International Compressor Engineering Conference

School of Mechanical Engineering

2002

Reflux Gas Densification Technology An Innovative Dry Compression Process

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REFLUX GAS DENSIFICATION TECHNOLOGY
AN INNOVATIVE DRY COMPRESSION PROCESS

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ABSTRACT

All positive displacement gas compressors that gain pressure increase by volumetric reduction of a fixed mass are characterized by heat co-generation, often called “the heat of compression”. This co-generated heat penalizes efficiency, and is the cause of many design problems arising from thermal distortion and from high temperature levels in mechanical components.

In contrast, Reflux Gas Densification is based on a constant volume, variable mass cycle that is closer to isothermal in thermodynamic nature. The process is governed more by Dalton’s Law of Additive Pressures and by Newton’s Laws of Motion. Thermal effects in the flow stream are those primarily associated with gas flow dynamics. Co-generated heat has been reduced to a point where temperature increase in the working fluid does not cause design or performance limitations.

INTRODUCTION

When compressing gaseous fluids by volume reduction, co-generation of heat is intrinsic to the process. Efforts to mitigate it include cooling the process gas as it passes through the compressor, and the use of multistage compression with cooling between stages. The initial concept for reflux gas densification was based on inserting a heat exchanger into the flow stream after discharge, and refluxing back into constant volume displacement cavities.

The first attempt to demonstrate the concept failed to show any improvement in process fluid discharge temperature level. After much study, it became evident that refluxing could only be done while displacement cavity volume remained constant. Subsequent design and development effort has been directed toward methods of refluxing while maintaining constant displacement volume, maximizing cavity pressure at refill closure, and minimizing reflux flow loop pressure drop.

The change from a variable volume to a constant volume process brought about a major change in thermodynamic nature. Disregarding any kinetic energy effects, heat co-generation for a variable volume compression process is determined by the specific heat ratio of the process fluid. The process requires the maximum amount of frictionless work for a given pressure ratio. The reflux gas densification process is theoretically isothermal, and there is no intrinsic co-generated heat. The process requires the minimum amount of frictionless work for a given pressure ratio.

BACKGROUND

The concept for Reflux Densification came from a study of the Roots blower carried out at the Los Alamos National Laboratory in support of a research program requiring non-contaminating gas compression in an experimental flow system. The study also covered modified versions incorporating cooled reflux to reduce the temperature level at discharge. Upon evaluation, performance of these fell far short of expectations. A concept for improving the reflux arrangement was identified from the study.

The concept was disclosed to the Laboratory. However, further development fell beyond the needs of the supported program, and the invention was released by the Department of Energy through a waiver of patent rights. It is the subject of four utility patents issued by the United States Patent Office. The technology has had little relevant operational history or analogy to draw on, and development activity has been directed toward proof-of-principle demonstration and the collection of supporting data to provide the basis for engineering and design.

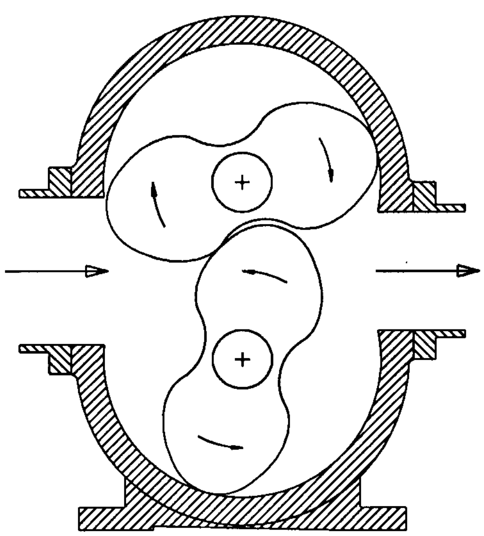
DESCRIPTION

The densifier design consists of a pair of involutely lobed rotors driven in opposing directions through a pair of timing gears. These feed intake pressure process fluid into an integrated reflux flow loop operating at discharge pressure. Reflux is directed into displacement cavities after intake completion, and is closed off immediately prior to discharge. By this means the pressure differential at discharge subject to compression by volume reduction is held to a very low level.

