

Pump Research and Development: Past, Present, and Future—Japanese Perspective

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The evolution of pump research and production in Japan after 1955 is surveyed. The post-war period has been divided into three stages of development with unique social and industrial characteristics: expansion, conversion, and globalization. The growth of pump production in sales amount and quantity is shown for various types of pumps. The post-war direct and indirect research on pumps is classified into eight groups of topics and their past trends are analyzed. These changes are correlated with the characteristics of the corresponding background stage. These analyses with the past suggest new trends of research for pumps of tomorrow.

Introduction

Pumps are an industrial product which meets the most basic needs of humanity. They supply city water for daily life; they feed water to boilers for power generation; and they circulate fluids in every kind of liquid-handling system including human bodies. Because of this, the production and development of pumps have been strongly influenced by society and industry. The present paper attempts to show how the characteristics of pump research and development can be explained in terms of the needs of society and industry in each respective age.

In order to crystallize the characteristics of society and industry, the present paper divides the post-war development of Japan into three stages with unique social and industrial characteristics, that is, the Stage of Expansion (1955–1973), The Stage of Conversion (1973–1991), and the Stage of Globalization (1991–present).

The growth of pump production in sales amount and quantity is analyzed for various types of pumps based on the annual industrial statistics (The Japan Association of Industrial Machinery 1995–1996). The post-war research on pumps, both with direct and indirect concern, is classified into eight groups of topics and their past trends are analyzed. These changes are correlated with the characteristics of the background stage.

The last stage started in 1991, at the beginning of the last decade of the 20th century. A paradigm shift of pump research and development may be required in the years to come. The shift of value can be described in simple wording as “from pre-delivery to post-delivery.”

Change of Background—Three Stages of Social and Industrial Development

The social, political, economic, and industrial development of post-war Japan can be classified into three stages with unique characteristics (Ohashi, 1996). Following are the descriptions of each stage.

The First Stage: Period of Expansion, 1955–1973 (18 years). Ten years (1945–55) were needed to overcome the post-war chaos caused by the surrender and occupation. In 1955, the Liberal Democratic Party gained political control and continued to hold the government until recently. This political stability allowed a consistent policy necessary for farsighted devel-

opment of the society and industry. The government started “Double the Income Initiative” to accelerate economic development and the domestic market grew accordingly.

Heavy industries, such as steel, petrochemical, synthetic fiber, ship building, automobiles, and heavy electric machinery; and infrastructure industries, such as power generation and construction, took the leadership in expansion. Exports increased rapidly and the international trade balance turned from deficit to surplus in spite of huge imports of oil and raw material.

As industries started to expand rapidly, the shortage of engineers became an urgent issue. The plea of industry leaders for more engineers evoked a national consensus and the government launched plans to quadruple the number of graduate engineers. This expansion in quantity had its peak around 1965 and the target was reached by the end of this expansion stage.

The influence of industrial waste on the pollution of the local environment gathered little attention until the end of sixties. This ignorance caused many severe and tragic consequences such as the Minamata-syndrome (pollution by organic mercury) in the decades to follow.

The Second Stage: Period of Conversion, 1973–1991 (18 years). The first oil crisis in 1973 terminated the expansion story of the first stage. Industries found that they thrived mainly by consuming huge amounts of oil and raw material. They were forced to reform themselves to be less dependent on the supply of energy and material. Conversion from “Heavy-Thick-Long-Large” to “Light-Thin-Short-Small” became a typical slogan of Japanese industries.

The information age started about this period with accelerated proliferation of computer and communication technologies. Products featuring the application of micro-electronics and precision-manufacturing, such as VCRs, DRAMs, and LCDs, became the front running exports, replacing previous heavy products such as steel and ships. Industries achieved this conversion far quicker than anticipated and regained competitiveness in the world market.

In the latter half of this stage, the GNP grew rapidly again, and Japan became the no. 2 economic power with a huge trade surplus. A booming economy and surplus money triggered an overheated investment rush on stocks and lands, leading to a spree called a bubbly economy. The bubbles started to burst in 1991, and the second stage terminated. History may explain that the essential and hidden cause of this collapse was the ending of the cold war.

