

1984

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Futakawa, A., "Improvements in Compressors with Special Emphasis on Interesting Developments in Japan" (1984). *International Compressor Engineering Conference*. Paper 472.
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IMPROVEMENTS IN COMPRESSORS WITH SPECIAL EMPHASIS ON
INTERESTING DEVELOPMENTS IN JAPAN

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Abstract - This paper is intended as a review of the recent research and development of refrigeration and gas compressors in Japan. The review has been carried out by the papers as source material that are reported in the transactions, proceedings, and magazines in mechanical engineering field. Most compressor companies in Japan have long efforted to develop and apply advanced technology for innovative refrigeration and gas compressor equipment and components. This effort is aimed at systems that can achieve sufficient energy cost reduction compared with current compressors. Increased efficiency has the potential for significantly lowering energy cost through improvement of performance and reliability and through reduction in the number of parts that must get higher productivity and their maintenance and operation. This trend promotes the development of rotary compressors such as rolling piston rotary compressor, mono-screw compressor, and scroll compressor.

INTRODUCTION

The progress of research program toward development of innovative refrigeration compressors and component concepts for application to refrigerators and air conditioners in both domestic and industrial uses can be assessed using efficiency, performance, reliability, and productivity targets. The purpose of this effort is to bring to bear results of refrigeration equipment and system studies on research and development program decisions. To attain this purpose, many compressor companies in Japan have long efforted to develop much higher and effective technique resulting from compressor technology - numerical simulation of compressor performance, valve dynamics, lubrication, motor design, and capacity control. By integrating machine dynamics, metallurgy, broad based approach to capacity control, heat transfer, and fluid dynamics, compressor technology in Japan already can produce several hundred billion dollars of compressor per year in these days.

Most of those compressor technologies are applied in the equipment design and system design stages. Here, service life can be predicting by using recently developed computer models that can simulate operating conditions. Designers are better

able to refine geometries, select suitable constructions, and develop improved refrigerant circulating methods. These techniques can also be beneficially applied during equipment operation for reducing noise, alleviating shock or cyclic loading, identifying compressor problems, and developing efficient maintenance programs - thus, extending service life and increasing reliability.

Amid growing concern about those new technologies, in general, two main streams of compressor industry in Japan have been pursued for the refrigeration and air compressors. The first is the development of rotary compressors of rolling piston type below a rating of 1 ~ 3 kW, which are mainly applied to refrigerators and air conditioners for domestic use. The second is the development of rotary compressor within a rating of 1 ~ 15 kW, which are mainly applied for industrial use. This tendency promotes the utilization of the rotary refrigeration compressors, leading to the development of new type rotary refrigeration compressors such as scroll compressors and mono-screw compressors. This paper is intended as a review of recent research and development of refrigeration compressors and gas compressors in Japan. This review is based in large part on the information which has been released in the field of mechanical engineering in Japan. In this paper, nationwide research and development trends have been described by separating into reciprocating compressor, rotary compressor of rolling piston type, turbo compressor, and other compressors.

RECIPROCATING COMPRESSOR

The steep rise of the conventional fuels, in 1974, that currently has supplied a major share of the nation's energy and the increasing pressure by society for energy saving have been stimulating a search for alternative compressors with higher performance and efficiency, small size, light weight, and low noise. Thus, a major thrust of the research and development program in the compressor industry has been the development of the new technologies to satisfy these demands that will supplement and eventually replace current means of power saving and productivity. This effort tends to be switched from the reciprocating compressors to the

rotary compressors in both domestic and industrial uses. Accordingly, most research and development activities on compressors in Japan place the focus on the rotary compressors during past decade. Very little information, therefore, is published in the reciprocating compressor.

Four major categories of research and development effort in the reciprocating compressor can be identified:

- Performance improvement
- Capacity improvement
- Noise improvement
- Component lifetime improvement

The design of compressors tends to rely increasingly on the pioneering advances that have been achieved in the field of thermodynamics and hydrodynamics design. With the aid of computer programs, for example, it is now possible to devise a more rational approach to the design of new compressors and to predict with accuracy their overall performance. The impact of improved characteristics on future reciprocating compressor design and operating considerations can be broken down as follows:

Performance Improvement

When computer simulation and data processing changes are made an increase of the performance improvement can be expected. In many instances, a portion of this improvement can be traded off for a performance improvement by understanding the source of power losses and flow rate losses and by changing geometrical dimensions of the key parts of the compressor.

