PROSPECTS FOR ENERGY CONVERSION EFFICIENCY IMPROVEMENTS BY THE USE OF TWIN SCREW TWO-PHASE EXPANDERS

I K Smith, and N Stosic

Centre for Positive Displacement Compressor Technology,
School of Engineering, City University, London, EC1V 0HB, U.K.

ABSTRACT

It is well known that there are large sources of low grade heat from which power can be recovered by means of two-phase expansion processes. Hitherto proposals to do so have rarely been economically viable either due to the low adiabatic efficiencies of the expanders or their relatively high manufacturing cost.
This paper describes the results of a long term R and D programme carried out at City University, London, which has resulted in the development of twin screw machines of great simplicity which can expand two-phase fluids with adiabatic efficiencies of more than 70% and are cheap to produce.
Two applications are given for these. The first is in a high efficiency system for the recovery of power from low temperature sensible heat sources, such as liquid geothermal brines. The second is to replace throttle valves in large refrigeration vapour compression systems. Here a device is being developed which recovers power from the two-phase expansion process and recompresses part of the vapour thus formed in a self driven sealed unit containing only a single pair of rotors. The authors have called this an "expressor".
Details are given of both analytical and experimental work on both expander and expressor units.

KEYWORDS

Expanders, Two-phase, Twin screw, Expressor

1. INTRODUCTION

1.1 Previous Work on Two-Phase Expanders

The need for two-phase expansion as a work producing process has been recognised for quite a long period. An early example of this was a proposal by Ruths [1] who filed a patent in 1920 to increase the energy storage capacity of steam accumulators by intermittent expansion of the water stored in them rather than the steam as shown in Figure 1. The type of expander was not considered in great detail and alternative designs were shown using either a reciprocating machine or axial flow turbine for this purpose. The authors found no record of such a two-phase expansion system being used and, apart from limitations due to the intermittent nature of the device, it is doubtful if satisfactory efficiencies would have been possible from such machines at that time. The thermodynamic process described by such a cycle is also shown on temperature-entropy coordinates.

In the early nineteen seventies, interest in using geothermal steam for generating electrical power grew rapidly in the United States where it was found that dry steam drawn from the California geysers could be used to produce base load electricity for an economically viable price. It was soon recognised that nearly ninety percent of geothermal resources were either wet steam or water dominated and that flash expansion to derive dry steam from them resulted in a large loss in power recovery potential.

In 1973, Sprankle [2] was granted a patent for the use of a twin screw machine to expand wet steam or even pressurised hot water as a means of recovering power from liquid or low dryness fraction geothermal brines. This process is shown in Figure 2 and, as may be observed, it is thermodynamically equivalent to Ruths' energy recovery concept with direct contact heating of the water in the geothermal reservoir. The temporary crisis in oil supplies at that time gave a strong incentive to investigate this device and alternative modes of expanding two-phase fluids in what was termed the "total flow" process. Much of the early work on these total flow studies is described by Kestin [3]. In parallel with the work on twin screw machines, other investigations were carried out on axial flow turbines [4-5], biphase turbines [6-7] and more recently on two-phase reaction turbines of the Hero type [8-9] in which to expand water steam mixtures more efficiently.

Apart from geothermal power applications, it was also recognised that throttling processes in chemical process plant and in large vapour compression plant used for air conditioning and heat pump units could be made more efficient by power recovery from them using radial inflow turbines, as shown by Swearingen [10] and screw expanders as shown by Shaw [11] and Linde [12].

All practical demonstrations of these proposals were characterised by relatively poor expansion efficiencies. The highest values were for radial inflow turbines for which adiabatic efficiencies of 67% were claimed.

1.2 Review of Work on Two-Phase Twin Screw Expanders

The first test results obtained from small twin screw expanders which operated on water or water/steam mixtures are given by Steidel et al [13]. This was followed by further publications [14-18] in which some limited efforts were made to model the expansion process either by empirical curve fitting or highly simplified and limited modelling. The highest adiabatic efficiency obtained from these tests was only 53%.

Taniguchi et al, after unsuccessful attempts to incorporate twin screw expanders in engine driven heat pumps for district heating [19], carried out a detailed analytical and experimental study of two-phase screw expanders using R12 as the working fluid [20]. The method of analysis used was identical to that developed for screw compressor performance prediction and is based on the assumption of the non steady flow energy equation applied to the volume of fluid trapped between the rotors and the casing and quasi steady one dimensional flow assumptions for the fluid flow through all ports and leakage passages. The performance predictions appeared to coincide well with the measured values on a small scale unit with rotors of 81 mm diameter. These led to predictions of internal adiabatic efficiencies approaching 80% in larger machines which would be reduced by bearing and timing gear friction losses.