The Third Stage: Period of Globalization, 1991–?. The end of the cold war relieved mankind of the nightmare of nuclear massacre and lowered the barriers between nations. It

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triggered the start of a borderless age. This new situation initiated, on the other hand, a war of a different nature, namely, competition of industries on a global scale. Leaders of every nation are now clearly aware that science and technology are the key factors for maintaining competitiveness and sound development of industries, thus ensuring employment and a growing standard of living. Every industrialized nation started to enhance "Strategic Research" with the determined object of maintaining leadership in industrial development.

In the age of globalization just started, Japanese industries are facing many difficulties: high costs of products owing to the over-evaluation of currency, shift of production plants abroad, over-capacities of domestic industries caused by production moving abroad ('hollowing'), change of the Japanese style management, decrease in the size of the young generation and so on.

The most competitive of Japanese industries have been mass production technologies of standardized products such as automobiles and electronic devices. These technologies can be transferred abroad together with transplanted production facilities. Industries urgently need new products which replace obsolete products and fill the large hollows of domestic factories. The fate of many Japanese industries depends on whether they are capable of replacing their mainstream products from traditional to globally competitive ones.

The industrial development of newcomer nations such as China and southeast Asian countries, is accelerating the consumption of energy and material at an enormous rate. The consequence will be the shortage of natural resources on a global scale and an ever worsening influence on the environment.

At the very start of the present stage in 1992, the Earth Summit in Rio de Janeiro (UN Conference on Environment and Development) declared that the environment is a global issue. Discharge of carbon dioxide or CFC gas at a location induces the greenhouse effect or depletion of ozone over the entire globe. The largest value and target of industrial development in the present stage lie in the key words "Sustainable Development."

Growth of Pump Production

The Japan Association of Industrial Machinery publishes annual statistics on the domestic production of industrial machinery of various kinds (The Japan Association of Industrial Machinery 1995–1996). The following data are taken and processed from these sources.

Figure 1 indicates how the annual sales of pumps in yen have increased since 1955, the start of the first stage. The sales

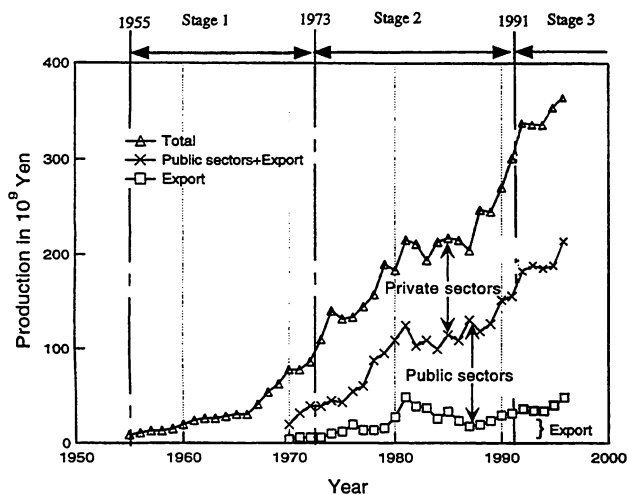


Fig. 1 Annual production of pumps in sales amount

amount is further divided into three categories according to the nature of clients, that is, export, the public sector, and the private sector. The clients of the public sector are the government and local authorities, and the pumps in this category are mainly for public infrastructure such as irrigation, drainage, water supply, sewage, dredging, water desalination, and so on. Pumps for the private sector include those for power plants, chemical and petrochemical plants, industrial facilities like steel works, ships, mining, buildings and miscellaneous purposes. Small in size, but huge in number, pumps installed in automobile engines, electric appliances, house heating and cooling devices, etc., are excluded from the present statistics.

As seen from the figure, the sales amount on a linear scale has been increasing remarkably (divide by 120 for a rough conversion to U.S. dollars). However, if we see this figure on a logarithmic scale, that is, in terms of growth rate, the situation seems quite different. The sales amount increased 15.3 times during the first Stage with an annual growth rate of 16.4 percent. This was indeed a period of expansion. The growth rate of the Gross National Product (GNP) during the same period was 12.5 percent, namely 4 percent less than that of pump production. This fact indicates that pumps used to be the forerunner of industrial expansion, since they are an indispensable element of investment in plants and facilities.