Constant volume displacement is maintained from intake through to discharge, a key design feature adopted from the Roots blower. Slippage or backfill is limited by design features, and by sonic choking. There are no valves and no contacting or rubbing parts in the flow stream to contaminate the process fluid. The physical design can accommodate high discharge pressure and high input shaft power.

The present design does not include a means for heat removal during the process. The arbitrarily set performance goal for the development effort was to obtain a pressure increase ratio of 10:1 within a temperature level increase of 100 degrees F (55.6 degrees C) from intake to output for an air cycle. From experimental evidence and from math model projections, that goal appears to be attainable.

Figure 1 displays a cross section of a Roots type lobed rotor compressor in simplified form, and lists the pros and cons of the process as well as design features essential for reflux densification. The basic design has remained unchanged since it was first introduced to industry in the mid 1850s. The transverse flow arrangement and constant volume displacement from intake through to discharge are design features that make Reflux Gas Densification possible.



Advantages

Simple and rugged design
No valves and no contacting or rubbing parts.
High volumetric input

Disadvantages

High “heat of compression” levels
Limited pressure ratio input
Very noise polluting
Poor volumetric efficiency

Requisite Design Features

Transverse Flow
Constant volume displacement
No process fluid contamination

Figure 1
ROOT'S BLOWER

Figure 2 displays a cross section of a six-lobe reflux gas densifier in simplified form. A reflux flow loop has been added to reduce the pressure differential at discharge. Rotor lobes have been added to make reflux more effective and to improve volumetric efficiency.

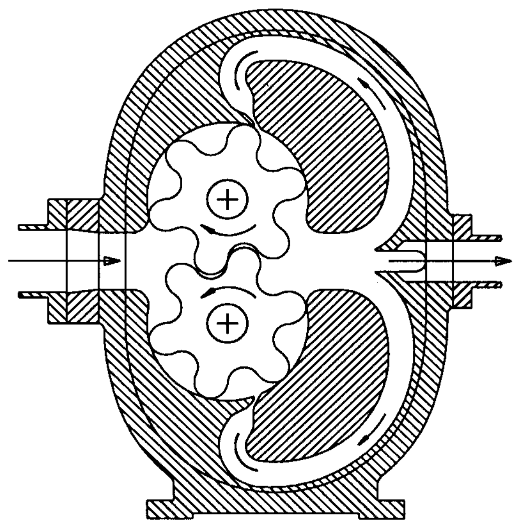


Figure 2
REFLUX DENSIFIER

Advantages

Simple and rugged design
No valves and no contacting or rubbing parts.
High volumetric input
Low heat co-generation. Near isothermal cycle.
High pressure ratio-capacity.

Disadvantages

High volumetric efficiency difficult to obtain for small displacements.

Requisite Design Features

Transverse flow
Constant volume displacement
No process fluid contamination

Figure 3 displays the densifier flow paths and terminology used in math modeling, design study, and cycle sequence description.