In 1981, the authors began an independent investigation of two-phase expansion processes based on the use of the twin screw machine as the prime mover. It was soon found that such expanders were unsuitable for the huge volume flow rates and volume ratios required for the expansion of water to normal condensing temperatures. From the outset, therefore efforts were concentrated on processes involving organic fluids where, for equal heat utilisation over the same temperature range, exit volume flow rates could be reduced by a factor of 10 or more and expansion ratios by two orders of magnitude.

The work, which was carried out over a long period, has been reported in detail [21-23]. The main results of the studies reported are as follows:

i) Provided that two-phase adiabatic expansion efficiencies of at least 75% could be attained, a closed cycle system using light hydrocarbons as working fluids, as shown in Figure 3 could recover almost double the power from a hot liquid stream than was possible from either flashed steam or indirectly heated simple organic Rankine cycle systems. The authors described it as a Trilateral Flash Cycle (TFC) system. Subsequently, they found that such a system had previously been proposed with a turbine as the expander [4]. However, the adiabatic efficiencies attainable with a turbine were too low to make it worthwhile.

ii) The key feature to obtaining high adiabatic efficiencies with positive displacement machines as expanders is for the built in volume ratio of the expander to be substantially less than the actual volumetric expansion ratio of the the fluid being expanded [24]. By this means it is possible for twin screw machines to expand two-phase fluids with adiabatic efficiencies in excess of 75%.

iii) In large vapour compression air conditioning and refrigeration systems there is considerable scope for replacing the throttle valve by a two-phase expander. A variety of options exist on how to use the recovered power. One method, which offers many advantages, is to use a screw expander to drive a screw compressor in a sealed unit, as shown in Figure 4. The rotational speed of this unit, which the authors described as an "expressor" [23, 25], can vary according to the refrigeration load without the need for a separate controller.

2. IMPROVEMENTS IN TWIN SCREW MACHINE DESIGN

2.1 Main Problems of Two-Phase Twin Screw Expander Design

A twin screw machine is of the positive displacement type. It comprises a meshing pair of helical lobed rotors contained in a casing which together form a working chamber, the volume of which depends only on the angle of rotation. Depending on its direction of rotation, it may be used either for expansion or compression and its mode of operation in the former mode is shown in Figure 5.

The main feature of its design, which determines its adiabatic efficiency, is the profile of the rotors. These must form a good seal both between each other and between the casing at all rotational positions in order to minimise internal leakage. The pioneering work which led to profiles with both effective sealing and a large flow area through which the working fluid could flow was carried out by the Swedish company, SRM, and most rotor designs used today are derivatives of these. The relative motion between the lobes in these profiles is a mixture of rolling and sliding. Thus direct contact between the lobe surfaces must be avoided to prevent seizure.

A consequence of this has been the development of oil injected and oil free types as shown in Figure 6. The oil injected machine relies on relatively large masses of oil injected with the compressed gas in order to lubricate the rotor motion, seal the gaps and reduce the temperature rise during compression. It requires no internal seals, is simple in mechanical design, cheap to manufacture and highly efficient. Consequently it is widely used as a compressor in both the compressed air and refrigeration industries.

In the oil free machine, there is no mixing of the working fluid with oil and contact between the rotors is prevented by timing gears which mesh outside the working chamber and are lubricated externally. In addition, to prevent lubricant entering the working chamber, internal seals are required on each shaft between the working chamber and the bearings. In the case of process gas compressors, double mechanical seals are used. Even with elaborate and costly systems such as these, successful internal sealing is still regarded as a problem by established process gas compressor manufacturers. It follows that such machines are considerably more expensive to manufacture than those which are oil injected.

A high percentage of oil contained in the working fluid will inhibit the two-phase flashing process. Hence, twin screw machines must be of the oil free type if they are to expand two-phase fluids efficiently. Detailed studies of such machines showed that for large units, as required for a TFC geothermal power plant , the unit cost of the expander alone would be of the order of US$1500/kW. This is higher than the acceptable cost of the complete system, including pumps and heat exchangers. In the case of smaller units required for throttle valve replacement applications, the unit costs were even higher. It followed that, despite their good adiabatic efficiencies, twin screw two-phase expanders were not cost effective.

2.2 Improvements in Screw Expander Design for Power Generation

Two recent developments have led to great simplification in two-phase screw expander mechanical design.

Firstly, Mathematical studies of rotor profiling based on gear tooth generation theory [26-29] have led to the development of a new family of rotor profiles, as shown in Figure 7. These offer many advantages over more traditional shapes but from the viewpoint of the expander design, the most significant are the low rotor contact stresses between the male and female rotors and almost pure rolling motion along the contact band between them. The authors concluded that rotors with these profiles would not require timing gear provided that even a low viscosity fluid is present in the working chamber. This was confirmed by extensive testing in an air compressor designed for oil injection with rotors lubricated by water only [30].