Suefuji [1] reported the combination method of computer simulation with data processing to eliminate the compressor performance based on experiment, where only average pressures and temperatures at four points in the suction and discharge chambers. Kawai [2] developed new muffler system by adopting a plastic suction and dual chamber muffler. An appreciable reduction of 14°C in suction gas temperature was attained, leading to a 20% reduction in suction pressure loss. Imaichi [3] reported the new method to evaluate the effects of the leakage from the piston clearance on the indicator diagrams, which is very applicable for numerical simulation of transient vibrations during stopping of the reciprocating compressor. Ohinata [4] developed a series of reciprocating compressor for air conditioners with high efficiency. Reported studies involved suction-discharge piping losses, suction gas heating, valving losses, mechanical losses relating to piston ring, crank shaft, and bearing, motor efficiency, leakage losses, and top clearance losses. Harā [5] also reported a new series of semi-hermetic compressors for low temperature, in which coefficient of performance of 2.1 was attained at a condensing temperature of 45°C and an evaporating temperature of -15°C when using R22 as refrigerant. This high efficiency was achieved by reducing internal losses described above.

As described above, a large percentage of the reported works on performance improvement was devoted to the reduction of internal losses in the compressors. Cumulative improvements of the

reciprocating compressors were reported in terms of typical coefficient of performance from 1.8 up to 2.3 for refrigeration and 2.8 up to 3.4 for air conditioning.

Capacity Improvement

The electrical motor is here to stay! Regardless of what innovative are developed in the future to transform energy, the one form of energy that all of these new means will generate in electrical energy - and thus the electric motor will outlast refrigeration and air conditioners. In looking to the future insofar as drivers are concerned, the real question is, what will the electric motor of tomorrow be like?

The first desirable development of drivers for compressors concerns the provision of electric current at frequencies from 20 Hz to 120 Hz, in which there is a bright future for solid-state frequency converter. The advent of silicon-controlled rectifier has given a new impetus to the search for economical frequency converters. At present in Japan, such converters are already available commercially in small sizes.

Itami [6] reported a study on the performance of frequency controlled compressor combined with power frequency inverters operated at a frequency range from 25 Hz to 75 Hz. The difference in required capacity between cooling and heating can be eliminated in heat pumps, and an SEER improvement can be realized by 20 up to 50%, in comparison with the conventional ON/OFF control method. Sano [7] developed multi-indoor-unit-room air conditioner in incorporating variable-capacity-control inverter and attained a reduction of about 30% in running cost. Okamoto [8] developed an inverter controlled air conditioner of heat-pump type and attained a wide range control from 56 up to 100% for cooling and from 36 up to 100% for heating. The energy consumption was reduced by 30%.

They are used principally to provide efficient speed variation for driven equipment. In the future, it is likely that solid-state control devices will be used both to multiply frequency and to vary it over whatever range is necessary to meet variable compressor service conditions. While it is difficult to predict the maximum size of individual adjustable frequency drives that will be ultimately used, there is no question that the maximum economical size will continue on an ascending curve in relation to time.

Another important effort in system improvement is the utilization of capacity control by using two-speed compressor, in which the compressor capacity matches more closely to the cooling load demand. Imasu [9] reported that by matching the compressor capacity exactly to the needed cooling capacity a 30 up to 35% energy reduction in an entire air conditioning season could be obtained. Morimoto [10] also proposed a new procedure driven by two-speed motor without starting capacitor.

Noise Improvement

Noise supplement is one of the most important requirements in air conditioners and refrigerators. This demand is getting more and more increased year by year with achieving higher performance of air conditioners and refrigerators. In Japan, it is fact that the noise reduction ratio in air conditioners and refrigerators is 2~3 dB (A) every year.

The research and development program in the field of noise control and reduction can be identified in looking directly at the noise sources in compressor such as vibrations and gas pulsations, and in interrupting the noise path such as suspension system characteristics and gas mufflers. Almost efforts of noise control and reduction in Japan, however, tends toward the reduction in the vibrations of hermetic shell.

