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THE FLOW WORK COMPRESSOR

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ABSTRACT

A new technology for the positive displacement compression of refrigerant vapors, air, and other gases is described. The technology integrates an open flow recirculation system operating at output pressure with a multi-lobed Root's type rotary compressor. The compressor feeds input pressure fluid into the recirculation system at constant temperature through flow work. Power for the flow work is supplied by equivalent shaft work.

Displacement cavities in the compressor rotors convey input pressure fluid into the recirculation system. After closing to inlet they open to intermediate refill ports, and recirculation fluid flows in. Pressure increases to within a few percent of discharge level before the cavities close to refill and then open into discharge. Final pressure increase is gained through adiabatic compression at a ratio which is near unity. The associated temperature rise is minimal.

Compressor units based on this technology are quiet and highly energy efficient. With the recirculation system there is no significant pressure pulse into discharge. At the same time there are no valves and no reciprocating, rubbing, or contact parts in the flow stream. The inherent simplicity of the Root's type rotary compressor has been preserved.

FOREWORD

With possible exception of the Root's lobed-rotor design, all present state positive displacement compressors increase pressure by reducing the size of displacement volume in moving from intake to discharge. This is true of the reciprocating piston, helical screw, spiral axial, rotary piston, sliding vane, liquid ring, and scroll type compressors. Molecules are mechanically forced closer together. Compression is primarily adiabatic (isentropic) and is characterized by temperature rise in the working fluid, often referred to as "the heat of compression".

This heat generation is the source of many design problems and performance limitations. It causes thermal distortion and high temperature levels in mechanical components. It shortens the life of seals, bearings, and lubricants. It requires more frequent staging to obtain high ratio compression while staying within acceptable temperature limits. It represents a source of waste heat that must be removed from the compressor components and from the flow stream by one means or another.

Isothermal compression creates none of these problems, as it is (theoretically) 100% thermally efficient. Although it represents a long-standing goal of the compressor industry, it cannot be reached by present state compressor technology in a practical manner. It can, however, be readily achieved through application of the design methods and procedures described in this and a previous manuscript.

INTRODUCTION

Flow work compression, although not so identified, was first described in a paper entitled "The High Ratio Circulating Compressor" and presented here at the 1988 International Compressor Engineering Conference. It discussed the design philosophy and described the geometric configurations and cycle sequences for obtaining high ratio compression from Root's type recirculating rotary blowers. However, discussion of the refill/highfill sequence was distorted by closed system analytical considerations. A revised description correctly reflects the open system nature of the compression cycle.

The previous manuscript discussed flow work compression fundamentals, but treated potential areas of application only in general terms. This manuscript is more application oriented. It discusses potential advantages, and looks at some specific areas of application where the technology can be effectively utilized. It describes physical arrangements that can achieve very high volumetric efficiency, even in smaller units. Finally, it discusses the present state of development, and what is being done to move it along.

DESIGN CRITERIA

In considering methods for achieving high ratio compression at high efficiency using recirculation flow, the prime consideration was that of fully exploiting the isothermal nature of flow work. Two design criteria were dominant. The first of these called for minimizing adiabatic compression by filling displacement cavities to the highest practicable level with recirculation flow prior to discharge. This design goal is achieved by:

Preventing communication through displacement cavities between recirculation ports and the intake/discharge regions.

Minimizing recirculation system dynamic losses by maintaining low flow velocities and by integrating low impedance flow paths with the compressor system.

The second dominant design criterion calls for obtaining high volumetric efficiency at high ratios by reducing back fill or slippage to the lowest practicable level. This design goal is achieved by:

Minimizing slippage paths by holding close tolerances for rotor mesh and rotor-to-housing clearances.

Using an involute rotor lobe geometry that maintains high impedance to slippage throughout mesh rotation.