Secondly, advances in the design of rolling element bearings [31], have shown that these may be used in twin screw refrigerant compressors to take both radial and axial loads without an oil supply, provided that there is a small trace of oil in the refrigerant. In the case of compressors, the oil would be present in the form of a fine mist but in the case of a two-phase expander, it would be wholly dissolved in the oil. It was not therefore certain how the bearings would perform.

An experimental screw expander was therefore designed and built by the authors without timing gear but with rotors based on their new “N” profile and which used standard steel rolling element bearings without oil lubrication [32]. Liquid refrigerant, which contained less than 1% oil, was permitted to flow fairly freely through the bearings by means of drilled passages and no internal seals were included in it. The only seal used was located at the drive shaft exit and this was of the standard refrigerator compressor shaft type. This wholly process lubricated machine had the added advantage that additional pumps, heat exchangers and filters needed for the oil lubrication system were thereby eliminated.

Test results with this machine were highly satisfactory. Firstly, it was found that local frictional heating in the bearings had the effect of evaporating the refrigerant while leaving the oil behind so that on strip down, the bearing housings were found to be full of oil. Consequently there was no detectable wear found either on them or the rotors after several hundred hours running. Although the design was not fully optimised from the thermodynamic viewpoint, peak adiabatic efficiencies of 76% were obtained, the highest ever recorded for any type of two-phase expander.

The cost savings achieved by this design simplification were impressive. In 1984, the authors purchased their first screw expander which was simply a standard oil free refrigeration compressor run in reverse. This had a swept volume of approximately 4.67 l/rev and cost US$72,000 at the then sterling/dollar rate of exchange. The experimental expander, as described was designed and manufactured in 1997 as a one off unit. This had a swept volume of 1.56 l/rev and, excluding rotor tooling and pattern costs, which were not large, its manufacturing cost was only US$6,000. Allowing for the usual scaling factor of cost ratio = size ratio$^{0.65}$, then, apart from the further gains due to the effects of inflation over a period of 13 years, this amounts to a sixfold reduction in price. There is little doubt that this figure could be further improved if such units were made on a batch production basis.

2.3 Improvements in Twin Screw Design for Throttle Valve Replacement

Although, the authors’ efforts to develop efficient cost effective two-phase expanders were originally mainly intended for large scale power generation applications, since 1995 the main emphasis of the work has been on throttle valve replacement, particularly in large scale air conditioning chiller units. Here the main aim was to improve the coefficient of performance of units operating on R134a which is thermodynamically inferior to other refrigerants used as CFC replacements even though superior to them in its ozone depleting tendencies.

In such systems, the power recovered from the throttling process may be used either to drive an electrical generator, as an auxiliary drive to the main compressor or to drive its own additional compressor using the “expressor” principle, already shown in Figure 4. Of these three options, the expressor appeared to be the most attractive since it actually boosts the capacity of the system by circulating more refrigerant for the same power input to the main compressor. Cost saving is therefore possible not only from reduced energy consumption per unit of refrigeration but also from lowering the plant cost per unit output.

This application has however, the additional cost of two pairs of rotors. Industrial sponsors of the investigation then enquired whether it were possible to use the same pair of rotors both to expand the working fluid and to recompress some of the vapour thus formed. After some consideration, this was deemed to be possible provided that:

i) the wrap angle of the screw rotors was increased substantially in order to permit the expanded liquid and part of the vapour formed to leave the machine before recompression of the vapour began and

ii) the rotor profile was modified to minimise leakage between the rotors during the recompression process.

The resulting concept is shown in Figure 8. A prototype unit suitable for installation in a 500 ton chiller unit has been built using this principle. It forms a fully sealed system in which the expansion power is absorbed in recompressing the vapour while the speed varies automatically to meet the load requirements of the system. Like the experimental expander already described, it has no timing gear and is entirely process lubricated with no seals of any kind contained in it. A photograph of the unit components is shown in Figure 9 and first test results have already been reported [33]. These are quite encouraging. In particular, it would appear that the inclusion of such a unit as a throttle valve replacement would be cost effective.

3. CONCLUSIONS

As a result of a long term research and development programme, it has now become possible to design and build twin screw machines as efficient two-phase expanders at an economically viable cost. Although other applications for such devices may be possible, the most significant are:

i) In the Trilateral Flash Cycle system. This may now be considered as a possible contender for cost effective power recovery from relatively low temperature liquid streams such as geothermal brines.

ii) In large industrial air conditioning chiller systems where preliminary studies on the two rotor expressor show promise of its being economically viable.

