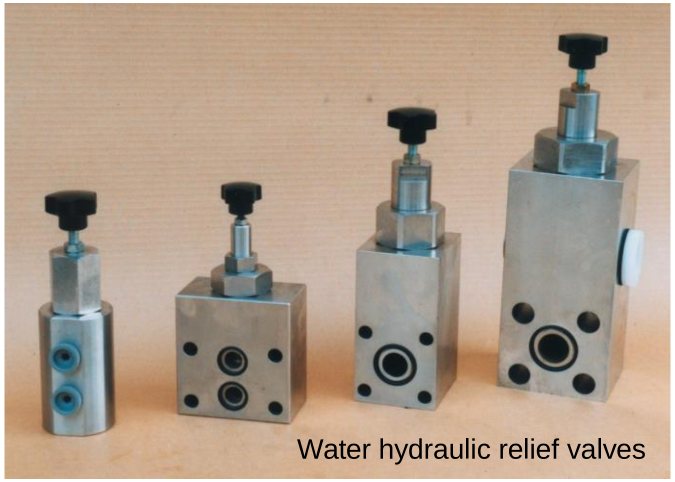
Water hydraulic servovalves

Size: When the valve is used at the maximum flow rate, the flow velocity in the pipe, which is separately specified, should be within the recommended range.

Structure: Two valve types, spool and poppet, are available. The valves with various functions are commercially available. The inner passage of the valve main body and the manifold should have a structure such that the working fluid does not stay still. The structure prevents the water quality change and accumulation of foreign substances caused by the residing working fluid.

Electric connection of the electric operational valve: The valve has to satisfy the IEC standard in regards to water- and damp-proof aspects.

Water and moisture proofing of the solenoid part: The user should select a safe valve according to IEC529 such that ingress of water and dust from the outside is prevented and leakage of the working fluid from the valve to the solenoid is prevented.


Water hydraulic relief valves

2.1.4 Pipe and Coupling

Pipe size: Select a pipe size such that the flow velocities in the respective pipeline should meet the following recommended values:

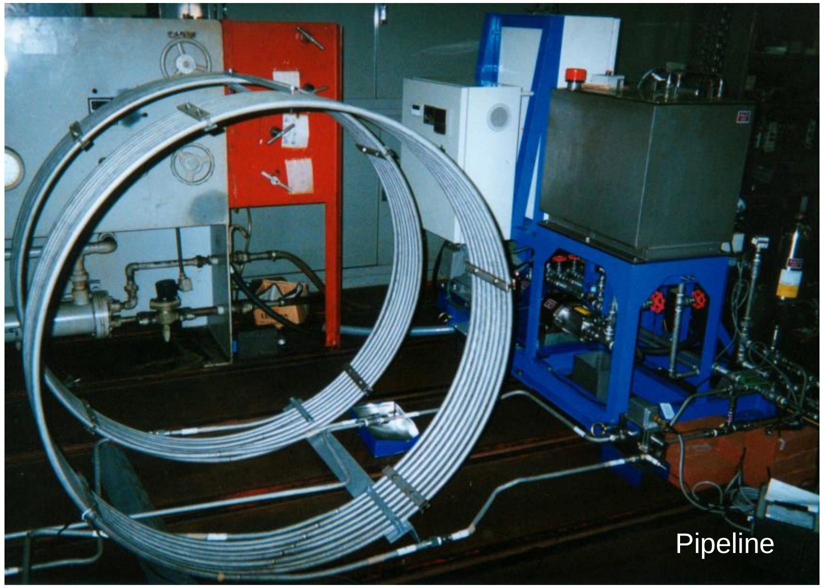
High-pressure line:	3～8 m/s
Return line:	2～5 m/s
Suction line:	0.5～1 m/s

Note) Comparison of the water and oil hydraulics: The pipe friction loss and surge pressure due to differences of the water and oil properties have been calculated on an assumption that the friction and oil flow through the same line at the same flow rate. The friction loss of the water is generally a half of that of the oil hydraulics. The surge pressure of the water is generally 1.3 times greater than that of the oil due to water hammer. If the friction loss value of the water hydraulics is allowed to be equal to that of the oil, the viscosity of the water can be increased up to twice as much as the oil. However, considering influence of the surge pressure, it is reasonable for the flow viscosity of the water to be 1.5 to 1.6 times of the oil. Therefore, if the upper limit of the flow viscosity through the oil hydraulic pipe is assumed 5 to 6 m/s, that of the water shall be 8 to 10 m/s.

Pipe for the high-pressure line: Despite of the velocity being within or beyond the recommended range described above, the user should consider possible generation of the surge pressure, depending on the operation methods and avoid any system damage when selecting the high-pressure line.

Hose assembly: Select a hose assembly confirmed its adaptability with the working fluid, such as metal jigs and rubber hoses.

Pipe connection: Pipes must have such a shape to allow no outer leakage. It is not desirable to use any connection method that requires taper screw threads for pipes or sealer.


Pipeline

Couplings for pipes and hoses: The coupling should be made of the elastic seal. Select the elastic seal confirmed its conformity with the working fluid.

Rated pressure of coupling: Select the coupling of which rated pressure is beyond the maximum operational pressure of the system.

Standard of pipe: It is desirable that the selected pipe shall conform to specifications described in JIS G 3448 (Light gauge stainless steel tubes for ordinary piping).

2.1.5 Reservoir

Capacity: The reservoir should be capable of holding the working fluid circulating in the system as well as be able to maintain a certain water level of the working fluid that guarantees safe use of the fluid. Also, the user should select a reservoir while taking water temperature rise, characteristics of separation of the entrained air and the falling speed of contaminants into consideration.

Water level: The reservoir should be designed so that a water level of the working fluid is higher than the pump suction port. Depending on the pump suction requirements, use of pressurizing reservoir or boost pump is preferred.

Interior surface structure: It is influential to the pump suction requirements. The circulating speed of the working fluid should allow the sufficient air discharge to the reservoir. Therefore, separate the suction and return sides of the pump with a buffer plate or other medium.

Shading: To prevent bacteria and germs growth, the structure should be designed so that no direct sunlight enters into the reservoir.

Suction line and its position: The user should use the suction line of which size can obtain the suction characteristics recommended by the pump manufacturer and install it where the line can obtain such characteristics. When a filter for the suction line is to be installed, cleaning or replacement of the filter should be taking into account.

Preventing residual contaminants: Contamination residue and deposit in the reservoir will cause rusts and help bacteria growth. Therefore, the reservoir structure should be designed such that no contaminants or deposits could stay on the bottom and at corners of the reservoir, and the working fluid should be completely drained.

Interior surface finishing: It should be finished such that contaminants, such as sludge, waste lint, scale and others, can be easily removed when entered.

2.1.6 Accessories

Filter

Filtration: Filtration is required to restrict the particle contaminants below an acceptable level following operational requirements such as the pressure range employed for the ADS. Indication of the contamination level should conform to ISO4406.

Selection: Generally, the inner clearance of the water hydraulic components is narrower than in the oil hydraulics. To select the filter, the user has to follow standards recommended by the manufacturer. Note that the pressure drop when the working fluid is passing through the filter must stay within the specified range provided by the supplier.

Water supply: When the water is supplied for the initial stage or for maintaining the water level, the user should fill the reservoir with the working fluid via the filter designed exclusively for water supply. It should have the equivalent or superior filtration accuracy compared to other filters already supplied to the system.

Pump suction line: The user should select a filter, which matches the suction requirements provided by the pump manufacturer and build the configuration with considerations over maintainability, such as replacement of elements. Note that the user must know some pump manufacturers do not allow filter installation to the suction line. The user should follow the instructions provided by the manufacturer and adopt the filtration configuration suitable for the system.

Accumulator

Structure: Accumulators such as the diaphragm, the bladder and the piston types are available. The bladder type accumulator is the most popular. When the water-hydraulics-specified accumulator is specified, the user can easily select standardized products from commercially available lines. Such an accumulator can be substituted from the counterpart of the oil hydraulics in the aspects of function and performance.

Pulsation prevention: If the triple-plunger pump is to be used as the water hydraulic pump, it is preferred to use the pulsation-absorbing accumulator according to the required pressure specification of the system.

Others

Heat exchanger: When the working fluid temperature exceeds the specified (refer to Section 3.2.3, System operation temperature) during natural cool down, the heat exchanger complying with the working fluid should be used. To prevent freezing, a heater may be used as required.

Air breather: Even when the reservoir is an open type, considering the ambient environmental conditions where the pump is installed, the air breather must be installed to purify the air entering the water reservoir. For the filtering accuracy, the user should also take the bacteria and germs flowing in the air into account.