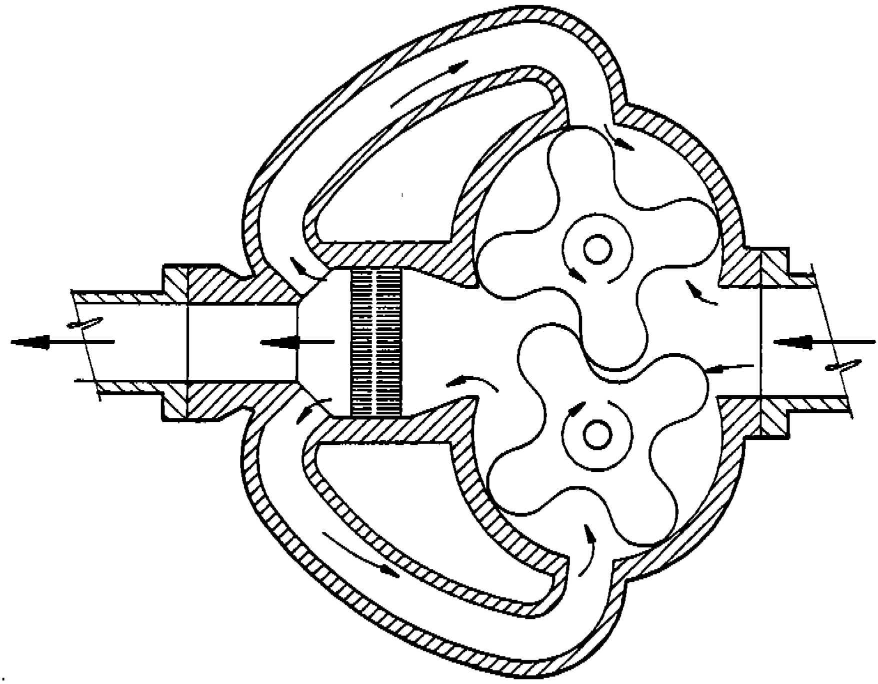
Providing intercept cavities on smaller units to collect peripheral slippage and carry it forward into the recirculation system.

BASIC GEOMETRY

The Root's lobed rotor blower design is uniquely suitable for development as a flow work compressor, and is a key element for establishing the technology. It is readily adapted to serve as an input feeder by adding additional rotor lobes and integrating a recirculation system consisting of flow ducts and refill ports. The recirculation system may include a heat exchanger to provide temperature control or thermal stabilization.

To meet the outlined criteria and provide adequate port areas, rotors with four or more lobes are required. The previous manuscript described the four-lobe arrangements, including rotor geometry and slippage paths. The geometry develops uniform mesh clearance throughout full rotation. Lobe root and tip radii are centered on the pitch diameter, with involute form in between.

Figure 1 shows a cross section of the four-lobe design arrangement.



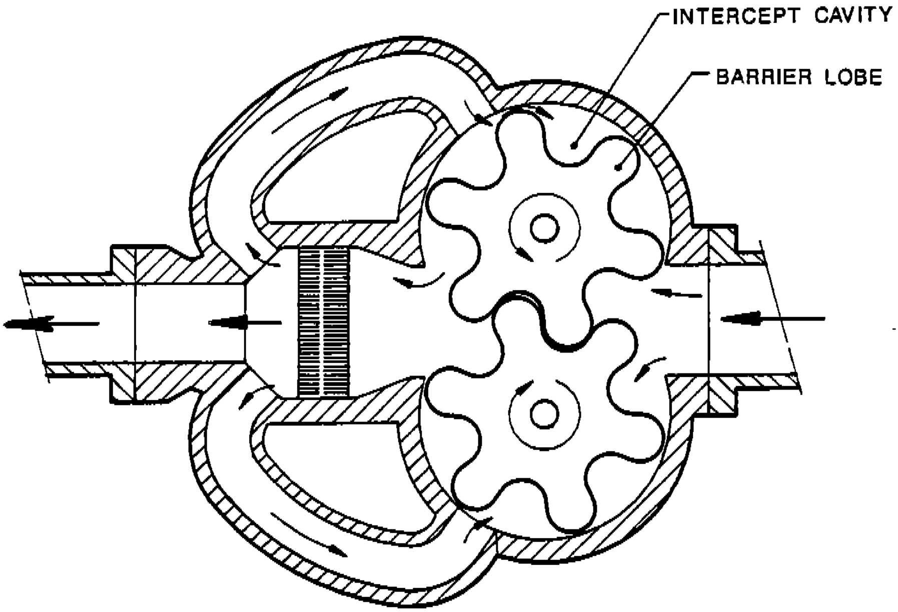
FLOW WORK COMPRESSOR
FOUR-LOBE ARRANGEMENT
FIGURE 1

For larger size compressors, volumetric efficiencies of 90% or better can be readily obtained. For smaller units it becomes much more difficult. Volumetric efficiency is a function of total slippage path area versus compressor displacement, and tends to improve with increased rotor center distance.