ACKNOWLEDGEMENTS

The work described in this paper summarises over eighteen years of investigation for which funding and technical assistance have been received from many sources. In particular, the authors wish to thank TPS, a venture capital company who funded the initial studies, the SERC, who supported the analytical studies together with the TRANE company of La Crosse, Wisconsin, USA, whose help came at a particularly critical time. Ongoing support has been maintained by Holroyd of Milnrow, Lancs, UK, who manufactured the rotors of all the latter machines. Since 1996, the work has been wholly funded by Carrier Corporation of Syracuse, NY, USA and the authors wish to acknowledge with thanks their permission to publish details of the twin rotor expressor on which Carrier have applied for world patent rights.

REFERENCES

1. Ruths, J. Method and means of discharging heat storage chambers containing hot liquid used in steam power and heating plants UK Pat. 217,952, 1924.

2. Sprankle, R.S. Electrical power generating systems. US Pat. 3,751,673, August 1973.

3. Kestin, J. Sourcebook on the production of electricity from geothermal energy DOE/RA/2830-2, August 1982.

4. Elliott, D.G. Theory and tests of two-phase turbines. Publication 81-105, Jet Propulsion Laboratory, May 1982.

5. Comfort, W. The design and evaluation of a two-phase turbine for low quality steam-water mixtures. UCRL 52281, Lawrence Livermore Laboratory, May 1977.

6. Studhalter, W.R. Rotary separator turbine enhances geothermal power recovery. *Modern Power Systems,* pp. 61-66, September 1982.

7. Cerini, D. J, Diddle, C. P, and Gonser, W. C. Project development, Desert Peak 9 MW power plant. Proceedings of Eighth Annual Geothermal Resources Council, Reno, Nev, 1984.

8. Fabris, G. Two-Phase reaction turbine US Pat 5,236,349, August 1993.

9. Fabris, G, Dhillon, J.S and Wortman, A. Two-phase Hero turbine with curved no separation nozzles; Energy related invention recommendation No 591, NIST, USA Dept of Commerce, 1993.

10. Swearingen, J. S. Flashing fluid runs turboexander. *Oil and Gas J,* 74(27), 70-71, 5 July 1976.

11. Shaw, D. N. Improvements in heat pump systems. UK Pat. 1,593,521, 15 July 1981.

12. Linde, A. G. Kompressionskaltemaschine mit einem Schraubenverdichter und deren Antrieb. German Pat. 1,811,284, 4 June 1970.

13. Steidel, R. F, Weiss, H and Flower, J. E. Characteristics of the Lysholm engine as tested for geothermal applications in the Imperial Valley. *J. Engng for Power,* 104, 231-240, January 1982.

14. Steidel, R. F, Pankow, D. H and Brown, K. A. The empirical modelling of a Lysholm screw expander. Proceedings of Eighteenth Intersociety Energy Conversion Conference, pp 286-293, 1983.

15. House, P. A. Helical-rotor expander applications for geothermal energy conversion. LLL Report UCRL-52043, April 1976.
16. Margolis, D. L. Analytical modelling of helical screw turbines for performance prediction. *Trans ASME, J. Engng for Power*, v100, pp 482-487, July 1976.
17. Dunbar, M. K. Altering the volumetric expansion ratio of a Lysholm helical screw expander. Report No: US DOE/ET/27252-T3,1984.