This situation changed in the second stage. The sales amount increased three times during stage 2 with an annual growth rate of 5.8 percent during the same 18 years. This change was triggered, of course, by the oil crises which urged the industrial conversion as described above. The annual growth rate dropped to 2.9 percent between 1975 and 1988, and the rate was far lower than that of GNP (7.5 percent), of the same period. Pumps proved to be the forerunner of industrial trends also in this case, but in a negative sense.

In the last few years of the second stage (1988–1991), the growth rate of pump production recovered to 7.3 percent and exceeded again the GNP growth, 5.7 percent, considerably. This fact indicates that Japanese industries had overcome the aftermath of the oil crises and recovered confidence for investing in the future. If we scrutinize the production of pumps during the second Stage by client categories, it is found that the growth rate of pumps for the private sector was 1 percent lower than the average, while the rate for the public sector 1 percent higher. This difference was due to the political decision of the government to increase the budget for social infrastructure as the means of stimulation for the stagnating national economy. Exports increased six times in sales amount during this period. However, the conversion rate of currency fluctuated so drastically, from 360 yen/\$ to 80 and again to 120 at present, that it is difficult to find any meaningful trends.

The outlook for the third stage is still opaque. The growth of pump production parallel to the GNP may be fundamental as the rule of thumb for such basic products as pumps.

Figure 2 indicates the annual production of pumps in number of units on a logarithmic scale. Besides the total number of pumps produced, the number of centrifugal pumps (single and multi-stage), of axial and mixed flow pumps, of rotary and reciprocating pumps (including regenerative pumps), of submerged-motor pumps, and of non-corrosive pumps (stainless pumps) are shown respectively. Centrifugal pumps kept the majority as easily imagined. A rapid increase of submerged-motor pumps since the late sixties and that of noncorrosive pumps since the middle of the eighties are two remarkable cases which reflected the interests of pump users. Demand for easy maintenance and stain-free water may be the underlying incentive of this rapid expansion.

Figure 3 illustrates the evolution of the largest unit output of electric power stations in Japan, both for fossil-fuel and nuclear power plants. Responding to ever increasing demand for electric power, unit output of oil-burning power plants had increased tenfold from 60 to 600 MW during the first Stage. It reached

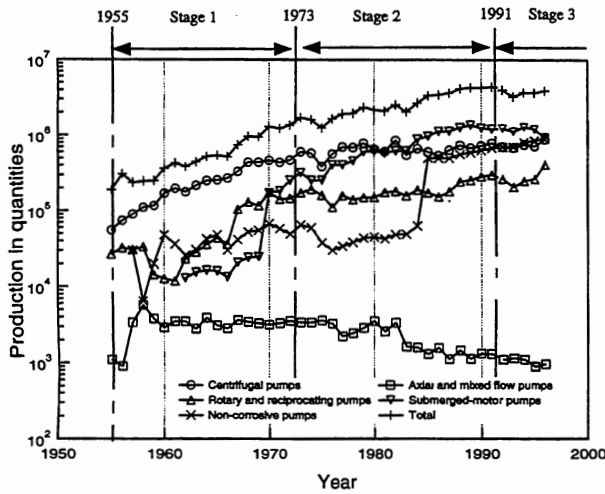


Fig. 2 Annual production of pumps in quantity

1000 MW in 1975 and has saturated since then. The situation of nuclear power plants is quite similar. The largest unit output of PWR and BWR plants reached the 1100 MW class at the end of the first stage and stayed almost constant till 1996 when an ABWR of 1300 MW class started operation.

The demand for bigger unit capacity has gone hand-in-hand with the demand for higher thermal efficiency. Figure 3 shows also the evolution of the highest delivery pressure and shaft power of boiler feed pumps (BFP). The pressure and temperature condition of oil-burning power stations jumped from sub-critical to super-critical in 1968. The development of BFPs succeeded in following the plant demands and played an essential role for the improvement of thermal efficiency.