Water treatment unit: Integrating the unit for sterilization, such as dechlorination, ozonation, ultraviolet treatment, and such into the water hydraulic unit or pipes as required, can prevent growth of bacteria and germs. Various and effective units are commercially available for respective purpose of sterilization. The user can select the suitable with appropriate specification, which complies with the required water quality and operations.

Sensor: For safe operation of the system and protection of the water hydraulic components, equipping the unit with switches such as the pressure switch, the level switch, the temperature switch etc., is desirable.

2.2 Working fluid

2.2.1 Working fluid

Definition

The “tap water” defined in the Article 69, Ministry of Health and Welfare Ordinance (1992) (see Table 2.1), shall be the standard working fluid used for the system.
If the ADS is to be used out side of Japan, serious consideration over the water quality is required for the tap water standard is assumed different.

Table 2.1 Standard of the water quality of tap water

Item		“tap water” in Article 69	Test item *1
Concentration of hydrogen ion	pH	5.8 ～ 8.6	○
Hardness	mg/ℓ (Ca, Mg etc.)	300 or less	○
Chloric ion	mg/ℓ	200 or less	○
Zinc	mg/ℓ	1.0 or less	
Iron	mg/ℓ	0.3 or less	
Copper	mg/ℓ	1.0 or less	
Sodium	mg/ℓ	200 or less	
Manganese	mg/ℓ	0.05 or less	
Residue of transpiration	mg/ℓ	500 or less	○
Turbidity	Degree	2 or loss	
General bacteria	Count/mℓ	100 or less	○

*1 Refer to Section 3.2.1.

2.2.2 Water quality

Water quality that may seriously affect on the ADS performance

Corrosion: pH-value, conductivity, free acid, free carbonic acid (CO_2), chloride ion (Cl^-), Cl_2, dissolved oxygen, hydrogen sulfide, etc.

Generation of scale: hardness, silica (SiO_2), Ca, Mg, sulfuric acid ion (SO_4^{2-}), oil and grease, etc.

Generation of slime: micro-organism including bacteria

Table 2.2 Characteristics of tap water

Item (Unit)		Tap water (20℃)	(Reference) Working oil for the oil hydraulics	Main characteristics of the ADS
Density	kg/m^3	1000	860 ～ 920	Impact of cavitation erosion is heavy.
Kinematic viscosity	m^2/s	1×10^{-6}…(low)	Low to enormously high	Friction loss of pipes is small. (The pipe size can be reduced more.) The leakage from the clearance is small.
Change of viscosity against the temperature	—	Small	Large	Even if the temperature of the fluid is changed, performance is not largely changed.
Bulk modulus	GPa	2.4	1.36 ～ 1.88	The system stiffness is large. The surge pressure is great and the damping is slow.
Vapor pressure	kPa	2.34	9×10^{-6}	Impact of cavitation erosion is heavy.
Specific heat	J/kgK	4180	2018	Slow temperature rise
Conductivity	W/m・K	0.6	0.13	High cooling effect
Flash point	℃	Incombustibility	200 ～ 230	No risk of the fire

2.3 Materials

Material selection: To select the materials such as corrosion resistant alloys (titanium, aluminum, copper and nickel alloys as well as stainless steel, etc.), plastics, ceramics etc., the user should understand and aware of their mechanical properties, corrosion resistance, workability, thermal properties, etc.

Surface treatment: The user should choose appropriate method of surface treatment such as plating, vapor deposition, spraying, etc. according to materials, either base or article, and where the item is to be used.

Cavitation erosion: The components should be designed and installed such that no cavitation occurs. It is desirable to select the materials that prevent serious damages even when cavitation occurs. The following materials are superior for strength and workability: Stainless steel, aluminum bronze, nickel aluminum bronze.

Seal for the ADS: The following seal materials are generally known for conformity with water as media in the ADS.

(1) Elastomer: NBR, HNBR, FKM (FPM), etc.
(2) Thermo plastic elastomer: Polyurethane, etc.
(3) Plastic: Filler-containing PTFE, super high-molecular PE, etc.

Element	Material	Notes
Pump & Motor	Ceramics & its Coating, Stainless Steel, Titanium Alloy, Engineering Plastics	Corrosion Wear Errosion Cavitation
Valve	Ceramics, Stainless Steel	
Cylinder	Stainless Steel, Ceramics & its Coating	
Tank	Stainless Steel & Plastics	
Filter	Stainless Steel & Plastics	
Pipe & Fitting	Stainless Steel & Plastics	
Manifold	Stainless Steel	

Table 2.3 Components and materials

Chapter 3　Operating Aqua Drive System

Currently, the user can easily configure the ADS of capability up to 14 MPa (140 bar) using parts and devices commercially available. However, attention should be paid to some points of the water property and the water quality.

Low viscosity: The pressure loss of the pipe is smaller than that of the oil hydraulics. It contributes to designing a smaller system. However, lubricating property is inferior; therefore, when the user use a high pressure, examination of the lifetime is required.

Cavitation: Cavitation is a phenomenon that air bubbles are generated due to local pressure drop of flowing fluid. Taking some preventive measures is required. Selecting materials that can resist to cavitation erosion is important. Also, creating the shape of flow effective to prevent the cavitation erosion is important.

Bulk modulus (Fast propagation): Sudden shutdown of the circuit increases the surge pressure, which indicates the impact is also great. Consider some methods to prevent the sudden shutdown of the circuit during operation.

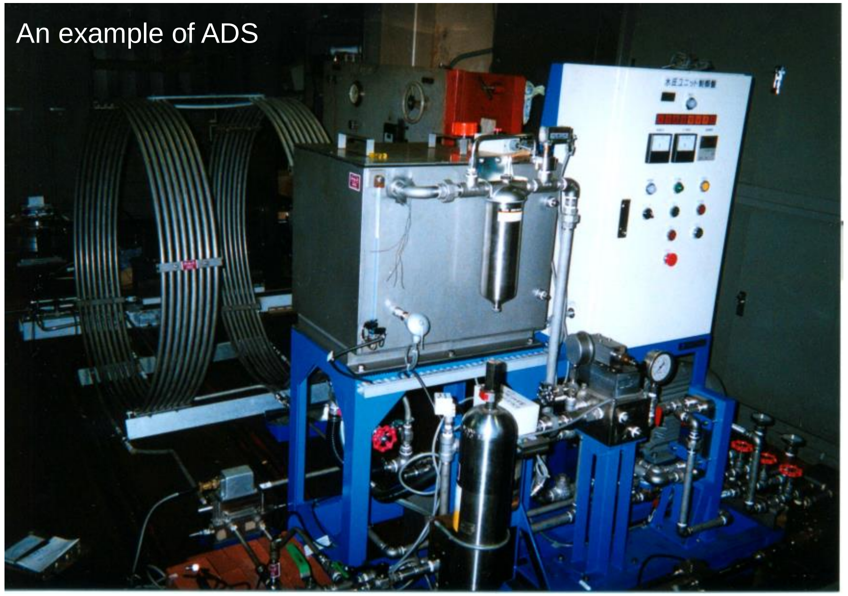
Water quality: To make the tap water as the working fluid, use a reservoir that prohibits ingression of dusts and foreign materials. Also, shutting off the direct sunlight is important to prohibit growth of bacteria and microbial organic materials.

Large specific heat: The rate of temperature rise of water is slower than that of the oil when their volumes are the same. With use of a cooler, the exchanged amount of heat is greater than that of the oil, comparing the same passing flow rate.

This chapter summarizes the theoretical and experimental aspects concerning the items mentioned earlier and divides them into “technological considerations” to the ADS operation and “operational guideline”.

Particularly, methods to demonstrate the ADS advantages and the effective ADS operation are focused. The segmented operation of the input signals with the servovalve proves the possibility to reduce the surge pressure effectively. The test result of the frequency response characteristics with the servovalve used is also shown.

The water quality was monitored for 12.5 months in total using the test circuit. No phenomenon to induce any trouble was observed.



An example of ADS

3.1 Technical issues of ADS

3.1.1 Pressure loss in a pipeline

Water is a fluid of low viscosity and its pressure loss in lines is much less compared to that of oil. Therefore, following can be some of the advantages that water can provide as a working fluid.

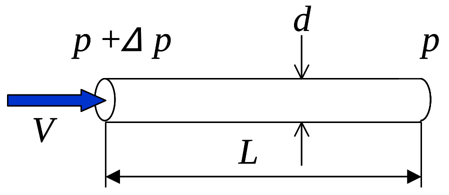


Fig. 3.1 Pipe

- Inner diameter of fluid lines can be smaller.
- Energy loss is minimized even when the actuator and pump should be separately installed.