18. Ng, K. C, Lim, T.B and Bong, T. Y. Analysis of screw-expander performance. . *Proc Instn Mech Engrs, Part E, Jrnl of Proc Mech Eng,* 203(A3), 15-20, 1989.
19. Taniguchi, H, Giedt, W. H, Kudo, K, Kasahara, K, Ohta, J and Kawamura, K. Energy-conserving heat pump-boiler systems for district heating. Proceedings of Eighteenth Intersociety Energy Conversion Conference, v4, pp. 1862-1868, 1983.
20. Taniguchi, H, Kudo, K, Giedt, W. H, Park, I and Kumazawa, S. Analytical and experimental investigation of two-phase flow screw expanders for power generation. *Trans ASME, J. Engng for Gas Turbines and Power*, 110*,* 1988.
21. Smith, I. K. Development of the trilateral flash cycle system. Part 1: fundamental considerations. *Proc Instn Mech Engrs, Part A,* 207(A3), 179-194*,* 1993.
22. Smith, I. K. and Pitanga Marques da Silva, R. Development of the trilateral flash cycle system. Part 2: increasing power output with working fluid mixtures. *Proc Instn Mech Engrs, Part A,* 208(A2), 135-144, 1994.
23. Smith, I. K. Stosic, N and Aldis, C. A. Development of the trilateral flash cycle system Part 3: the design of high efficiency two-phase screw expanders. *Proc Instn Mech Engrs, Part A,*, 210(A2), 75-93, 1996.
24. Smith, I. K and Stosic, N. R. US Pat 5,833,446, November 10th 1998.
25. Smith, I. K. and Stosic, N. R. The Expressor: An efficiency boost to vapour compression systems by power recovery from the throttling process. AES-vol.34, Heat pump and refrigeration systems design, Analysis and applications, ASME 1995, pp. 173-181,1995.
26. Stosic, N and Hanjalic, K. General method for screw compressor profile generation. Proc 1996 International Compressor Conference at Purdue, v1, Purdue University, West Lafayette, IND, USA, July 23-26, pp 157-162, 1996.
27. Stosic, N, Smith, I. K, Kovacevic, A and Aldis, C. A. The design of a twin-screw compressor based on a new rotor profile. *Jrnl of Engng Design*, v.8, n.4, pp389-399 , 1997.
28. Stosic, N and Hanjalic, K. Development and optimization of screw machines with a simulation model - Part 1: Profile generation. *Trans ASME, J. Engng of Fluids Engineering,* 119, pp 659-663 September 1997.
29. Stosic, N. On gearing of helical compressor rotors. . *Proc Instn Mech Engrs, Part C,* 212, 587-593, 1996.
30. Stosic, N, Smith, I. K, Brasz, J. J and Sishtla, V. The performance of a screw compressor with involute contact rotors in a low viscosity gas-liquid mixture environment. VDI Berichte NR. 1391, pp 279-292, 1998.
31. Jacobson, B. Ball-bearing lubrication in refrigeration compressors. Proc 1996 International Compressor Conference at Purdue, v1, Purdue University, West Lafayette, IND, USA, pp 103-108, July 23-26, 1996.
32. Smith, I. K, Stosic, N. R, Aldis, C.A, Brasz, J and Sishtla, V. Twin screw expanders in large chiller units. Proceedings of International Conference on Industrial Compressors and their Systems, City University, London, September 1999.
33. Brasz, J, Smith, I. K, Stosic. Development of a twin screw expressor as a throttle valve replacement for water cooled chillers, Proc 2000 International Compressor Conference at Purdue, v2, Purdue University, West Lafayette, IND, USA, pp 979-986, July 25-28, 2000.