The story of BFPs is just an example of many other success stories. Tankers became bigger and bigger. The capacity of blast furnaces expanded year after year. We could find the introduction of numerous record-breaking pumps every year in the Annual Review Issue of *JSME Journal* during the first stage. This glorious age of pumps was terminated by the assault of the oil crises. The development of pumps thenceforth became difficult to recognize from the superficial figures of specifications. Improved efficiency, higher reliability, easy maintenance, rationalized design, and manufacturing processes leading to cost reduction; all these advances are invisible but quite essential to the demands of present society.

Evolution of Research

For the survey of past research on pumps carried out in Japan, papers published in the *Transaction of JSME*, Series B were

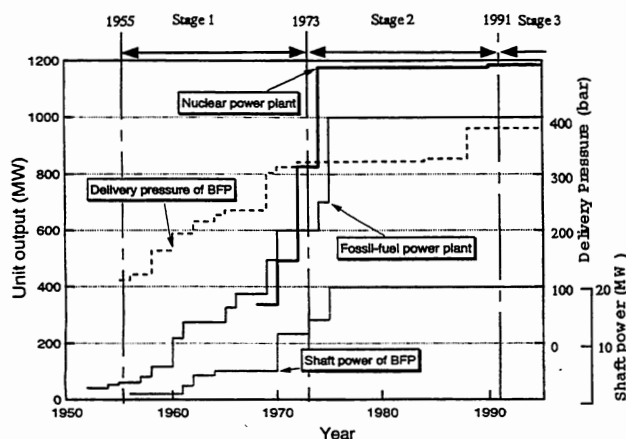


Fig. 3 Evolution of the record capacities

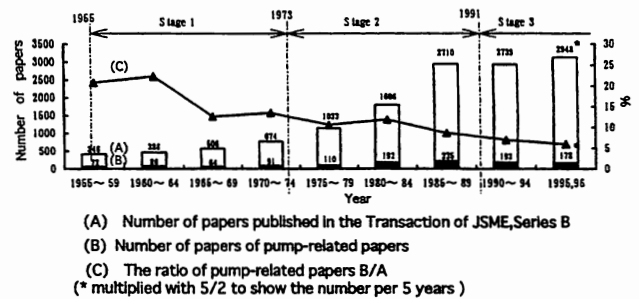


Fig. 4 Number of papers published in the *Transactions of JSME*, Series B

surveyed. Series B includes papers on fluids engineering (fluid mechanics and turbomachinery) and thermal engineering (thermodynamics, heat transfer and thermal power plant) of roughly equivalent number.

Figure 4 shows the evolution of research publications. To reduce an excessive fluctuation, the number of papers published in the five years duration is summed and shown by histogram. The height of white bars (A) indicates the total number of papers published in Series B, while the shaded height (B) that of pump-related papers. Research on gas-handling machinery such as fans and blowers are considered as pump-related, as long as the effect of compressibility does not play a primary role on the result. The ratio of pump-related papers to the total, B/A, is indicated by line C. The number of pump-related papers has been increasing, however, the increase is relatively low compared to the increase of total papers. The ratio has decreased from 22 percent to 6 percent over the last 40 years. In the fifties and early sixties, nearly half of fluids engineering research was pump-related, a vast field of application. The pump share has decreased by two-thirds since then, and this fact shows that fluids engineering has cultivated new fields of application in emerging technologies.

It is interesting to observe that the increase of pump-related papers was rather low (1.2 percent annually) in the first stage when pump production was soaring. On the contrary, the pump research was remarkably activated by the annual growth rate of 5.2 percent in the second stage when the pump production was rather stagnant. This implies that a booming economy may spoil the driving force for innovative products. Difficulty is the mother of progress. In order to follow the shift of interest in pump research, pump-related papers were classified into the following eight groups of topics:

- (1) Flow phenomena in pump elements such as impellers and diffusers, sub-divided into steady and unsteady phenomena.
- (2) Analysis and prediction of overall performance of pumps, sub-divided into steady and unsteady aspects.
- (3) Fluid force on pump elements like vanes and impellers, sub-divided into steady and unsteady phenomena.
- (4) Cavitation study; inception, collapse, performance, noise and acoustics, damage, etc., sub-divided into fluid phenomena and material damage.
- (5) Multi-phase flow in pumps; phenomena and performance of pumps handling solid particles in liquid and gas bubbles in liquid.
- (6) Application of Computational Fluid Dynamics (CFD) to pumps, and active control of performance.
- (7) Unsteady phenomena in piping system.
- (8) Non-turbo pumps; rotary and reciprocating pumps, jet pumps, water-hammer pumps, air-lift pumps, etc.