Saito [11] achieved the reduction in compressor noise by restricting the compressor shell and decreasing the amplitude of vibration. The application of asymmetrical shape to the shell, by which compressor noise was decreased by 6 dB (A), made it possible to reduce the thickness of the shell 1 mm thinner than the current one. Tojo [12] interrupted the complex noise transmission paths, thus leading to countermeasures for noise control and reduction. Compressor noise could be reduced by improving the characteristics of the air borne path and the internal suspension and solid paths, by improving the structure of the shell, and by equipping a resonant type suction silencer. Matsuzaka [13] carried out the experimental and theoretical analyses to clarify the noise radiation mechanism and showed the suction pressure pulsation in the compressor shell as noise source.

Component Lifetime Improvement

Since reliability and long life are the most important factors for reducing the operating cost, the optimum design of the compressor can be allowed to increase only if the material can be made stronger or the operating stresses lower. The means for achieving high quality while maintaining or increasing life and reliability include refinement of existing designs and manufacturing processes and introduction of new materials and processes.

This category includes many areas, such as valve stresses, lubrication, bearing, piping vibrations, gas pulsation, moisture removal, electric motor, and monitoring. Very little information, however, is published on component lifetime improvement. This tendency comes from that this category is strongly close to the development of innovative compressors. Successful research and development can lead to stronger competitive positions in the refrigeration and air conditioning field. This situation results in a strong tendency toward withhold information about component lifetime improvement.

Imaichi [14] examined the vibration of a single-cylinder reciprocating compressor during motor turned-off. The frequency and the damping property of the observed high frequency damped

vibration components and the exciting force which caused the vibratory components were examined. Author [15] reported the transient stresses produced in internal suspension springs of a hermetic refrigeration compressor during start and stop operations. The effects of operating conditions and the frequency of power source on the dynamic stress of the suspension spring were revealed.

Valve system failures occupy a continuing important research and development position. A valve of a refrigeration compressor is subjected to two types of fatigue damages: bending fatigue and impact fatigue. The bending fatigue implies manageable problems because the motion of the valve would be estimated in blueprint stage of compressor design by using the simulation programs of valve dynamics, and the fatigue strength of valve materials would be evaluated by using a commercially available fatigue testing machine. The concern of research in this field is changing from the bending fatigue to the impact fatigue. The prediction of impact stresses in the operating compressor involves both impact fatigue testing techniques and mathematical modeling and prediction methods.

Author [16][17] reported the dynamic stress of refrigeration compressor reed valve with oval shape and the deformations and stresses of refrigeration compressor flexible ring valve. In these studies, finite element method was used for prediction of the stress and deformation of the valve, and the design concept of the discharge valve was shown. Author [18] examined the wave transmission mechanism by using two bars which were simulated to the valve seat or valve stop and the valve. The oblique impact of valves against the valve seat or valve stop is important for clarifying the generation of impact fatigue failure of valve materials. Moreover, author [19] reported the impact fatigue failure mechanism of a suction valve that involved the fracture with fragments turn off from the edge or surface.

ROTARY COMPRESSOR OF ROLLING PISTON TYPE

Rotary compressors of rolling piston type have many dominant characteristics such as high efficiency and reliability, small size, light weight, small number of parts, and productivity, in comparison with reciprocating compressors. These advantages prompt to switch from reciprocating compressors to rotary compressors in these days. The rotary compressors, therefore, are widely used for domestic refrigerating and air conditioning units in Japan.

Many compressor companies in Japan have extensively efforted to develop much innovative and effective compressor resulting from compressor technology - especially rotary compressor of rolling piston type. This effort involves numerical simulation of compressor performance, dynamics of rolling piston, lubrication, and manufacturing process. Accordingly, many companies routinely subjected rotary compressors to a simulation - design process. In this process, they build prototypes of only the most promising candidates

for direct comparison with the simulation predictions, leading to the reduction in the number of prototypes made on experimental bases. The sophistication of the prototypes in terms of the geometrical variable and accuracy of predictions has reached the level where computer controlled optimization of compressor design has been successfully utilized.