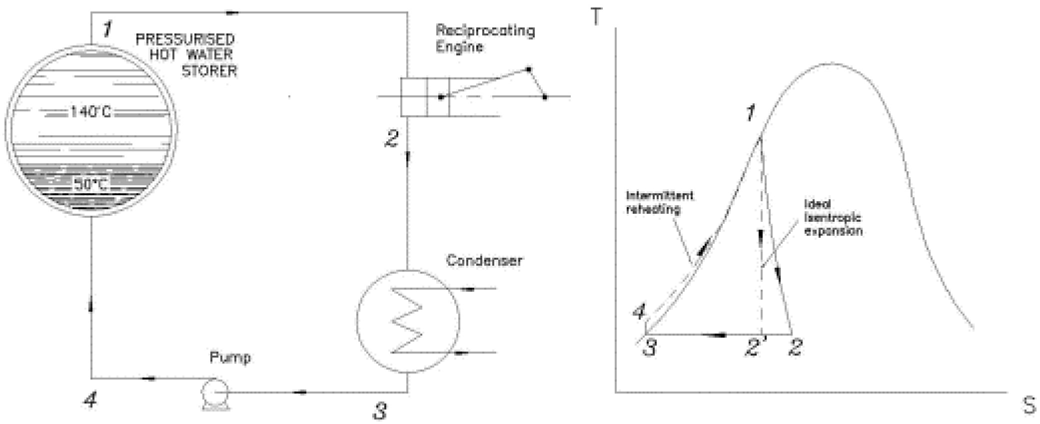
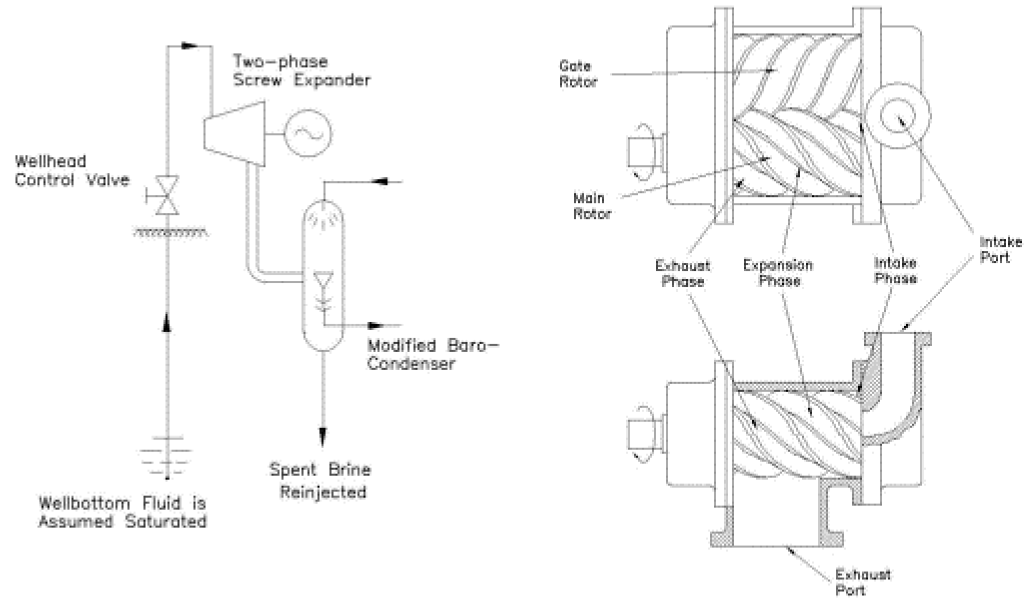
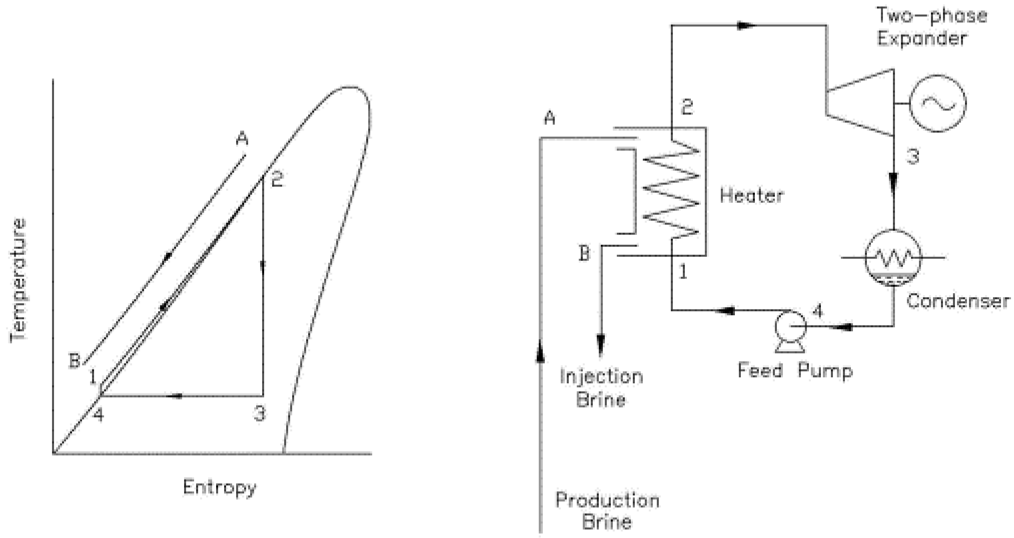