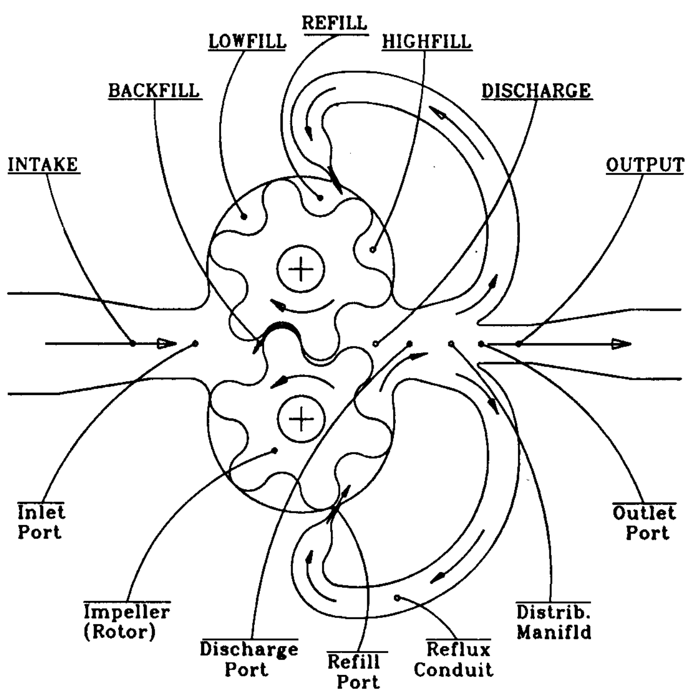


Figure 3

FLOW PATHS AND TERMINOLOGY

Low impedance is a prevailing consideration throughout the flow loop design. Flow velocities of Mach 0,05 or lower are maintained from the discharge port through the distribution manifold and the reflux conduits. Conduit width is equal to rotor length. Conduit depth and reflux flow area are uniform up to the refill port, where the depth converges to form a linear nozzle,

For pressure ratios above critical, the refill nozzle throat will flow at sonic velocity until cavity pressure rises to the critical level, then fall off to slightly above rotor tip speed at refill closure. The use of linear nozzles serves to keep volumetric change to a minimum as displacement cavities pass by refill ports.

CYCLE SEQUENCE

Backfill

Backfill or slippage is fluid mass freely expanding back from discharge into the intake region through rotor mesh and rotor end-to-housing clearances. It acts as a partial pressure already within the displacement cavity when it is open to the intake port. Backfill is limited by design features and by sonic choking, and varies with pressure ratio.

Intake

Fluid mass entering through the intake port is the primary source of initial cavity charge. It acts as an additive pressure to that of backfill, and brings cavity pressure up to suction line level. An intake adapter converts suction line geometry to a rotor length equivalent area passage.

Lowfill

The lowfill state is established when backfill and intake fluids are mixed together and come to thermal equilibrium at intake pressure. The ratio of backfill to intake mass determines volumetric efficiency.

Refill

The refill port is part of the reflux system flow loop. As a displacement cavity opens to the port, additional mass circulated back from discharge flows in through the refill port and freely expands into the cavity. At refill completion, total cavity pressure is due to the pressure from mass already contained within the cavity and the additive pressure component from reflux.

Highfill

The highfill state is established when the reflux fluid is mixed together with the fluid already contained within the cavity and comes to thermal equilibrium. Dynamic effects associated with flow loop impedance, refill port configuration, non-ideal process fluid properties, and a fixed rotor geometry all contribute to the amount of pressure drop from the discharge to the highfill state.

Discharge

After refill closure, displacement cavities open into discharge. The contained process fluid is compressed from highfill to discharge pressure, with an associated reduction in volume and rise in temperature. Discharge over intake temperature increase is a product of the temperature difference between highfill and discharge and the pressure ratio of discharge to intake pressure.