Slippage paths in the four-lobe arrangement include peripheral clearances as well as the rotor mesh clearance. The peripheral paths include two rotor tip-to-housing clearances and four rotor end-to-housing clearances. Pressure across the peripheral paths varies from zero to full output-input differential, while the rotor mesh path is always at full differential. However, less than 50% of total slippage passes through mesh clearance. End clearances become especially troublesome for short rotor lengths.

The problems associated with obtaining high volumetric efficiency in smaller size compressors led to a low-slippage arrangement. Refill port spacing has been changed to provide one additional cavity between intake and refill. The second cavity intercepts and collects peripheral slippage and carries it forward into the recirculation system. Only slippage through rotor mesh returns to intake. Short rotors are just as efficient as long ones for a particular center distance. However, displacement for a comparable center distance and rotor length is one-third less than the four-lobe arrangement.

Figure 2 shows a cross section of the low-slippage design arrangement.



FLOW WORK COMPRESSOR
LOW SLIPPAGE ARRANGEMENT
FIGURE 2

ANALYTICAL PROCEDURE

Adiabatic positive displacement compressors are usually analyzed as closed systems in which a fixed control mass is reduced in volume to achieve pressure increase. Flow work positive displacement compressors cannot be treated in the same manner. Mass within the cavity increases, while the volume remains constant. The compressor only serves to feed input fluid into the recirculation system through flow work.

When the compressor is viewed as an open flow system having the recirculation system pressure boundaries as control surfaces, a valid steady-state, steady-flow control volume analysis can be carried out. For any particular set of operating parameters, mass within the recirculation system remains constant. This contained mass is continuously circulated at low velocity, and develops a small amount of pressure and temperature variation. The pressure variation is normalized by additional shaft work, while the temperature variation can be normalized by a heat exchanger.

Mass is brought into the control volume at constant temperature through flow work. Power for the flow work is supplied by shaft work equivalent to isothermal compression input. The same amount of mass leaves the control volume as system output and as backfill or slippage. No work is done by or on the input fluid, although a small amount of entrance loss and flow energy conversion may be encountered.

APPLICATION COMPARISON

In general, a valid comparison can only be made in context with particular application requirements, operational parameters, and an evaluation of the type of compressor equipment presently serving the application. The flow work compressor technology will show greater advantage when operational requirements are the most demanding. Favorable comparison may be gained from some of the following properties.

1. Non-contaminating.

There are no reciprocating, rubbing or contact parts in the flow stream. Units can be completely sealed; either hermetically, or by using non-leakage shaft seals.

This feature is a major consideration for many applications in the chemical processing industry, for gaseous electric-discharge laser flow systems, for microchip processing vacuum systems, and for food industry freeze drying systems.

2. Thermally Efficient.

Working fluid temperature throughout the compressor remains nearly constant. No significant waste heat is generated, and problems and limitations associated with thermal distortion do not occur.

This feature is not present in any positive displacement compressor now available. It provides an inherent energy efficiency advantage that improves with compression ratio. The nearly uniform working fluid temperature is also an advantage in many CPI applications

3. Volumetrically Efficient.

High volumetric efficiency at high compression ratios is obtained from a favorable rotor geometry, and by minimizing the slippage passages between rotors and between rotor lobes and housing. Efficiencies of 90% or more can be readily achieved at compression ratios up to 10:1.

4. Quiet.

There is no significant pressure pulse into discharge. Slippage flow toward the intake may create some noise in the 400 to 1000 Hz frequency range, but is not expected to be troublesome. Port and recirculation flow velocities are less than mach 0.05. Rotor tip velocity is less than Mach 0.10.

5. Simple.

The inherent simplicity of the Root's type blower has been maintained. Fabrication is straight-forward and requires no new technology. Rotor geometry is involute and cylindrical, and can be readily generated by existing machine tools. Design is fully supported by present state drive train components and by current rotating machinery engineering practices.