Four major categories of research and development effort in the rotary compressor of rolling piston type can be identified:

- Design improvement -- mathematical modeling and simulation
- Performance improvement
- Noise improvement
- Component lifetime improvement

During past five years, almost research and development are concentrated to the 1st and 2nd categories. This comes from that the need for better energy utilization and the improved performance without sacrificing capacity will be increasingly necessary to develop highly innovative rotary compressor of rolling piston type.

Akatsuchi [20] developed high-efficiency rotary compressor for energy saving room air conditioners. The compressors have mechanical and leakage losses reduced by optimizing the geometrical variable and clearances between sliding pistons. Oishi [21] developed rotary compressor for low temperature. The volume was reduced by 67%, the weight by 54%, and the coefficient of performance was increased by 30% in comparison with the conventional reciprocating compressor.

Design Improvement - Mathematical Modeling and Simulation

The mathematical model to simulate a rotary compressor is considered to predict behavior adequately for many design purposes. Assuming that a compressor can be simulated by a mathematical model, then it may be used to select the values of the many parameters involved in a best design. The designer must first decide what is the criterion of the best, i.e. define an objective function to be maximized or minimized, and then stipulate the constraints to be applied during the optimization.

Shimizu and Yanagisawa [22][28] carried out a series of fundamental studies on the radial and face leakages, effects of these leakages on performance, dynamics of rolling piston and frictional loss, suction gas heating, effect of volumetric efficiency, and vibration of rotary compressors. Imaichi [29][30] also carried out dynamic analysis of crank shaft, rolling piston and blade of the rotary compressor, and then clarified the constraint forces and sliding speed at each pair of movable compressor elements.

Okada [31] analyzed the dynamic behavior of the rolling piston with attention to the frictional forces acting on the rolling piston and the vane. Yanagisawa [32] also reported the analytical and experimental approach of the rotating motion of the rolling piston. They clarified that the positive and negative sliding between the vane tip and the

outer surface of the rolling piston occurred alternately during one revolution of the crank shaft and that the rolling piston rotated at average rotational speed of a few percentages of that of the crank shaft.

Performance Improvement

The development and application of advanced technology for innovated refrigeration compressors are being performed by many compressor industries in Japan. This effort is aimed at new type compressors - rotary compressors - that can achieve significant energy cost reductions compared with current reciprocating compressors. Increased efficiency has the potential for significantly lowering energy costs through reductions in the leakage and mechanical losses and clearance volume. A net cost reduction will result, provided that higher efficiencies only impose modest cost increases on related components. To satisfy these requirements, the increasing and improving the coefficient of performance of the rotary compressors become a highly important matter in Japan. A lot of efforts, therefore, have been carried out by many compressor companies in Japan.

Iida [33] developed a high efficiency rotary compressor which has capacity control function with little loss of efficiency in partial load operation. An efficiency improvement of 12% compared with reciprocating compressors heretofore in use was achieved. Chu [34] presented an analytical approach on the volumetric efficiency and the power consumption to evaluate the performance of rotary compressors. Wakabayashi [35] measured the influences of the cylinder pressure, temperature of refrigerant gas, oil, and cylinder wall on internal losses, and then examined the rate of various losses. A motor loss was about 30%, and a heat loss about 20%, to a total loss. Matsuzaka [36] also carried out an experimental and theoretical analysis of loss factors of a rotary compressor. A synthetic efficiency of 72.4% for the rotary compressor was obtained.

Noise Improvement

Since the rotary compressor has less unbalance mass in the crank shaft and much more lenient variation in the cylinder pressure than that of the reciprocating compressor, exciting forces acting on the rotary compressor are smaller than those of the reciprocating compressor. In the rotary compressor, however, the pump-motor assembly is directly fixed on the shell. This means that it is hard in the rotary compressor to control the noise by interrupting the noise path between the pump-motor assembly and the shell. Much effort, therefore, needs to reduce the vibration of the rotary compressor, leading to noise control and reduction. Very little information, however, is published in this category.