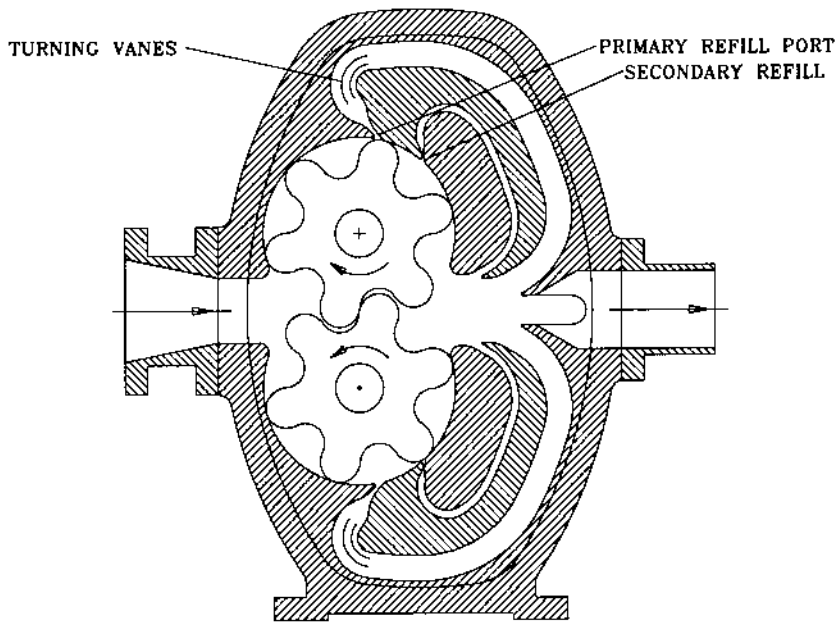
Discharge Distribution

From the discharge region, backfill mass flows back to the intake region through rotor-to-rotor and rotor-to-housing clearances. Reflux and output mass flows through the discharge port into the distribution manifold. Reflux mass is directed back through the reflux flow loop conduits, and output mass exits the densifier through the outlet port.

DESIGN EVOLUTION

Including the original concept, there have been four major design iterations to this point. The first was based on a four lobed rotor configuration, with an integral heat exchanger placed in the flow loop. The second iteration adopted a six lobed rotor configuration to improve volumetric efficiency. The third iteration incorporated linear nozzle refill ports to better maintain constant volumetric displacement, and eliminated the integral heat exchanger.

The fourth iteration moved the primary refill ports forward toward intake and added secondary refill ports to extend the time available for refluxing. Turning vanes were also added in the reflux loop. Figure 4 displays a cross section of the reflux densifier with secondary refill ports added.



<u>Figure 4</u>

EXTENDED REFLUX DENSIFIER

PERFORMANCE

Figures 5 and 6 display graphs of performance comparisons between volumetric compression and reflux densification. Theoretical graphs are based on an ideal frictionless process fluid with a 1.40 specific heat ratio, 100% volumetric efficiency, no heat transfer in or out, and no mechanical losses. Actual or realistic graphs are based on projected performance of a reference compressor or densifier design having mechanical and volumetric efficiency losses but no heat transfer.

The Figure 5 graphs show the theoretical and actual discharge temperatures for both cases from an inlet temperature of 72 deg. F. (22 deg. C). Densifier performance projections are based on a 95% displacement cavity fill completion. Volumetric compression projections are based on the same unit, without reflux. They do not take into account performance limitations imposed by the temperature increase.

The Figure 6 graphs display theoretical and actual net efficiencies for both cases, referenced to the theoretical frictionless isothermal work requirement.