6. Versatile.

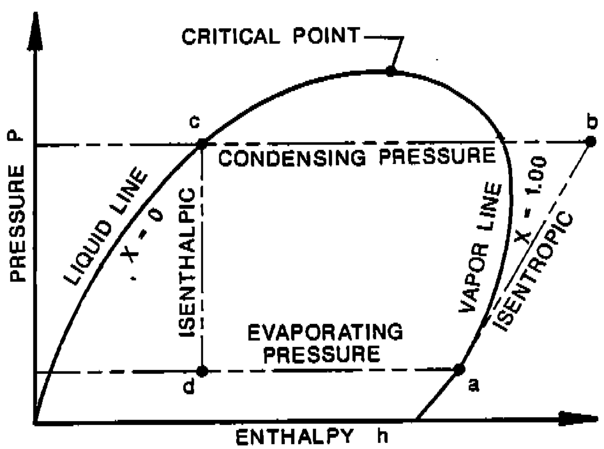
Compressor units based on this technology can accommodate a wide variety of gases and vapors. They can serve as high-volume, non-contaminating vacuum pumps, as air and other gas compressors, and as refrigerant vapor compressors. Volumetric input can range from 30 to 8,000 cmh, and discharge pressures up to 250 psig.

Refrigerant Vapor Compression.

This application presently utilizes reciprocating piston, helical screw, sliding vane, rotary piston, and in smaller sizes, scroll type positive displacement compressors. Flow work compression is readily adapted to the vapor refrigeration cycle, and can be used for all except small capacity units. Low slippage designs coupled with naturally-induced wet compression can achieve high efficiencies, even in the sizes (15-85 cmh) needed for domestic air conditioning.

In the typical refrigeration cycle, compression is isentropic. Refrigerant vapor at compressor output is superheated, and must be cooled before condensation begins.

Figure 3 shows a Pressure-Enthalpy diagram for a vapor refrigeration cycle based on isentropic (adiabatic) compression.



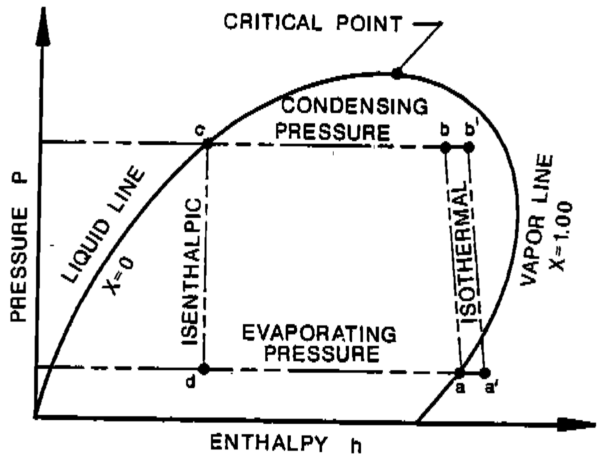
PRESSURE-ENTHALPY DIAGRAM
IDEAL REFRIGERATION CYCLE
ISENTROPIC COMPRESSION

FIGURE 3

When flow work compression is used, the cycle diagram is altered. Saturation temperature vapor leaving the evaporator is superheated in an input-output counterflow heat exchanger to within a few degrees of condensation temperature before entering the compressor. It is then fed into the recirculation system and mixes with output pressure fluid. Thermodynamic equilibrium is maintained through partial liquefaction induced by the increase in pressure. The recirculation system does not require an integrated heat exchanger.

In comparison with the present isentropic cycle, thermal load on the condenser has been reduced. Compressor output is at condensation temperature. It is already partly liquefied from the isothermal compression and from conversion of sensible to latent heat within the counterflow heat exchanger.

Figure 4 shows a Pressure-Enthalpy diagram for a vapor refrigeration cycle based on flow work compression.



PRESSURE-ENTHALPY DIAGRAM
IDEAL REFRIGERATION CYCLE
ISOTHERMAL COMPRESSION
FIGURE 4

Air and other Gas Compression.

This application is primarily served by the reciprocating piston, helical screw, rotary piston, and sliding vane type positive displacement compressors. Flow work compression of air can be provided by single units with from 40 to 4,000 cmh volumetric input and at discharge pressures ranging from 50 to 250 psig. By using dual staging above compression ratios of 5:1, volumetric efficiencies ranging from 90 to 95 percent can be maintained throughout the entire range of sizes and discharge pressures.

Dual staging may be done on single rotor shafts with only one input. The high pressure stage would be located away from the drive end, and would only be from 1/4 to 1/3 as long as the lower pressure stage. When compared with single stage operations this dual stage arrangement substantially lowers pressure drop across the drive end shaft seals. It also reduces bearing loads due to output-input pressure difference by a factor of 2.