Water pressure loss and oil pressure loss, of which flow rates are the same and are flown in a pipe of the same size, are compared. When a fluid of density ρ, kinematic viscosity υ and flow velocity V is flown in a pipe, of which inner diameter is d and length is L, the pressure loss Δp can be expressed by the following equation.

$$\Delta p = \frac{\lambda \rho L}{2d} V^2$$

The coefficient λ is the pipe friction coefficient and can be expressed as follows:

$\lambda = \frac{64}{\mathrm{Re}}$ (laminar flow) and $\lambda = \frac{0.3164}{\sqrt[4]{\mathrm{Re}}}$ (turbulent flow), respectively.

The Reynolds number Re is expressed by the equation $\mathrm{Re} = Vd/\nu$.

Assuming that flow in the water hydraulic pipe is turbulent and the flow in the oil hydraulic pipe is laminar, the ratio of the respective pressure loss can be expressed by the equation below. In the equation, a subscript w means water hydraulics whereas a subscript o means oil hydraulics.

$$\frac{\Delta p_w}{\Delta p_o} = \frac{\lambda_w \rho_w}{\lambda_o \rho_o} = 6.46 (Q/d)^{3/4}$$

Pressure losses, Δp_w in the water hydraulic pipe line and Δp_o in the oil hydraulic pipeline, are both plotted in Fig. 3.2. See Table. 2.2.

Requirements:

Density ρ (kg/m^3): ρ_w = 1000, ρ_o = 880

Kinematic viscosity ν (m^2/s): ν_w = 1.0×10^{-6}, ν_o = 34.0×10^{-6}

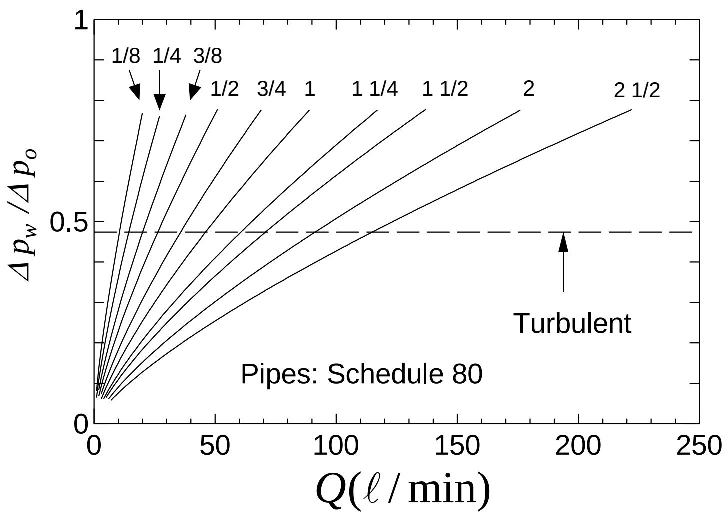


Fig. 3.2 Comparison of pressure loss in water hydraulic pipeline and in oil hydraulic pipeline

The y-axis indicates the ratio $\Delta p_w / \Delta p_o$, while the x-axis indicates flow rate Q. The pipe size d is taken as its parameter. The pressure loss ratio in both fluids is smaller than 1 in the range shown in the figure. The pressure loss ratio obtained in turbulent flows in both fluid types is indicated with a broken line. Also, the ratio remains smaller than 1. From this result, the pressure loss in a water hydraulic pipeline is smaller than that in an oil hydraulic pipeline.

Due to low kinematic viscosity of water, the pressure loss in a water hydraulic pipeline is small, and thus, advantageous as a power transmitting line. Application of water hydraulics to a drive system where the pump and the control valve or the actuator are separately installed and a compact system of which pipelines are of small diameter is suitable.

3.1.2 Cavitation and erosion

- Cavitation

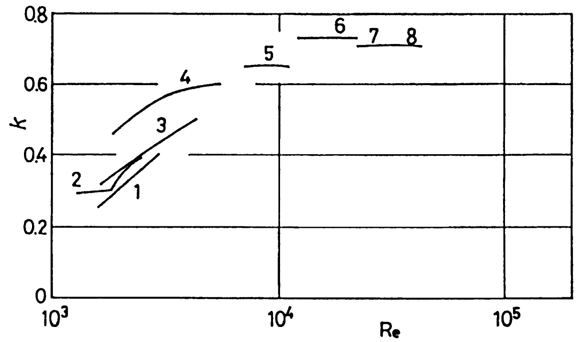
Cavitation is a phenomenon that local pressure of flowing fluid drops locally and generates air bubbles (vapor nuclei). The vapor pressure can be practically regarded as the critical pressure point where the air bubbles are generated. The simplest preventive measure is controlling the pressure. For a pump, set system's operation parameters such as water supply pipe diameter, length and water such that the lowest pressure in the pump suction area must be exceeding the vapor pressure.
At throttles such as valves, the cavitation coefficient $k = (p_2 - p_v)/(p_1 - p_2)$ can be regarded as a threshold, where p_1 is an inlet pressure, p_2 is the outlet pressure and p_v is the inlet vapor pressure. For the countermeasure, make the figure p_2 high to make k larger than the critical point by using two-stage throttling and applying backpressure.

- Cavitation erosion

Cavitation erosion is a phenomenon that component materials are damaged due to impact pressure generated upon bursting of air bubbles. To suppress erosion and accompanying pressure fluctuation and noise, it is effective to reduce the number of bubbles as well as bubble size, to separate the bubble bursting area away from the material surfaces and to select anti-corrosive materials for the components.

- Critical pressure point of cavitation generation at the throttle and erosion mass

Cavitation is easily occurred by jet fluid at the throttle and valve area where transiently configured upon switching pressure of a valve or a pump motor. It is a serious problem to produce much high-pressure machines as well as to improve their performance and lifetime. Critical point of the cavitation generation caused by the jet can be sorted out with the cavitation coefficient k and the Reynolds number Re as shown in Fig. 3.3.
The difference of erosion mass is large between by water and by oil. The erosion mass, which the cavitation water jet was impacted on the test specimens, was reported 5 to 6 times greater than that by oil.



1: Oil hydraulic fluid A
2: Water-glycol
3: Oil hydraulic fluid B
4: Spindle oil
5: Polymer solution
6: Emulsion A, B
7: Surfactant solution
8: Tap water

Fig 3.3 Working fluid types and Re - k characteristics

3.1.3 Surge pressure prevention

Surge Pressure

Generation of surge pressure must be paid attention to when flow rate of a fluid power system is high while demanding sudden run and stop of the system. In the ADS, the surge pressure becomes higher compared to that of the oil hydraulic system due to properties of water. Therefore, if the user's ADS is expected to run for fast action while anticipating generation of excessive surge pressure, excogitating the water hydraulic circuit and devices configuring the system in designing stage is desirable. For example, realizing a shock-less drive using some controllable devices, such as a proportional valve and a servovalve, can be considered.

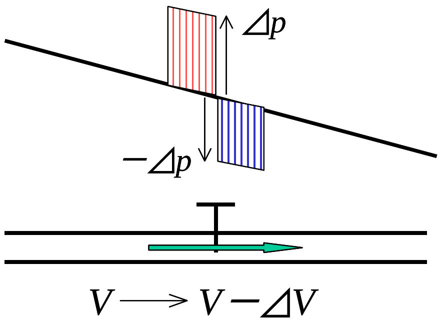


Fig. 3.4 Surge pressure generation due to shutting a valve

When the surge pressure is generated by sudden change of valve state due to operation, the pressure propagates through the pipe, affecting operations of other devices. The surge pressure Δp has a close relationship with the wave propagation velocity c.

$$\Delta p = \rho c \Delta V$$

Propagation velocity: The speed is determined by the bulk modules K and the density ρ. It is expressed as $c = \sqrt{K/\rho}$. Accordingly, the surge pressure Δp will be as shown below, respectively. It can be seen that the water's surge pressure to the same flow rate fluctuation ΔV is higher than that of the oil.

Water	$\Delta p = 1.55\Delta V$ (MPa)	Note that $c \approx 1550$ m/s .
Oil	$\Delta p = 1.15\Delta V$ (MPa)	Note that $c \approx 1305$ m/s .

Density ρ (kg/m^3) herein is defined as 1000 for water and 880 for oil, respectively. Kinematic viscosity V (m^2/s) herein is defined as 1.0×10^{-6} for water and 34.0×10^{-6} for oil, respectively. Bulk modulus K (GPa) herein is defined as 2.4 for water and 1.5 for oil, respectively (see Table 2.2).