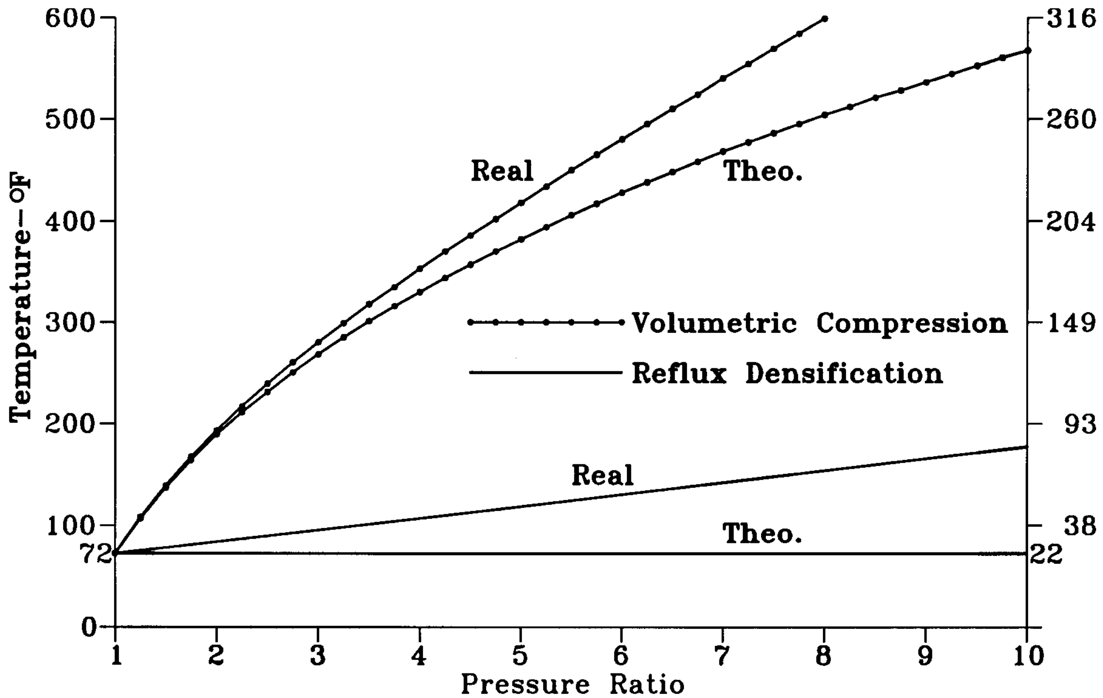


Figure 5

DISCHARGE TEMPERATURE

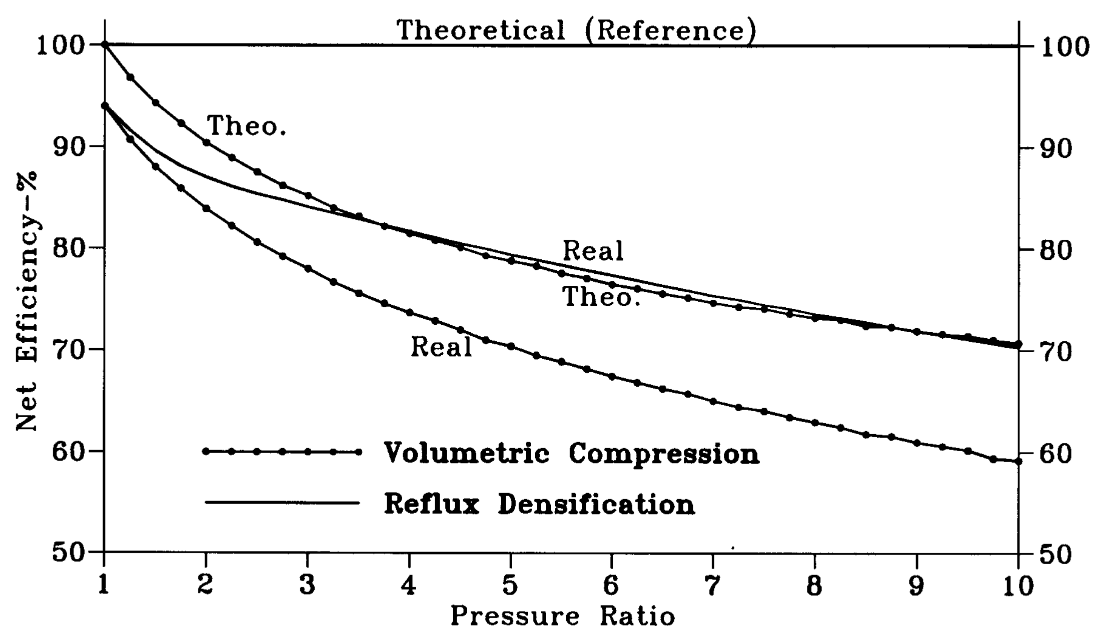


Figure 6

NET EFFICIENCY

APPLICATION CONSIDERATIONS

Many features of the densifier design were carried over from present state lobed rotor compressors. In the absence of relevant operational history, arbitrary limits have been placed on rotor tip speeds and on reflux flow loop velocity. The large improvement in pressure ratio capability is largely the result of close tolerance in rotor running clearances made possible by the reduction of co-generated heat.