The number of papers in each group is summed up for five years duration and the percentage of each group to the total pump-related papers in the same period is plotted in Fig. 5. It can be seen from this figure that the study of steady flow phenomena in pump elements and unsteady phenomena in piping

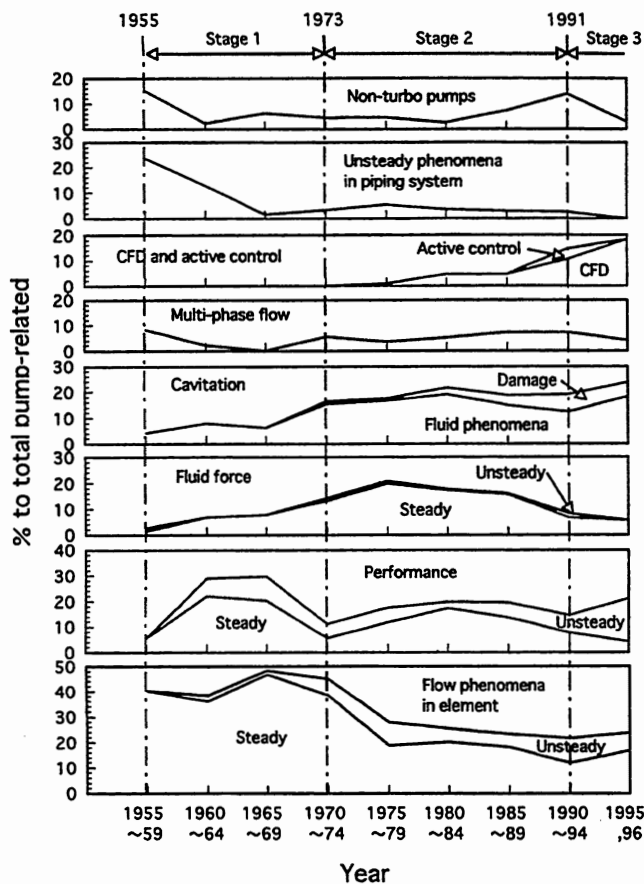


Fig. 5 Composition of the topics of pump-related papers

systems showed a drastic decrease from the first to the second stage. The opposite tendency is obvious in the study of unsteady flow phenomena in pump elements, fluid force, cavitation, gas/liquid multi-phase flow, CFD, and active control of performance.

The research trends may be characterized by a closer approach to real internal flow mechanisms and diversification of research topics. In stage 1, most of the studies were on axial or centrifugal machines characterized by 2D linear or circular cascade analysis. This evolved into the studies of mixed flow impellers, diffusers and volutes in stage 2, with the shifts through quasi 3D to pure 3D analysis. Studies in stage 3 include detailed internal flow measurements and CFD to correlate the development of secondary flows including tip leakage flows with over-all performance, studies on specific pumps such as inducers, screw pumps, regenerative pumps, pumps for high viscosity fluids and so on. Recent increase of non-turbo pumps includes jet pumps, air-lift pumps, oscillating-pipe pumps and pumps utilizing Weis Fogh mechanisms. Developments of drainage pumps operable at any suction water level in stage 3 symbolize the diversification of demand from classical performance to reliability in operation.

Turning to unsteady flow research, classical studies of cascade flutter, surge, rotor-stator interactions and unsteady performance in stage 1 are followed by studies that include the effects of stall, boundary layer response, cavitation and 3D effects. Studies of transient performance and those of rotordynamics were started in stage 2 and extended to cover various cases.

The evolution of cavitation studies is somewhat different from others. In stage 1, observation of cavitation and cavitation performance in real pumps were of major interest. More fundamental studies of cavitating flows on foils and cascades, bubble dynamics and damage were made in stage 2, leading to the

efforts to quantitatively predict damage in real pumps in stage 3. Cavitation surge, is more closely correlated with internal flow effects and the mechanisms of rotating cavitation were studied in stage 3.