Tanaka [37] examined the relevant factors to the noise and the efficiency of a rotary compressor for household refrigerator and freezer. The relationship between the crank angle, the vane, and the discharge valve motions and the vibration at each part

was measured and then the noise generation mechanism was clarified. Asami [38] also measured the performance, noise, crank shaft motion, vane and discharge valve motions, and vibration at each part, and optimized the shape and dimensions of the muffler, the discharge valve port, and the radial and face clearance.

Component Lifetime Improvement

There are two major elements to planning for continuing compressor integrity. First there are the provisions made during design, development, and manufacture. Second, there are the provisions made for counting maintenance of the structure during service. When these two elements are properly planned for and implemented, a rotary compressor can be expected to provide long and safe service until such time as economics dictate its replacement.

To be successful, compressor integrity planning must be implemented in the initial stages of design and carried out through the life of the rotary compressor. In many compressor companies in Japan, the various elements that must be considered in planning are considered as follows. During preliminary design, initial sizing of the rotary compressor is accomplished based on the customer's requirements. Data from previous rotary compressor designs, as well as theoretical analysis and some testing, are used to size the structure of the rotary compressor to meet durability and safety requirements. During design development, an extensive amount of testing and analysis is considered for final selection of materials, allowable stress levels, and design details. For the design of a new type of rotary compressor, verification tests are conducted toward the end of the design development phase. These tests would include performance, start and stop, and running tests on actual rotary compressors. The information obtained from these tests provides the basis for the material and process specifications and quality control procedures used during fabrication and also the initial inspection and maintenance practices to be applied to the rotary compressor in service. The studies on design concept and component lifetime improvement include a lot of know-how of compressor design and manufacture. The situation results in a strong tendency toward withhold information in this field. Very few literature, therefore, is found.

Hirahara [39] analyzed the discharge gas flow through a cylindrical discharge port in consideration of the effect of the inertia of compressor gas and then estimated the variations in cylinder pressure and gas speed, leading to overpressure in the cylinder. Ozu [40] estimated the metallic contact between the crank shaft and the rolling piston, the rolling piston and the blade, and the roller and the sub-bearing. From this examination, countermeasures were driven such as improvements of lubrication, clearances, surface roughness, metal combination, and running conditions. Nagatomo [41] made an experimental and theoretical approach on the starting torque and then clarified the effect of the coefficient of friction in the moving parts, the lubricant conditions and the radial magnetic

pull of motors on the starting torque.

TURBO COMPRESSOR

The aerodynamic design of turbo compressors tends to rely increasingly on the pioneering advances that have been achieved in the field of aerodynamics and aerofoil design. The advanced concepts that have been successfully used for the space age are also being applied in the development of higher head per stage, in more effective use of inducers and diffusers, and in a greater understanding of the stability of aerodynamic performance criteria. With the aid of computer programs, for example, it is now possible to devise a more rational approach to the design of new turbo compressors and predict with accuracy their overall performance. The impact improved aerodynamic characteristics on turbo compressor designs and operating considerations in Japan can be broken down without any limitation to turbo refrigeration compressors.

Three major categories of research and development effort in the turbo compressor can be identified:

- Measurement technique improvement
- Performance improvement
- Basic aerodynamic design improvement

The customer demand for greater reliability and higher performance is increasingly and will inevitably be met by the compressor companies. There will be a growing number of installations that will eliminate entirely spare compressor equipment. In order to meet the stringent reliability and performance requirements, there will have to be further basic aerodynamic investigation on boundary layer control, unsteady aerodynamic forces, and component characteristics and to be further improvement of the heads per stage, operating speed, efficiency, compact design, drivers, and reliability. The growing emphasis on the environment will lead to stronger regulations specifying lower noise levels, either through aerodynamic improvement and by the increased use of attenuating devices and insulating materials.

Measurement Technique Improvement

Hayami [42] measured the steady and turbulence flow in the impeller of rotor blade of a centrifugal compressor by using laser-2-focus velocimeter and examined the relationship between the flow and the pressure distribution. Hagihara [43] showed a fundamental principle of the measurement technique by means of the transfer function evaluated by applying the exciting force to the rotor blade with an excitor availing bimolf effect. Nakano [44] developed optical blade vibration measurement technique by using He-Ne laser probes and data processing system. Endoh [45][46] also reported non-contact measurement of rotating blade vibration by three optical probes installed in the casing and then calculated both bending and torsional modes of blade vibration. The tip clearance measurement techniques were shown using fluoroscopy, contact pin, and exploring needle.