Chapter 3　Operating Aqua Drive System

Surge pressure test in a cylinder drive circuit

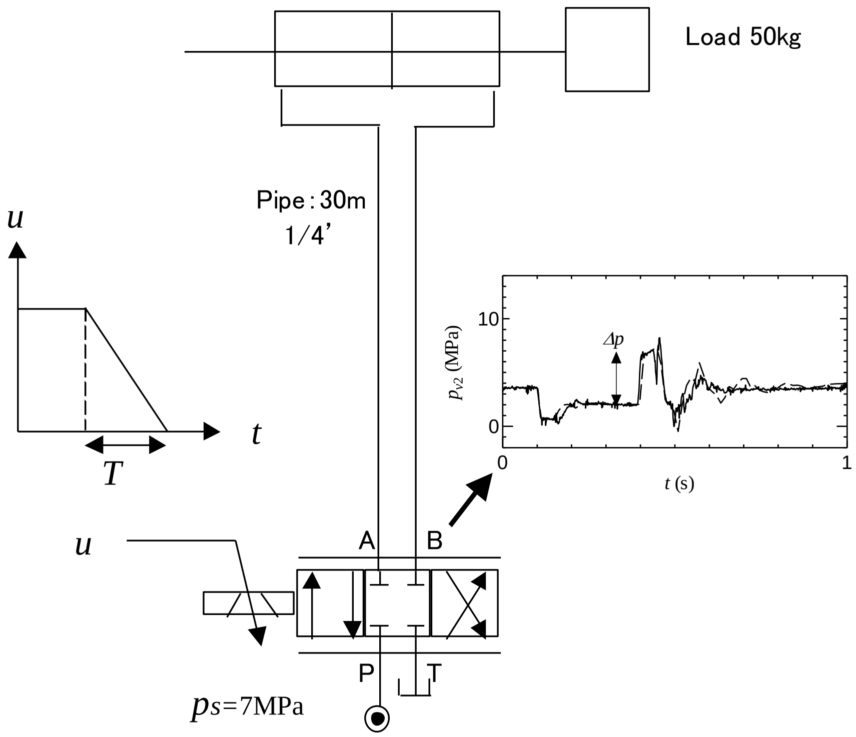


Fig. 3.5 Surge pressure test

Using a cylinder drive circuit described in Fig. 3.5, an experiment was conducted to examine the surge pressure that occurs upon a sudden shutting of a valve. A mass of 50 kg was driven by the double rod cylinder. Prior to the experiment, the supply port P is connected to the port A. The port B is connected to the return port. The cylinder and a servovalve are connected with a 1/4-inch stainless pipe of 30 m long. While the load is driven at a constant speed, the servovalve is shut suddenly. The valve was linearly closed. The surge pressure Δp was measured from the transient pressure wave of the port B.

The relationship between the valve shutting time $T(s)$ and the surge pressure Δp is described in Fig. 3.6. Circles in the figure indicate the measured values, and a broken line indicates the result of simulation. Thus, the result that calculated the pipe dynamic properties by the characteristic method and the equation of motion of the servovalve and the load mass was taken into consideration.

The figure shows that the longer the valve shutting time T, the smaller the surge pressure Δp becomes.

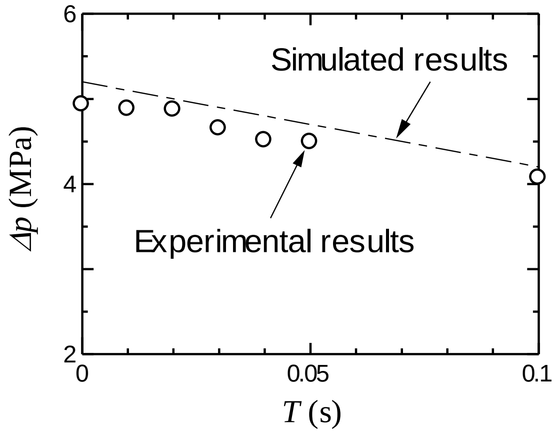


Fig. 3.6 Valve shutting time and surge pressure

Surge pressure prevention by two-slope valve shutting manipulation

Instead of sudden throttling of the valve, two-slope manipulation can effectively control the surge pressure.

In Fig. 3.7, the pattern A shows sudden throttling of the one-stage manipulation and the pattern B and C show that of the two-slope manipulation. The test settings were as follows: the valve-opening angle of the breaking point is a constant value (1 Volt). The time of the breaking point is set to $T/2$, which is the half of the valve throttling time T, or $(3/4)T$.

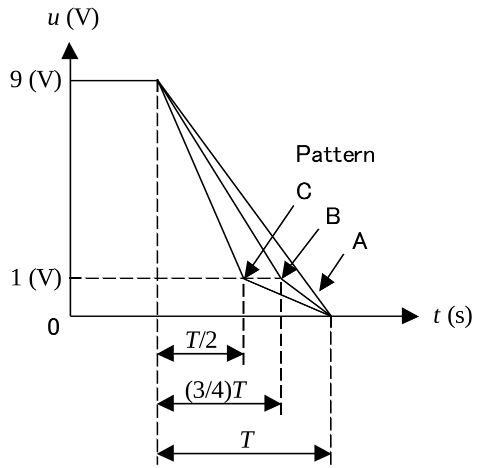


Fig. 3.7 Two-slope manipulation

Fig. 3.8 shows the measuring result of the surge pressure T to the valve throttling time T.

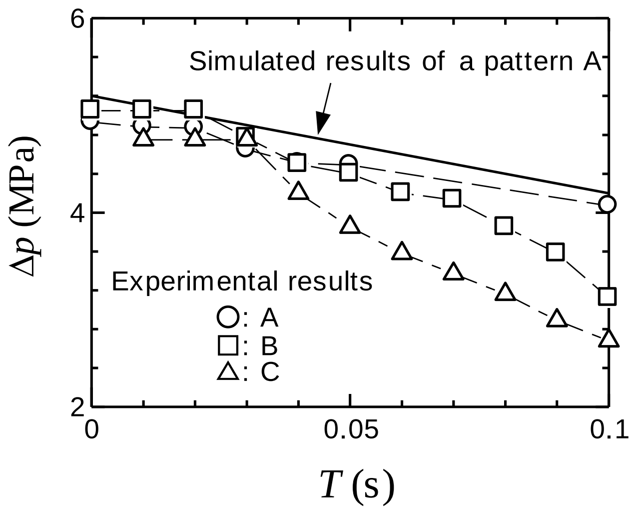


Fig. 3.8 Control of the surge pressure with the two-slope manipulation

The results shows that the surge pressure generated in the patterns B and C, which is the two-slope manipulation is smaller than the pattern A, which is the one-phase manipulation even when the valve throttling time is the same. Moreover, the surge pressure in C is smaller than that in B. That is because the throttling rate just before the valve is throttled in the pattern C is slower than that of B.

3.1.4 Frequency characteristics with use of servovalve

(1) Effect of the water temperature change (10℃ and 45℃)

From the experimental results, we can see that the frequency characteristics at the subjected temperature did not change for the water viscosity by temperature change hardly changed.

Circuit: Fig. 3.5, Pipe length: 0.8 m, Cylinder: single rod

Result: Fig. 3.9, Input signal amplitude: constant, Gain: the reference output (cylinder displacement) amplitude at 0.05 Hz.

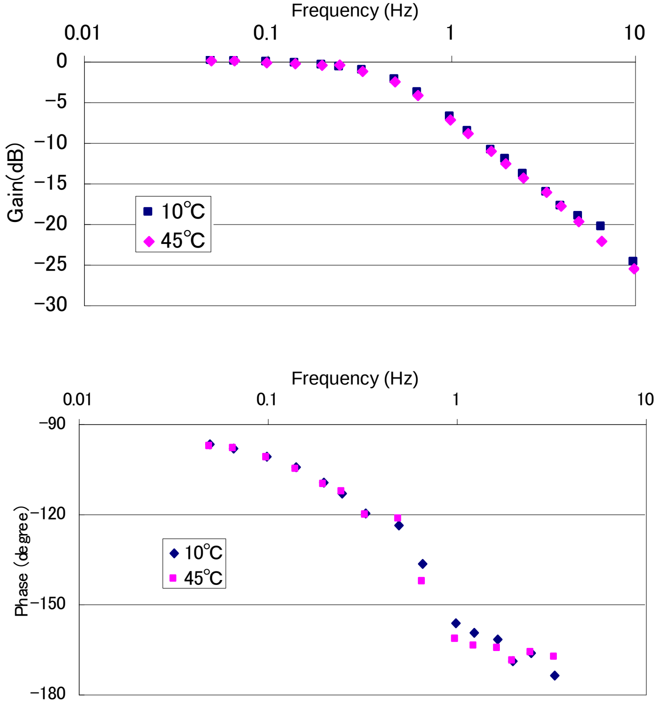


Fig 3.9 Frequency responses (Influence of temperature change)