High volumetric efficiency is achieved by sonic choking at pressure ratios above critical (about 2:1), by the addition of barrier lobes to carry perimeter slippage forward into discharge, by limiting rotor mesh clearances, and by limiting rotor end face to housing clearances. Small displacement units may require sacrificial coatings on adjacent housing end faces.

Bearing Loads

The transverse flow arrangement produces a radial load on rotor bearings in the direction of the intake side. Rotor timing is achieved by straight spur gearing that does not produce thrust, resulting in very low axial bearing load components.

Oil lubricated spherical roller bearings support the rotors and maintain alignment. The input bearings are fixed in axial position within the rotor housing to maintain end face clearance. The opposite end bearings are allowed to float axially to adjust for any thermal expansion difference between rotor and housing. This difference is minimal, since the temperature difference between rotor and housing is low.

Single Unit Sizes

In general, the upper size limit for densifiers will be determined by tradeoff between the difficulty of fabricating large massive units driven at lower speeds, and using smaller units piped in parallel to meet high volumetric input requirements. The following sizes are based on holding to a range of rotor pitch diameters from 4 to 16 inches (100 to 400 mm).

Single unit displacements can range from 0.10 lpr (liters per revolution) to more than 60 lpr.

Single unit pump speeds can range from 0.20 cmm (cubic meters per minute) to more than 75 cmm.

Large displacement single units with low intake pressure (i.e.- 20 bar and below) can operate at pressure ratios up to 10:1.

Small displacement units with high intake pressure (i.e.- 80 bar and above) can only operate at lower pressure ratios as determined by allowable bearing loads, (i.e.- possibly not more than 2.5:1).

Staging

The transverse flow arrangement and the rugged rotor design with large solid center section permit an in line arrangement for two or three stages, joined together by flexible couplings and driven from a single ower source. By placing the largest unit first in line and the smallest last, reduction in torque is matched with diminishing rotor size.

This arrangement is suitable for compressing from a suction line pressure of 20 bar up to 300 bar in two stages, and compressing from a suction line pressure of 2 bar up tp 300 bar in three stages. In either case the footprint area is relatively small. Rotor shaft diameters are suitable for transmitting the power required to drive all stages.

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CLOSING COMMENTS

The Reflux Gas Densification cycle and the Reflux Densifier design have evolved together and are interdependent. Together they can reduce heat co-generation associated with positive displacement compressors to a level where it no longer represents a design or performance limitation. The resulting process is non-contaminating, near-isothermal, and fundamentally more efficient.

The design is scalable over a wide range of operating parameters, and can be applied wherever gases or vapors must be compressed. Studies of potential applications have included single unit pressure ratios up to 10:1, single unit displacements of from 0.10 lpr to 60 lpr, single unit pumping speeds of from 0.2 cmm to 75 cmm, and discharge pressures from staged units up to 300 bar.

The reflux flow loop arrangement in the present design has evolved without the benefit of relevant analogy or operational history, and without extensive research and development. Information obtained from a broader development effort can be expected to further improve performance as operational results are obtained and a strong, empirically derived design base is established.

The immediate motivation for developing and deploying this technology is to remove a major barrier to public acceptance for the adoption and use of natural gas as a primary ground-based vehicle fuel. The physical arrangement and operational characteristics of the reflux densifier are particularly well suited for the compression of natural gas for CNG vehicle refueling.

Successful development will also provide a key element of technology needed to support and enable a gradual transition from hydrocarbon to hydrogen based vehicle fuels. The technology base required for natural gas infrastructure systems is also fully applicable for gaseous hydrogen systems. While still in abundant supply, natural gas can serve as a bridge fuel during the lengthy development period.

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Filed on May 27, 2000