Performance Improvement

Mashimo [47] examined the mechanism of loss caused by leakage through the impeller tip clearance of a centrifugal compressor, employing the curved flow channels modeled after the flow channels of the impeller. The leakage through tip clearance originated the additional secondary flow in the main flow, and the larger the tip clearance was, the larger the additional secondary flow became. Yamane [48] reported two-dimensional and three-dimensional analysis and their computer programs to calculate performances of axial flow compressors based on two-dimensional cascade data, including the influence of blade thickness, blade surface roughness, and tip clearance. Mishina [49] carried out an analytical approach on the performance prediction of centrifugal compressors in which the flow loss at each section was simplified to make numerical model and the flow-loss relationship was expressed with numerical formula.

Basic Aerodynamic Design Improvement

Much of the research and development efforts were dedicated to the basic approach in turbo compressors. These efforts led to the tremendous growth of the research in the university and industry. Basic research is now considered as necessities to attain heads per stage, performance, reliability, operating speeds, and aerodynamic stability.

The inherent aerodynamic characteristics required of a modern turbo compressor so that continuing compressor equipment integrity objectives can be met are as follows:

- Steady flow
- Unsteady flow
- Hydroelastics (vibration and flutter) and noise

Steady Flow: Research on blades and cascades is extensively carried out to get higher heads per stage. Matsumiya [50][51] carried out an analytical and experimental study on the performance of slotted blades in cascade. An exact solution of two-dimensional potential flow was proposed and the effect of slottles in cascades was shown. Shirakura [52] reported a conformal transformation of the cascade of flat-plates into a row of circular cylinders. Inoue [53] proposed a compensation method varying camber angle and stagger of cascade so that the enthalpy distribution was kept constant. Daiguji [54] performed an analytical improvement of transonic cascade flow to get higher stability and convergence of solution. Senoo [55] converted the performance of circular cascade diffusers into that of inviscid cascades with conformal transformation and showed a possibility of circular cascade designs by using experimental data for single blade and inviscid cascade. Shirahata [56] solved stream function by finite element method with triangular element and then examined a possibility to estimate non-viscous subsonic flow field in cascades on the rotating flow surface. Miyazaki [57] carried out a rigorous and numerical solution of compressible potential flow past two-dimensional cascades of airfoil. Daiguji [58] reported a finite element analysis of three-dimensional potential flow in centrifugal

turbo machines. Sakamoto [59] investigated the slip factor dependence on the flow rate using a new technique to estimate the mean flow condition at the inlet of vaneless diffuser. Kuroumaru [60] measured three-dimensional flow field behind an impeller by means of periodic multi-sampling of a slanted hot wire. Namba [61] reported mathematical expressions for disturbance flow fields and their characteristics for rotating annular transonic and supersonic cascades. Sakamoto [62][63] devised a 1-dimensional treatment for the complex 3-dimensional flow field by expressing the velocity distributions by means of simple formula approximations.

Studies on impellers, inducers, and diffusers are also extensively performed. Mishina [64][65] reported the performance of impellers with different specific speeds and blade load distribution, and low flow rate characteristics of impellers with different diffusion ratios and specific speeds. Ishida [66] carried out an experimental approach with different impellers and specific speeds, clarifying generation mechanisms of the head loss, relationship between the diffusion ratio and the specific speed, and countermeasures for improving efficiency. Kanemoto [67] examined internal flow and performance of annular diffusers. Takehira [68] reviewed annular diffusers for axial flow compressors and turbines. Sakurai [69] reviewed diffusers for centrifugal compressors. Tsurusaki [70] reported swirl stall in non-vaned diffusers of centrifugal compressors. Sakamoto [71] showed a simplified analytical method of the inlet flow of non-vaned diffusers. Oda [72] discussed effects of inducers on the performance of centrifugal compressors. Kano [73] studied the performance of vaned diffusers in centrifugal compressors. Ogawa [74] examined the flow in the impeller of centrifugal compressors with inducers.