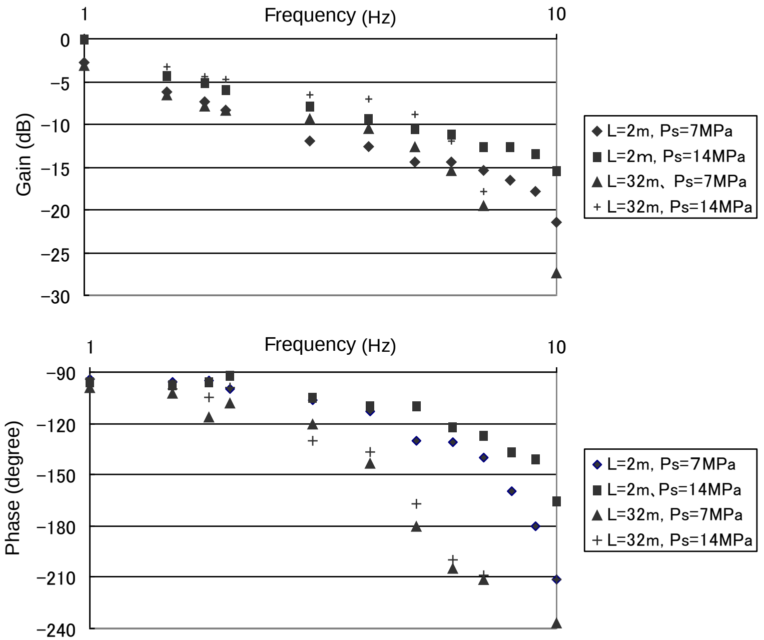


Fig 3.10 Frequency responses (Influence of pipe length)

(2) Influence of the pipe length (2 m and 32 m)

Regardless of the water supply pressure, the longer the pipe is, the lower the gain becomes when the input frequency is high. Thus, the phase delay becomes large. This is considered due to increased pipe friction and decrease of load pressure at the cylinder.

Circuit: Fig. 3.5, Pipe length: 2 m and 32 m, Supply pressure: 7 MPa and 14 MPa

Result: Fig. 3.10, Gain: 14 MPa, the reference output (cylinder displacement) amplitude for the pipe length of 2 m.

Chapter 3 Operating Aqua Drive System

3.2 ADS operational guideline

3.2.1 Water quality evaluation test

The change of water quality of the tap water during the ADS operation was tracked and tested twice. In the first run, the water temperature was set to 30 ℃ and the run time was 1600 hours (9 months). In the second run, the temperature was set to 40 ℃ and the run time was 1650 hours (12.5 months). The results of both tests show that no problem was observed in the water quality. In addition, no considerable impact to the water hydraulic components was also observed.

(1) Test apparatus and conditions

Fig. 3.11 is a view of the water quality test unit. Fig 3.12 is the circuit diagram of the test apparatus. Before starting the test, flushing of the apparatus was sufficiently performed. During the test, the water was circulated without newly supplying any water. The water used was tap water supplied around the Tokyo metropolitan area.

Fig. 3.11 Water quality test unit

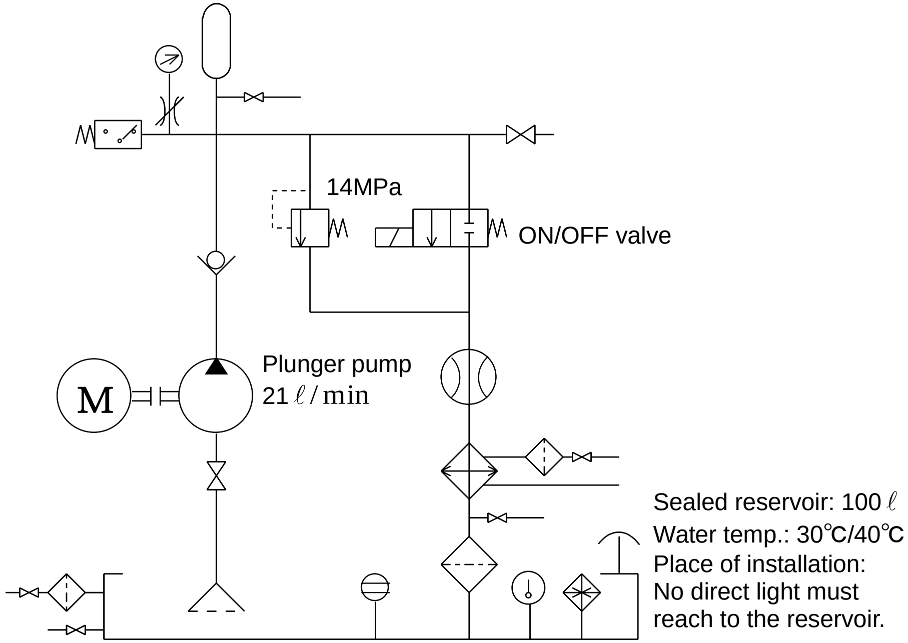


Fig. 3.12 Circuit diagram of the test apparatus

(2) Inspected items and Test result

【Monitored points】 Inside of the reservoir, just before the return filter, and the mid way of the connecting pipe line of the accumulator

【Monitored items】 pH value, chloride ion, hardness, residue of transpiration, and general bacteria.

【Test result】 See Fig 3.14.

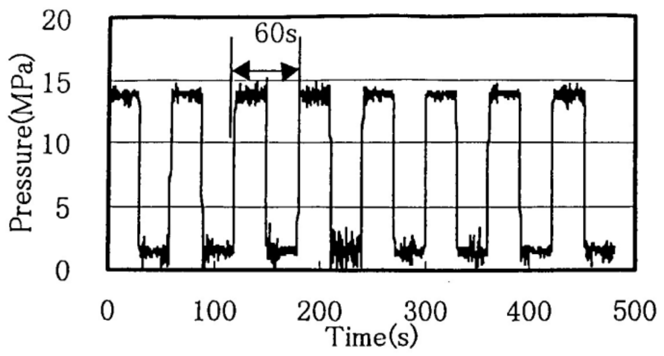


Fig. 3.13 Apparatus circuit pressure (Experimental value)

(3) Analysis and evaluation

About the pH value, chloride ion, hardness, and residue of transpiration: While the changes of the water quality were monitored, the values of these items remained sufficiently lower than the standard values for tap water. No great change was observed. No difference was also observed according to the monitored places.

About the general bacteria: Excepting the 4th sampling, the growth was observed in the initial period (0 to 15 days, up to 120 hours) regardless of sampling locations. However the number of bacteria then decreases due to malnutrition and firing.

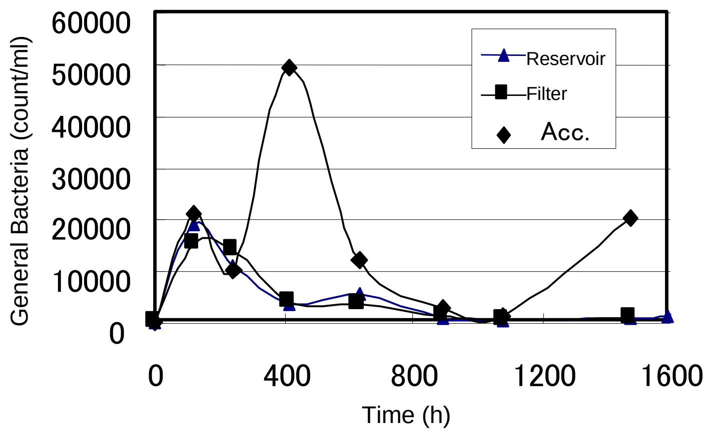


Fig. 3.14 Water quality evaluation results (30℃) (Measured values)