Figure 1 Ruths Patent



System Components Screw Expander Details

Figure 2 Total Flow System



The Process System Components

Figure 3 Trilateral Flash Cycle (TFC) System

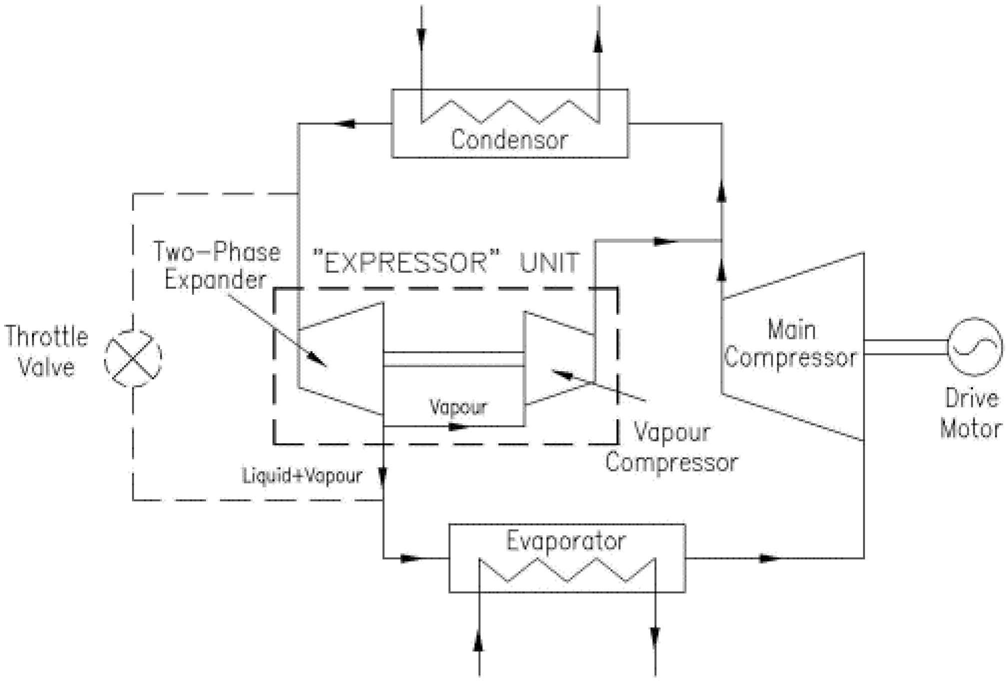
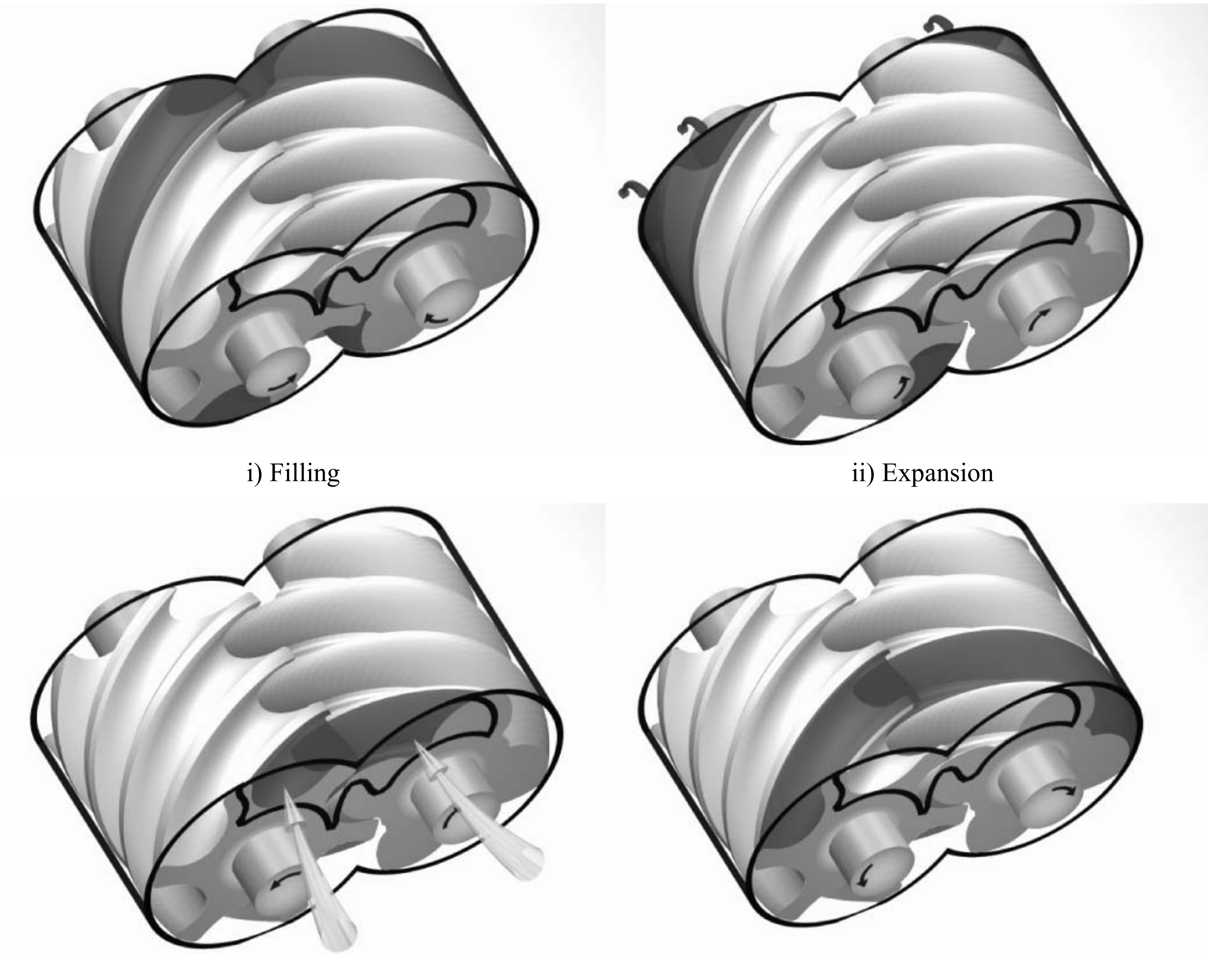