Flow work compression of air is oil free, and requires no after-cooling. When the input air has a high enough moisture content, no heat exchanger is required in the recirculation system. Thermal stabilization would be maintained through partial liquefaction of the contained moisture when the air is raised to output pressure. For dry air this same effect can be obtained by raising the moisture content prior to compressor input.

Flow work compression of gases other than air would typically be done in completely sealed, closed-loop flow systems, with the contained fluid in continuum. Input pressure may be either above or below atmospheric. In this type of application an integrated heat exchanger in the recirculation system would probably be required to maintain thermal stabilization and temperature control.

Figure 5 shows a graph of predicted Volumetric Efficiencies versus Compression Ratios for typical 4-lobe and 6-lobe (low slippage) compressor units driven at 3450 rpm.

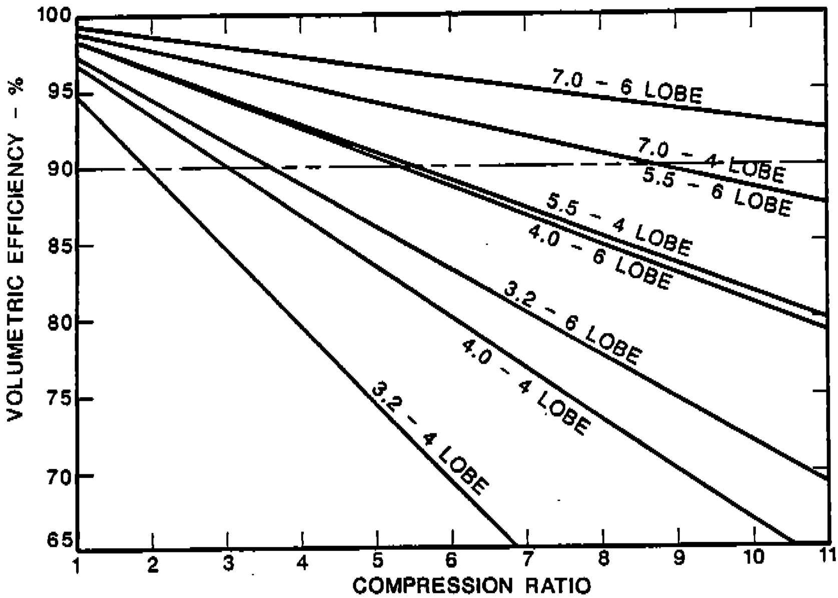


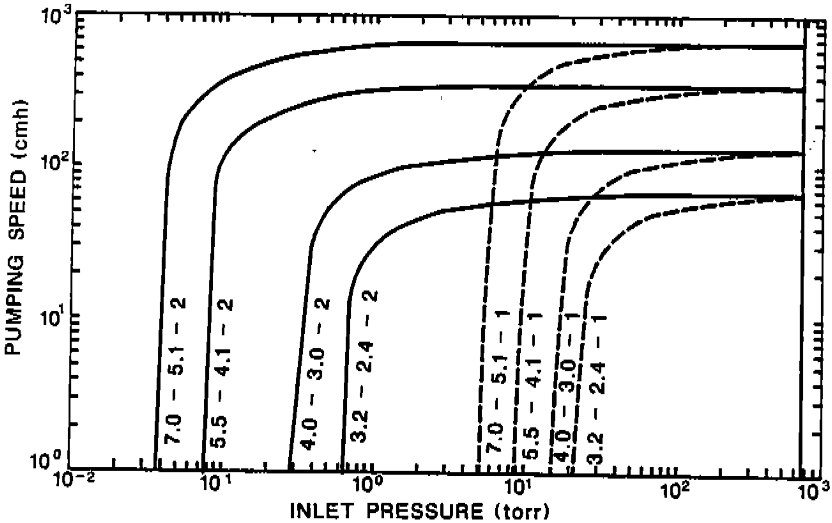
FIGURE 5

Evacuation and Sub-Atmospheric Compression.