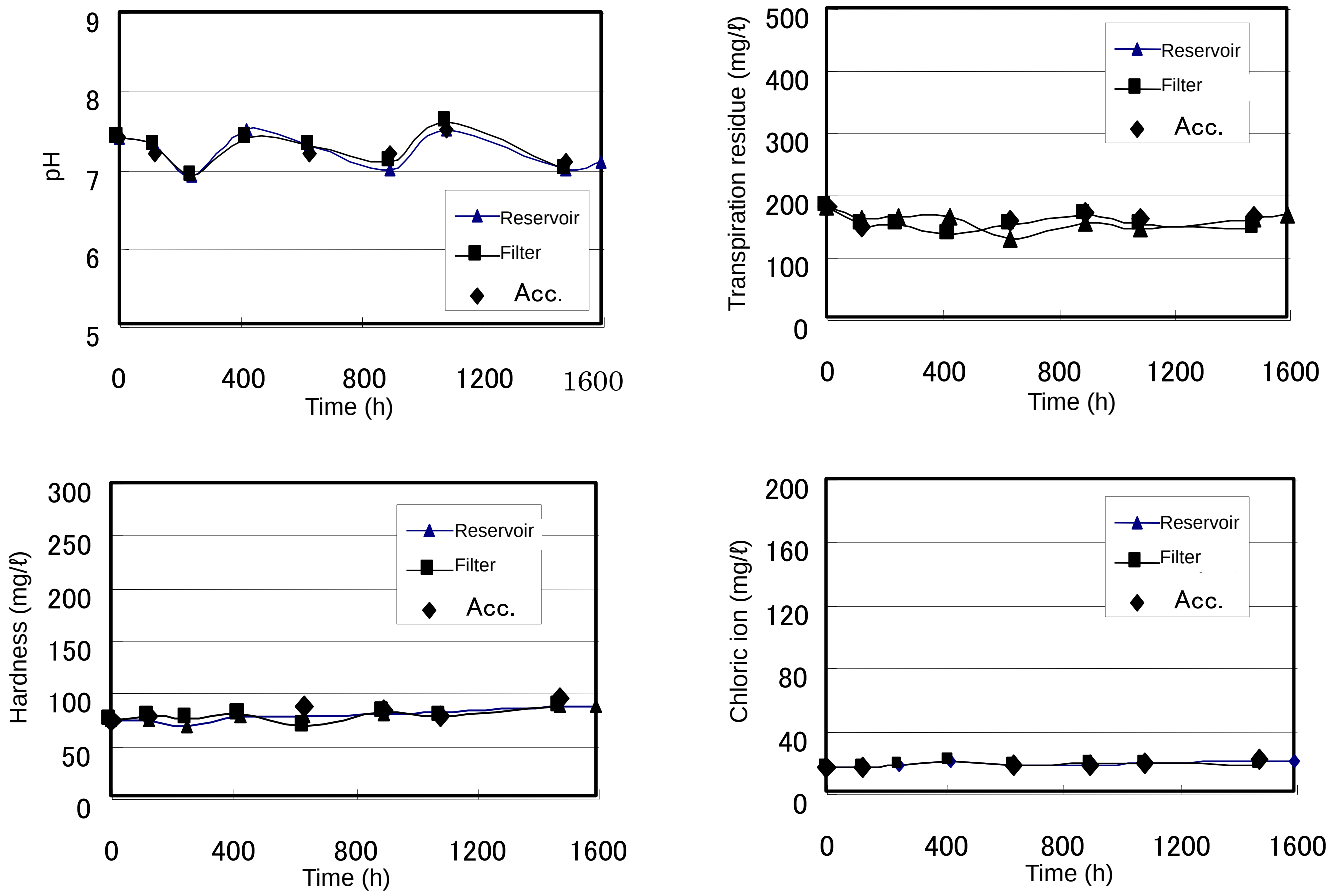


Fig. 3.14 Water quality evaluation results (30℃) (Measured values)

3.2.2 Control and maintenance of water quality

(1) **Filtration equipment**: To eliminate substances causing contamination, bacteria, and other microbe organic substances, the filtration equipment shall be equipped with lines such as the water supply line, the return line, the suction line, and so forth, if necessary. The system is desirably designed so that it enables to monitor the clogging of such filters.

(2) **Water supply filter**: The water supply filter should be equipped at the initial stage of operation and when the water is supplied for maintaining the water level.

(3) **Replacement of the working fluid**: The working fluid should be replaced according to frequency of the use and the operational environment.

(4) **Service**: Periodical service should be done to the air breather and filters to keep them clean.

3.2.3 System operation temperature

(1) **Temperature of the system**: To prevent the freezing and to restrain the generation of vapor, the water temperature should be + 5 ℃ to 45 ℃.

(2) **Temperature of the components**: When operation temperature is specified by each component manufacturer, the component should be used within such a specified temperature. When the user decides the operation temperature for the system, this point should be considered. Note that the temperature of surfaces of each component should always be touchable by the human being.

(3) **Temperature control**: If operating the system within the proper temperature range is difficult, proper countermeasures should be taken according to situations. The working fluid will be frozen at 0 ℃. Therefore, when the system is used in cold climates or where the ambient temperature may become 0 ℃ or lower, installing some heating equipment will be required to prevent the fluid from being frozen at any place in the system. Contrary, when the system is used where the working fluid may be evaporated due to the temperature rise of the reservoir, modifying the reservoir shape and size or installing heat exchangers will be required. Especially, the countermeasure for places where the working fluid does not circulate, such as the cylinder and rotary oscillating torque actuator, is important.

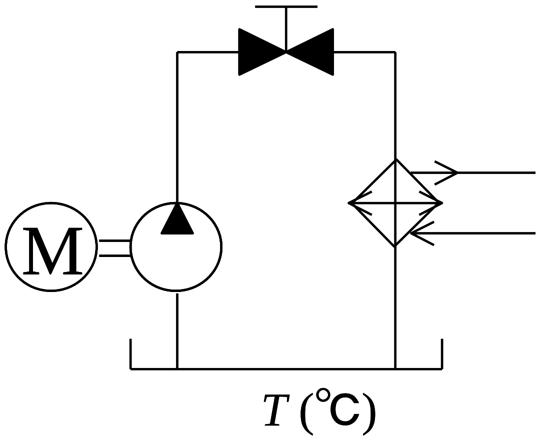


Fig 3.15 Experimental apparatus for observing the effect of cooler

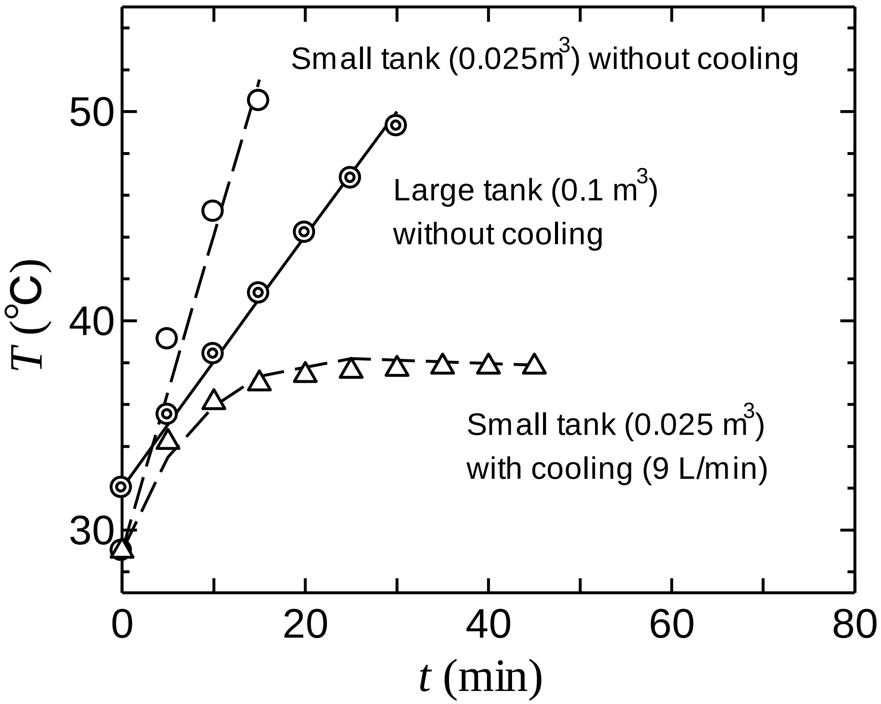


Fig 3.16 Differences of the water temperature rise and effects of cooler per reservoir size

- If the water temperature exceeds the specified temperature range, use a cooler. As shown in Fig 3.15, the experiment was performed to observe the effect of the cooler. The water ejected from the pump runs through a valve. Then, the water returns to a reservoir via a cooler after flowing through the valve. When the valve is throttled, the pressure loss that is generated by throttling the valve heats up the water. In addition, the power loss at the pump also becomes the cause of heating.

- The circles in Fig 3.16 indicate the measurement result of the change of the reservoir temperature per run time when the cooler is not used. It shows that when the water quantity in the reservoir is small, the rising rate of the temperature becomes higher.

- The triangles indicate the measurement result of the water temperature when the water quantity is small (0.025 m^3) and the cooler is used. It shows that using the cooler helps the water temperature to be within the specified temperature range. Both the solid and broken lines indicate the calculated water temperature with considering the heat budget of the circuit.