Unsteady Flow: Most of studies in this field are concerned with unsteady flow around a blade and cascades. Some efforts are reported in looking directly at aerodynamic forces and stall of turbo machines. Nishiyama [75] examined unsteady responses of turbine cascades to sinusoidal gust and 1st wake energy. Nishiyama [76] clarified effects of steady lift and nonlinear cumulation on unsteady characteristics of oscillating supersonic cascade with subsonic axial flow. Nishiyama [77][80] proposed a two- and three-dimensional unsteady cavity flow model of oscillating hydrofoils of finite cavity. Kikuchi [81] reported the interaction of the supersonic linear cascade with sinusoidally distorted flow between two parallel plates and then examined the effects on unsteady aerodynamic forces, noise, and energy loss. Murakami [82][83] analyzed the unsteady pressure on an unbalanced blade under periodic gusts in accordance with Naumann-Yeh's analysis. Namba [61][84] showed a mathematical expression for disturbance flow fields and their characteristics for rotating annular transonic and supersonic cascades, and then analyzed unsteady aerodynamic forces on oscillating blades. Matsushita [85] carried out a numerical analysis of unsteady laminar boundary layers with separation using one-parameter integral method. Nishiyama [86] proposed an analytic flow model of

unsteady partial cavitation.

Hydroelastics and Noise: Ishida [87][88] examined aerodynamic forces acting on blades under sinusoidal gust and vibratory response. Murai [89][90] established two-dimensional theory at zero cavitation number when clamped at trailing edge and supported elastically. Hamamura [91] showed countermeasures of flutter due to ill-balanced cascades. Matsudaira [92] analyzed unsteady characteristics of an oscillating cascade with separation in case of high turning angle. Kikuchi [93][96] examined the radiation of acoustic energy generated by the interaction of supersonic cascade with inlet-distortion. Kaji [94] reported the flutter of cascades in parallel shear flow. Nishiyama [95] proposed an oscillating loaded aerofoil cascade theory by perturbation expansion. Tanaka [97] reported the flow ratios at which each of the inlet and outlet return flows starts and their order with respect to the internal flow condition.

OTHER COMPRESSORS

Advanced technology concepts are under development that have the potential for significant performance, reliability, productivity, and cost on refrigerating and air conditioning systems. Emphasis is being placed on improving system efficiency through the use of high-performance refrigeration compressors, highly efficient heat exchangers, drivers with high potential for cost reduction, and long-life, low cost parts. The purpose of advanced component development is to identify new, innovative concepts for refrigeration compressors. This effort provides the focus for developing new rotating compressors such as screw and scroll compressors.

Three major research and development efforts can be identified as follows:

- Rotary compressor for automotive air conditioners
- Screw compressor
- Scroll compressor

During past five years, there has been significant advances in the level of understanding of performance of those compressors. While it is not always necessary to exercise this knowledge to its full extent, an underlying understanding of performance is essential to proper interpretations and use of simplified procedures suitable for guiding the design and development of those compressors. In addition, continued refinement in casting technology and numerical cutting technology has permitted the complex shape blades and screw to have features that improve clearance. Clearance details between blades or screws as small as a few micron are now obtained as a production routine. These design and manufacturing technologies in Japan permit rapid development of new compressors and design modification.

Rotary Compressor for Automotive Air Conditioners

Up to this time, reciprocating compressors and axial piston compressors have been widely used for automobile air conditioners. In these days,

however, vane and rolling piston compressors, and screw compressors are getting more and more used for automobile air conditioning units. This trend comes from the severe requirement for improvement in fuel consumption in automobile industry. Many compressor companies in Japan have been developing new rotary compressors to get higher performance and reliability, smaller space, light weight, and low noise.

Maruyama [98] developed a sliding vane rotary compressors for automotive air conditioners which would combine the characteristics of little loss of refrigerating capacity at low speed operation and effective suppression of refrigerating capacity at high speed operation. Tojo [99] reported the dynamic behavior of sliding vane in a sliding vane rotary compressor theoretically and experimentally and examined the effects of relevant parameters on the generation of the chattering noise of the sliding vane rotary compressor. Fukazawa [100] developed a screw compressor for automotive air-conditioners, which had a pair of rotors, casings, unloader device, oil injection valve, and magnetic clutch.