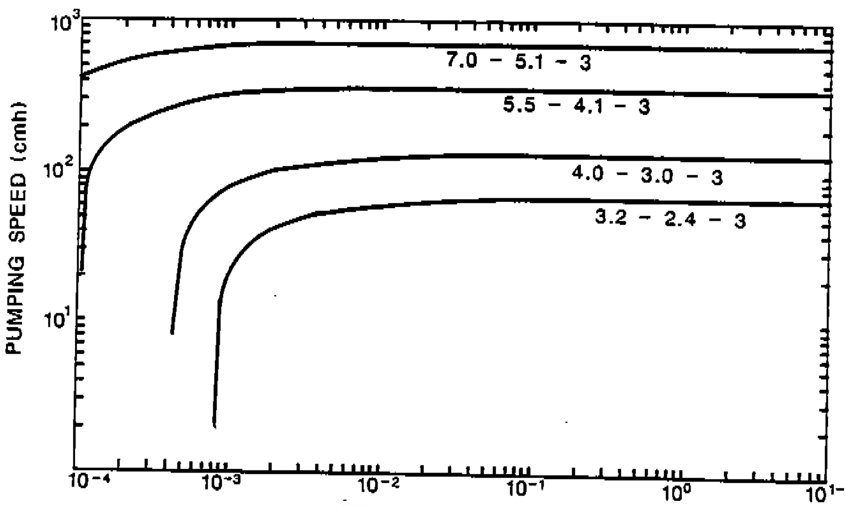
This type of application is presently served by reciprocating piston, sliding vane, rotary piston, liquid ring, and lobed rotor (Root's) type positive displacement compressors. Of these, only the Root's type blower is suitable for non-contaminating or dry vacuum service. It is normally used as a vacuum booster in combination with a rotary piston, liquid ring or sliding vane roughing pump. It is also used in multi-stage, single shaft arrangements for direct evacuation to atmosphere. Ultimate base pressures below 10 milli-torr can be obtained from five and six stage combinations.

Vacuum pumps based on flow work compression technology are inherently non-contaminating. In this application the 6-lobe low slippage design is particularly suited for smaller size units. Continuous operation can be maintained over a pressure range from atmospheric down to 1 micro-torr. Single unit volumetric input can range from 40 to 4,000 cmh. Ultimate base pressure obtained from 2 stages is in the molecular flow transition region. An additional stage would drop the base pressure below 1 milli-torr.

Figures 6 and 7 show predicted performance curves for smaller size units driven at 3450 rpm. These are based on using the 6-lobe low slippage design in single and multi-stage arrangements.



PERFORMANCE CURVES
SINGLE AND TWO-STAGE
FIGURE 6



PERFORMANCE CURVES
THREE-STAGE
FIGURE 7

STATE OF DEVELOPMENT

Flow Work Compressor technology is covered by utility patent number 4,859,158, entitled "High Ratio Recirculating Gas Compressor". The patent was issued on August 22, 1989. A second application entitled "Recirculating Rotary Gas Compressor" was filed on June 20, 1989 and assigned serial number 07/368,873. It broadens the coverage of the first patent for applications where no integrated heat exchanger is required. A continuation-in-part has been submitted to obtain specific coverage for the low slippage arrangement.

Industrial participation and support is required to carry out a broad-based development program and establish the technology in the major areas of application. Past efforts to gain participation by domestic compressor and blower manufacturers have not been productive to date. Further solicitation for support is being made to both public and private organizations who appear to have significant usage or market interests for the technology.

SUMMARY

Of all the present positive displacement compressor arrangements, only the Root's lobed rotor design is a suitable candidate for development as a flow work compressor. None of the other types appear to have a favorable geometry. The original Root's design can be readily adapted by adding recirculation ducts, intermediate refill ports, and additional rotor lobes.

Flow work compression is now in an early stage of development. However, the path to full development is level and straightforward, with no apparent obstacles or pitfalls. The technology is fully supported by existing manufacturing methods, machine tools, and assembly components. The nature of the required effort is primarily distinguished by application of good engineering design and production practices. No major technical breakthroughs are needed.

Products based on the technology are inherently quiet, non-contaminating, and in dynamic balance. When compared with present state devices and systems they indicate significant advantage from the standpoint of simplicity, performance capability, and overall efficiency in all three major areas of application. From the standpoint of design compatibility, many of the problems associated with adiabatic compression have been eliminated, without simultaneously creating any new difficulties.

Flow work compression has the potential to become the best possible method of moving gaseous fluids in many of the diverse applications considered. When fully developed, it can establish new levels of performance and efficiency that are not now attainable with present state-of-the-art products.