- The specific heats of the water and working oil are different $C_p(J/kgK))$: 4180 for the water and 2018 for the oil. The specific heat of the water is large about as twice as that of the oil. Accordingly, if the same amounts of heat are heated up, the rising rate of the water temperature is a half of the counterpart of the working oil.

3.2.4 Effectiveness of cooler

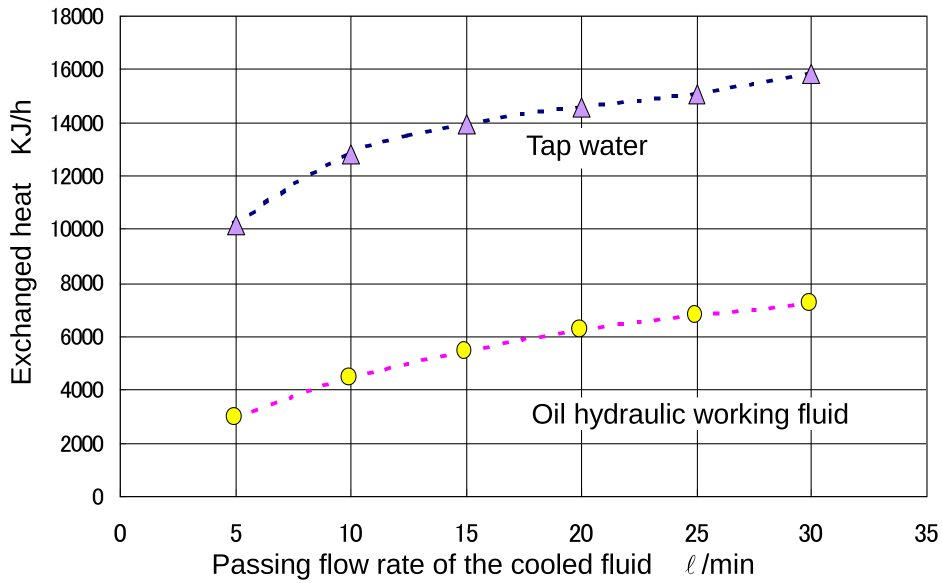


Fig. 3.17 Relationship between the flow rates of the cooled fluids and the exchanged amounts of heat

(Requirements)

Model of the heat exchanger: TCW-106-2
Temperature of the cooled fluids at the inlet: 45 ℃.
Temperature of the cooled fluids at the outlet: 42℃.
Temperature of the cooling water at the inlet: 27 ℃.
Flow rate of the cooling water: 9 ℓ/min

Fig. 3.17 shows the passing flow rate and the exchanged amount of heat when the tap water and the mineral working oil are cooled down by the heat exchanger

The exchanged amounts of heat are expressed as follows:

$$Hc = p_o \times C_o \times Q_o \times \Delta T \times 60 \text{ (oil)},$$
$$p_w \times C_w \times Q_w \times \Delta T \times 60 \text{ (water)}.$$

The exchanged amount of heat of tap water is about 2.5 times greater than that of the oil due to the water's property. It means that the cooler for the ADS can be more compact than that for the working oil of mineral oils.

Data and the heat exchanger presented in this page are supplied by TAISEI KOGYO CO., LTD.

3.3 Other issues

(1)	Avoidance of the dry operation	To avoid damages due to the dry operation, the pump should be always operated with the working fluid supplied.
(2)	Ventilation	At the very first operation of the system, the air of the water hydraulic unit, pipes, actuator, etc., must be completely evacuated to protect the components and obtain the required performances.
(3)	Monitoring of the filter pressure loss	Proper filtration of the working fluid not only extends the lifetime of the water hydraulic components, but also is important to demonstrate the maximum performance of the system. Therefore, the system is desirably designed so that the monitoring of the filter pressure loss is allowed.
(4)	Flushing	To prevent troubles due to entry of foreign substances into the working fluid, oils and dirt attached on the pipes, couplings, and components shall be sufficiently removed before integrating them into the system. In addition, to remove such foreign substances in the water hydraulic unit and the pipes, flushing shall be done when the system is operated anew. The water temperature should be kept higher within the operational range during the flushing to improve the effect.
(5)	Pulsation and noise of the triple plunger pump	As the triple plunger pump is mainly used at the lower rotational speed, troubles may occur to the system due to pulsation. Therefore, the pulsation-prevention measures should be taken on the accumulator and rubber pipes. Otherwise, the system should be configured with the pump unit separated.
(6)	Storage of the components and unit	The user should follow the instructions provided from the suppliers when the user stores the components and unit. Many overseas manufacturers fill the non-freezing solution for the purpose of preventing freezing and the components interior surface from rusting during storage and preservation (e. g., mono propylene glycol). When the system is operated anew, the non-freezing solution should be sufficiently washed away.
(7)	Periodical inspection	Vibration generated from the pump may loosen the pipe connecting elements. To prevent the working fluid leakage and the air suction, the periodical inspection should be performed to check and re-tighten the joint parts and screws of the pipes.

Chapter 4　Application of Aqua Drive System

The applicable environment and promising applicable range in the future are listed below.

(1) **Production and manufacturing environment for which cleanness and sanitation are required**: Food processing machinery, food and drink wrapping and canning machinery, production lines for semiconductor and information devices, medical and pharmaceutical production lines, general production and processing machinery for cleaner and better work environment

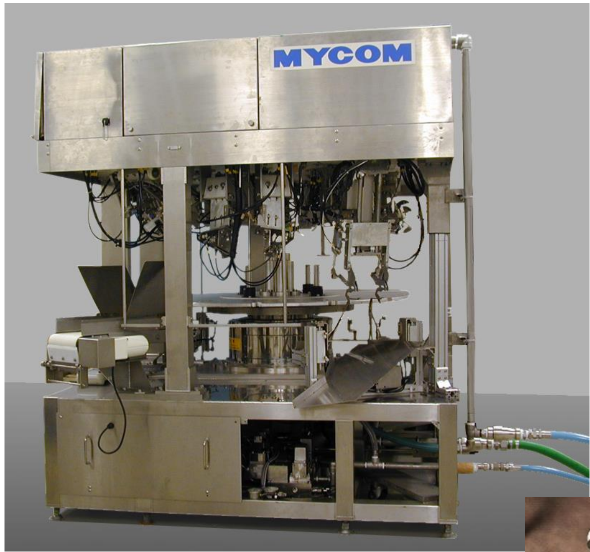
(2) **Working environment for which the natural environment preservation has to be considered**: Machinery operated on offshore and rivers, operating systems for sluice gates and others, machinery operated underwater and undersea

(3) **Specialized atmosphere environment such as the radioactive atmospheric field of atomic energy**: Inspection and repairing machinery for the internal reactor core, demolition machinery

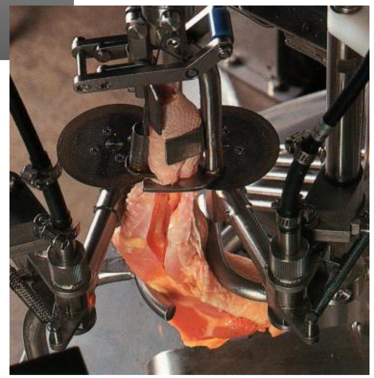
(4) **Environment for human beings which requires the fire protection and safety**: Devices and tools for fire fighting and rescue, machinery for medical and social welfare services and facilities for housing for the senior, sports gear and leisure equipment, mobile stages

In recent years, instructions and regulations base on the law, particularly ISO9000, ISO14000, and HACCP (Hazard Analysis Critical Control Point), have increasingly penetrated. In such a background, significance of the aqua drive technology has also been increasingly recognized as a mean to acquire such certification. In addition, on the base of the superior fluid power driving property that is described in Chapter 3, expectation to the ADS has been rising as the fundamental technology to achieve the “emission free” policy of each kind of production machines.

Figure 4.1 visualizes the whole concept of ADS. It contains the fundamental technology, which supports the “aqua drive technology”, accessories, which are necessary to configuration of the system, and applicable environments and promising fields of application as mentioned above.



YIELDUS
(Automated poultry breast deboner)



TORIDAS
(Automated poultry thigh deboner)

Photographs: Courtesy of MAEKAWA MFG. CO., LTD.