Screw Compressor

Screw compressors have a lot of advantages such as light weight, lenient vibration, low noise, and easy maintenance and inspection. These merits prompt to increase tremendous demand for screw compressors. In past years, twin screw compressors were most conventional ones. Advancement in design and manufacturing technology of screw compressors makes single stage or mono-screw compressors possible to attain much higher performance and efficiency in comparison with the conventional screw compressors. The main stream of the development of screw compressor in Japan, therefore, places the focus on single-stage, oil-free screw compressors and mono-screw compressors within a rating of 1 ~ 15 kW.

Gyobu and Mori [101][102] developed single-stage, oil-free screw compressors with a rating of 37 ~ 55 kW and a compression ratio of 8. This compressor was applied to energy saving type clean air system, in which efficient speed variation for driven equipment was provided by micro-computer control system. Sawai [103] developed single-screw compressor unit, in which energy saving was attained by 10 ~ 15% at a full load operation, by 40% at a 25% partial load operation. Tanabe [104] developed mono-screw compressor with gate rotor. Shigekawa [105] developed geothermal steam screw compressor.

Scroll Compressor

Scroll compressor has been developed as the alternative compressor to the reciprocating compressor within a rating of 1 ~ 15 kW. Arai [106] developed scroll compressor with a rating of 2.2 ~ 3.75 kW. Volume reduction was attained by 40%, weight reduction by 15%, adiabatic efficiency improvement by 10%, and noise reduction by 5 dB in comparison with the conventional reciprocating compressor. Terada [107] applied this scroll compressor to packaged air conditioner.

CONCLUSIONS

Over one hundred technical papers which have been published in Japan for past five years have been reviewed. Recent research and development efforts in compressor technology have been surveyed by separating into reciprocating compressor, rotary compressor of rolling piston type, turbo compressor, and other compressors. The conclusions obtained from this review are as follows:

(1) Planning for continued equipment integrity is the process of blending an increasing understanding of the factors affecting performance, efficiency, and durability with accumulating data base from simulation, test, and service experience. It is an evolutionary process of compressor technology in Japan. Recently this evolutionary process resulted in amendments to market requirements. These will be applied to the next generation of refrigeration compressor.

(2) Two main streams of compressor industry in Japan have been pursued for next refrigerating compressors. The first is the development of rotary compressor of rolling piston type below a capacity of 1 ~ 3 kW. The second is the development of new rotary compressors within a rating of 1 ~ 15 kW, which are scroll compressor and mono-screw compressor. Beyond this rating, twin-screw compressor and turbo compressor will be remained.

(3) Compressor performance, capacity, noise, and component lifetime improvement is the most important research and development program for reciprocating compressor. Effort, however, is getting more and more receded from the spotlight of attention upon these items for reciprocating compressor because of switching from reciprocating compressor to rotary compressor.

(4) Rotary compressors of rolling piston type have many dominant characteristics such as high efficiency and reliability, small size, light weight, small number of parts, and productivity, in comparison with reciprocating compressors. These prompt to switch from reciprocating compressors to rotary compressors in these days in Japan

(5) Many compressor companies in Japan have extensively efforted to develop much innovative and effective rotary compressor from compressor technology. This effort involves numerical simulation of compressor performance, dynamics of rolling piston, lubrication, noise reduction, and manufacturing process. As a result, rotary compressors of rolling piston type below a rating of 1 ~ 3 kW have been widely used for refrigerators and air conditioners in these days.

(6) Cumulative improvements on rotary compressor of rolling piston type have been attained in terms of a 40 ~ 50% volume reduction, a 40 ~ 50% weight reduction, and a 30 ~ 40% COP increase, in comparison with reciprocating compressors.

(7) Measurement technique, performance, and basic aerodynamic design improvement is the most important recent research and development program

for turbo compressors. Most of efforts have been concerned with steady flow, unsteady flow in blades and cascades, hydroelastics, and noise.

(8) Another stream of refrigeration and gas compressor in Japan in the development and improvement of mono-screw and scroll compressors within a capacity of 1 ~ 15 kW. The single-stage, oil-free compressor and scroll compressor have been practically used for clean air system and packaged air conditioner, respectively.

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