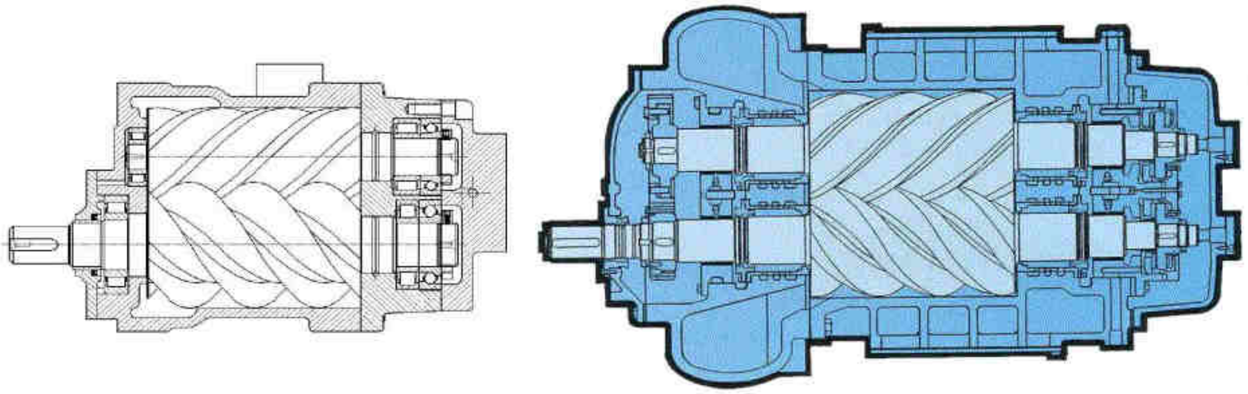
Figure 4 Throttle valve replacement by expressor



i) Filling ii) Expansion

iii) End of expansion iv) Discharge

Figure 5 Twin screw expander - Principle of operati



Oil injected Oil free

Figure 6 Twin screw compressors

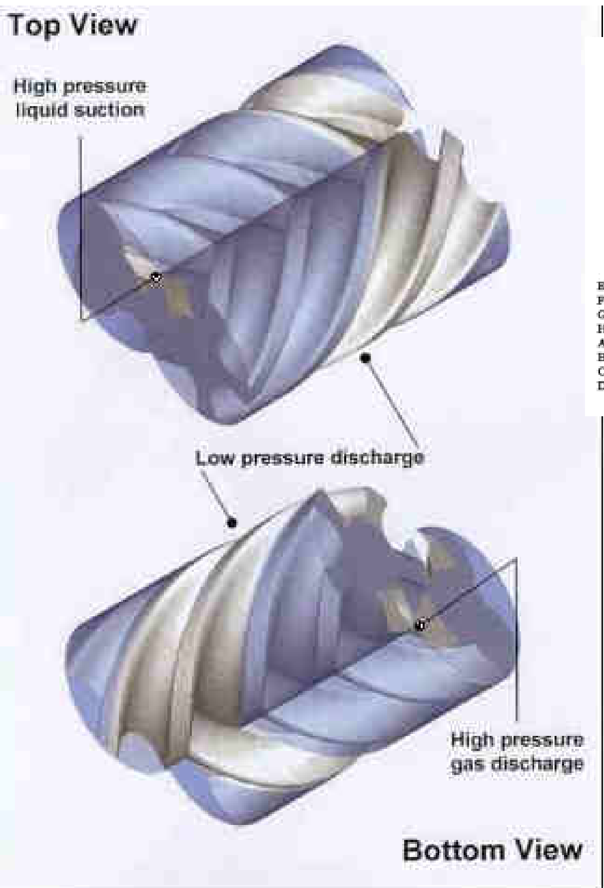


Figure 8 Two rotor expressor principle of operation

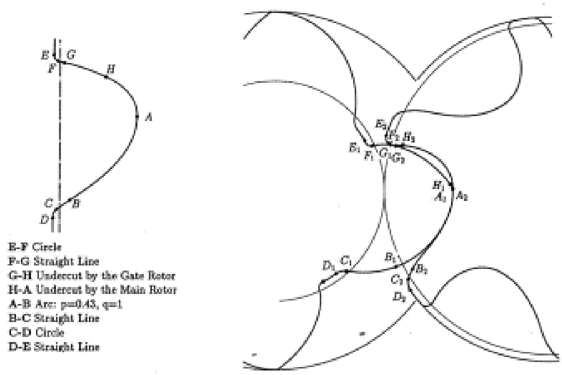


Figure 7

N-Profile Rotors

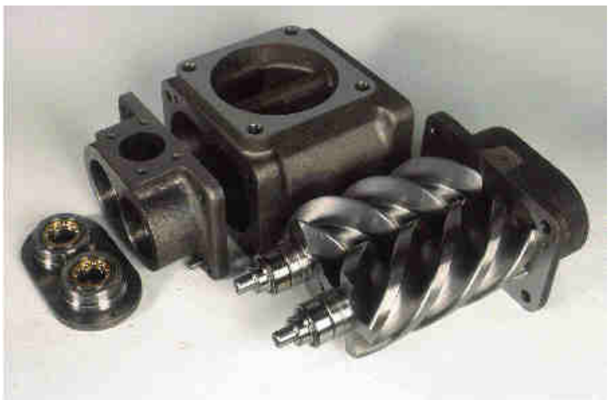


Figure 9 Expressor components