The study of fluid force and cavitation is closely connected with the assurance of noise and vibration-free operation, which became increasingly important to meet the regulations for the surrounding environment. The largest feature of the second stage is the proliferation of computer and information technologies. The application of CFD to the research and design of pumps will accelerate further into the third stage. Application of the inverse method will become a common tool of design also in this stage.

Papers on active control of performance appeared a decade ago and have been increasing. If active control of turbulent flow becomes a realistic technology, it will evoke new research that apply it to the internal flow of pumps.

Pumps in the Third Stage

Pumps have two different faces. One is the face of a record-challenging machine with the utmost in advanced technologies. Pumps are the heart of every liquid-handling system. The more challenging the system, the more difficult the development of the required pumps becomes. A good example is the turbopumps of liquid-propellant rocket engines. High performance rocket engines require the most advanced pumps in terms of compactness and lightweight. This face is worth demonstrating in the showcase of pumps.

The other is a quite common face as a component of a piping system. The function of pumps in a piping system is to increase the pressure and is just opposite to that of valves, which reduce pressure by adjusting flow resistance. Pumps are merely one of numerous piping components, as it is the case for valves, bends, branches, etc. The majority of pumps bear this common face. The value of these common pumps consists in high reliability, easy maintenance and operation, and low cost.

Engineers and researchers who have a stake in pumps, wish naturally to be involved in the R&D of record-breaking pumps with the former face. Such cases have been, however, quite scarce in recent years and we can mention only a few examples such as the hydrogen and oxygen turbopumps for the LE-7 rocket engine (Kamijo, 1993), a down-hole pump for geothermal power generation (submerged-motor pump in 200°C water) (Katsuta, 1996), a compact, high-powered pump for water jet propulsion (Kawakami, 1993), a 600 bar high pressure centrifugal pump for sea bedrock crushing (Manabe, 1981), etc. Such opportunities may be also scarce, sorry to say, in the present stage as was the case in the second stage.

A pump has a life cycle. Research, design, manufacturing, test, and installation constitute the predelivery cycle, while operation and maintenance do the postdelivery cycle. The costs incurred during the predelivery cycle make up the initial cost, while those during the postdelivery cycle make the operational cost. Poor reliability pays a big penalty as a consequence in term of increased operational cost.

Let us consider the case of a Primary Loop Recirculating Pump of a BWR plant. The pump is expected to operate for 40 years (plant life) with the highest reliability, since any trouble with the pump, even an excessive leakage from the shaft seal, leads to a shutdown of the whole plant. In order to maintain a high level of reliability for plant life, the costs during the postdelivery cycle become essentially higher than the initial cost (for pump reliability, refer to Makay and Szamody, 1978).

For the majority of pumps in service, long life, reliability and life-cycle costs will become the largest concern in the decades to come. This sort of target is not easy to handle, since a variety of engineering disciplines are involved and must be coordinated and integrated effectively. There are still a variety of key technologies that are waiting further advance and breakthrough. To

mention a few, countermeasures for cavitation erosion, quantitative prediction of unsteady fluid loading, air/water two-phase flow pumps with large void fraction, structural vibration analysis under liquid/structure interaction, maintenance-free bearings and shaft-seals, pumps with a wide operational range, fluid dynamical design for easy manufacturing, etc. are the examples of such technologies. Fluids engineering plays a fraction of the total role in the development of pumps; however, it has the possibility of making a fundamental breakthrough for higher reliability and lower costs.

Conclusion

The social and industrial background of post-war Japan has been classified into three stages of development with unique characteristics. The production of pumps in sales and quantity was analyzed by statistical data and the evolution was correlated with the features of the corresponding background stages. Similar analysis was made also for papers on pump-related research published in the *Transaction of JSME*, Series B (fluids and thermal engineering).

As the value of pumps, such qualifications as high reliability, easy maintenance/operation and low costs will be sought as top priority in the decades to come. The shift of value can be described in a simple wording as "from predelivery to postdelivery." Fluids engineering has the possibility of making an essential break-through for these targets.

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