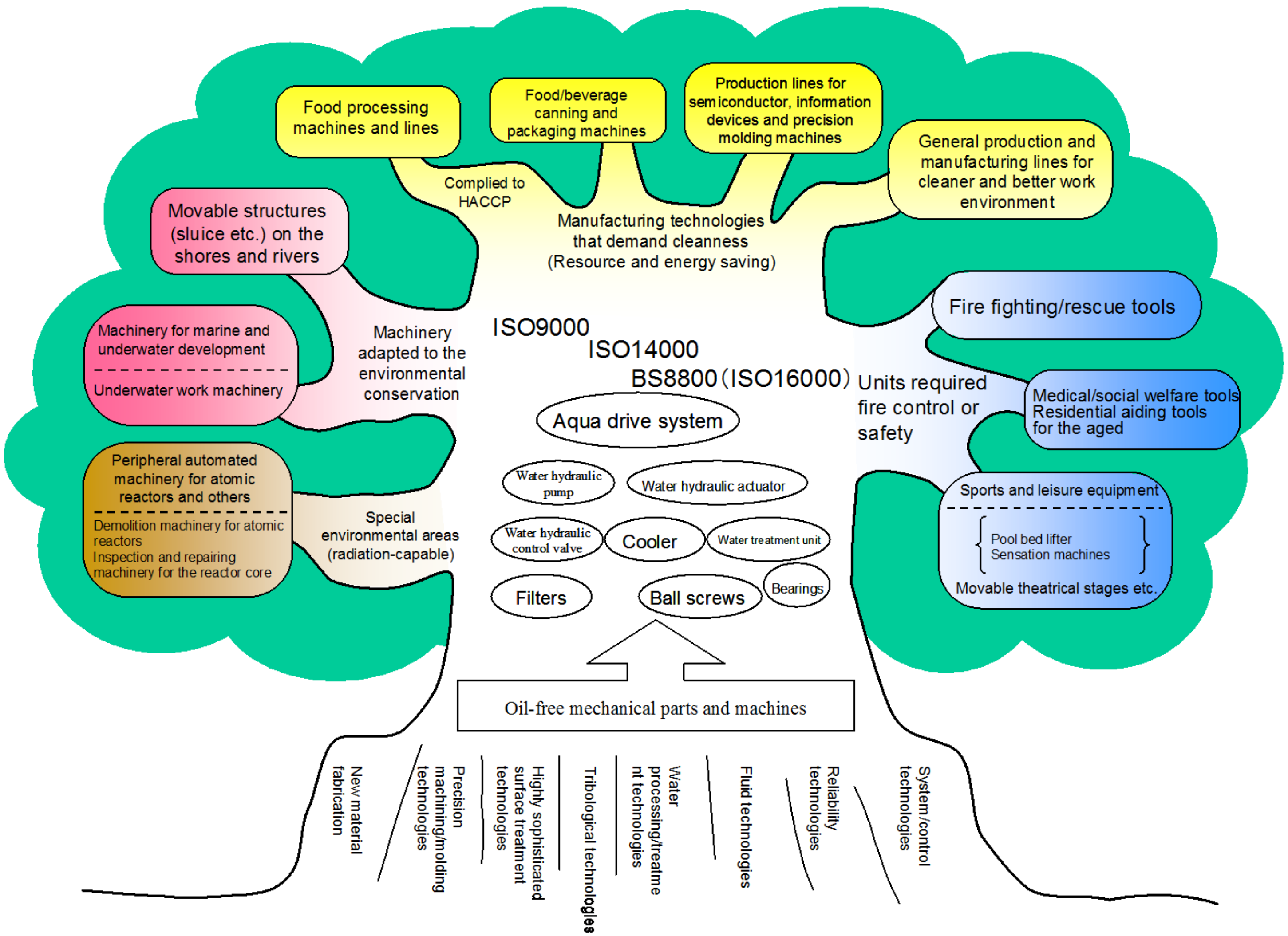


Fig. 4.1 Applicable fields of ADS and their supporting technologies

Chapter 4　Application of Aqua Drive System

JFPA Water Hydraulics Committee Members (Alphabetical order):
Contact JFPA regarding context of this book or the products shown.

EBARA RESEARCH CO., LTD.
4-2-1 Honfujisawa, Fujisawa-shi
Kanagawa 251-8502 Japan
Phone: +81-466-83-7111
Fax: +81+466-82-2630

KAYABA INDUSTRY CO., LTD.
World Trade Center Bldg.
2-4-1, Hamamatsu-cho
Minato-ku, Tokyo 105-6125 Japan
Phone: +81+3-3435-3581
Fax: +81-3-3436-6759

KITAMURA SHOKO CO., LTD.
2-1-7 Motoasakusa
Taito-ku Tokyo 111-0041 Japan
Phone: +81-3-3843-3218
Fax: +81-3-3843-2718

NABCO LTD.
2-21, Isogami-Dori 2-chome
Chuo-ku, Kobe 651-0086 Japan
Phone: +81-78-251-8106
Fax: +81-78-251-8090

NACHI-FUJIKOSHI CORP.
World Trade Center Bldg.
2-4-1, Hamamatsu-cho
Minato-ku, Tokyo 105-6125 Japan
Phone: +81+3-3435-5111
Fax: +81-3-3436-6366

SAKAGAMI SEISAKUSHO LTD.
4-17-6, Kinshi
Sumida-ku, Tokyo 130-0013 Japan
Phone: +81-3-3625-1111
Fax: +81-3-3625-8270

TAKAKO INDUSTRIES, INC.
3-1-48, Nunoichi-cho
Higashi-Osaka-shi
Osaka 579-8004 Japan
Phone: +81-729-88-2622
Fax: +81-729-88-2920

TOYOOKI KOGYO CO., LTD.
45 Aza-Kaizan, Hatchi-cho
Okazaki-shi, Aichi 444-3592 Japan
Phone: +81-564-48-2311
Fax: +81+564-48-7908

YAMAMOTO SUIATSU KOGYOSHO CO., LTD.
2-8-8 Shomoto-scho
Toyonaka-shi, Osaka 561-0835 Japan
Phone: +81-6-6331-4651
Fax: +81+6-6331-2516

YUKEN KOGYO CO., LTD.
Hamamatsucho Seiwa Bldg.
4-8 Shiba Daimon 1-chome
Minato-ku, Tokyo 105-0012 Japan
Phone: +81-3-3432-2110
Fax: +81-3436-2344

Reference

Special Acknowledgement to:

Sophia University
Mechanical Engineering Dept.
Kioicho 7
Chiyoda-ku, Tokyo 102-0094 Japan
Phone: +81+3-3238-3302
Fax: +81-3-3238-3311

Yokohama National University
Department of Production
Engineering, Faculty of Engineering
156 Jobandai, Hodogaya-ku
Yokohama-shi, Kanagawa 240-0067
Japan
Phone: +81+45-335-1451
Fax: +81-45-331-6593

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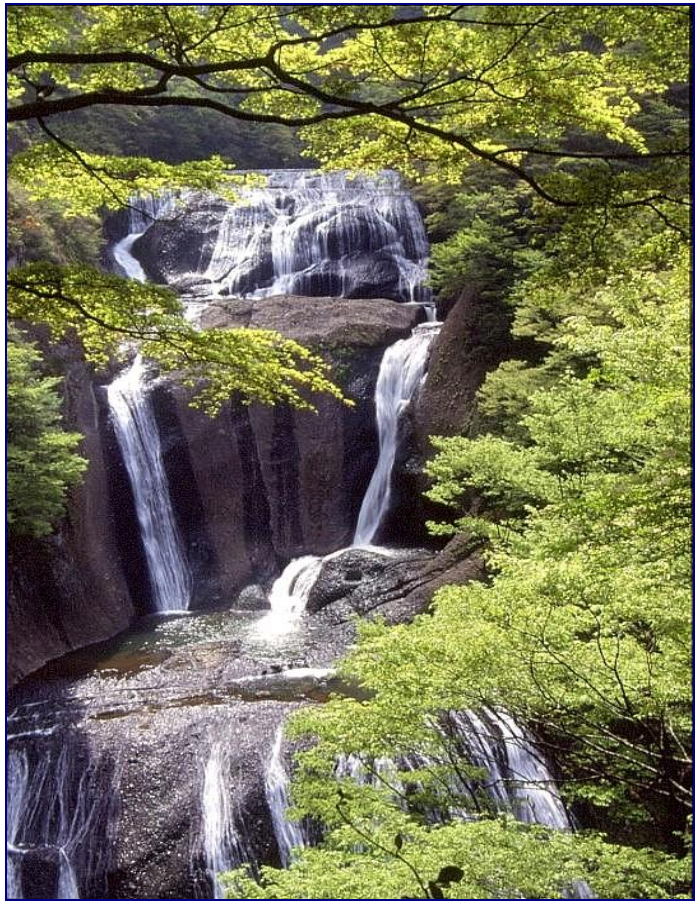

Japan Fluid Power Association
Kikai Shinko Bldg., Room 311
3-5-8 Shiba-koen,
Minato-ku, Tokyo 105-0011 Japan
Phone: +81+3-3433-5391
Fax: +81-3-3434-3354