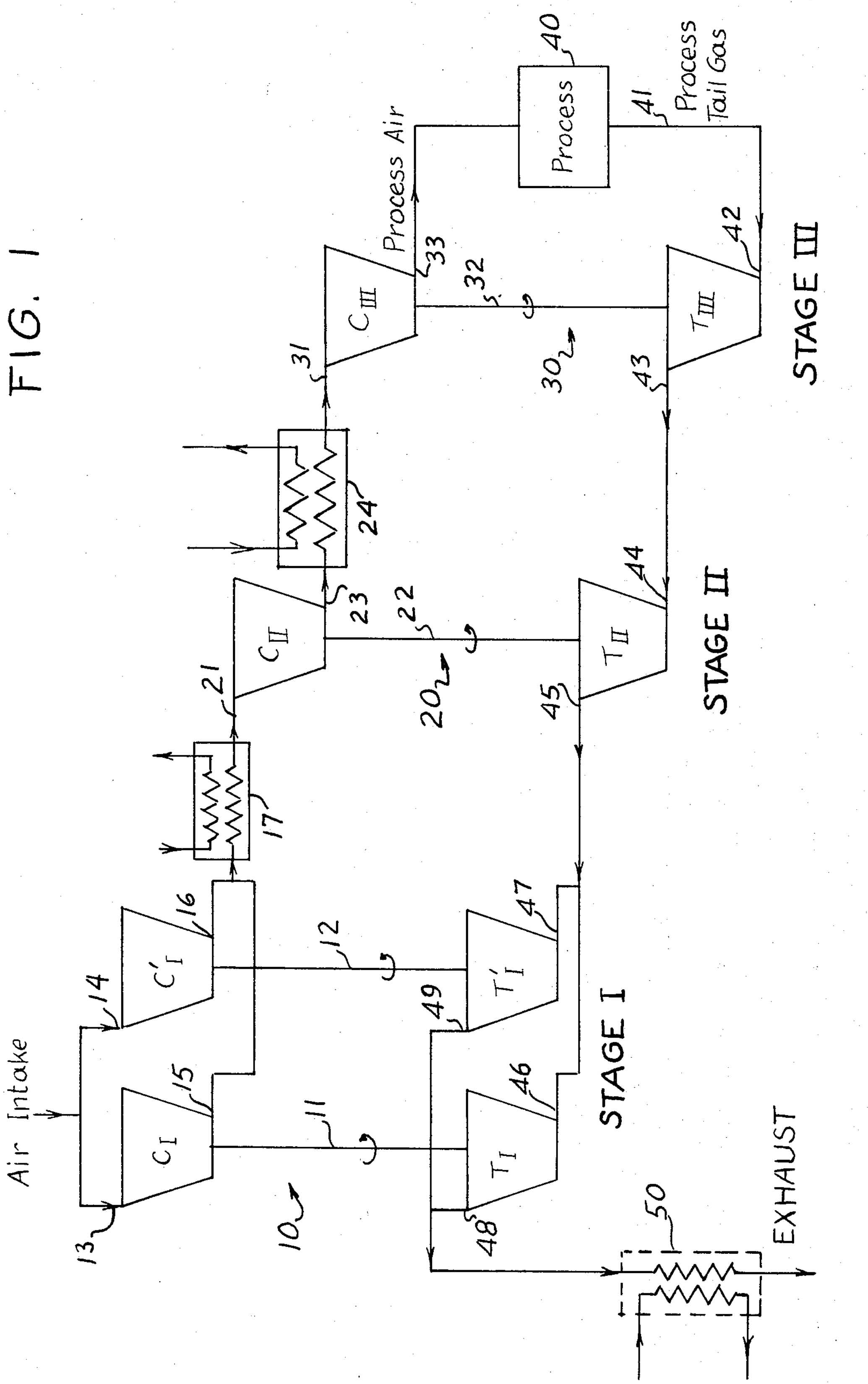
MULTIPLE STAGE GAS COMPRESSION APPARATUS AND METHOD

Filed Sept. 10, 1971

FIG. 1



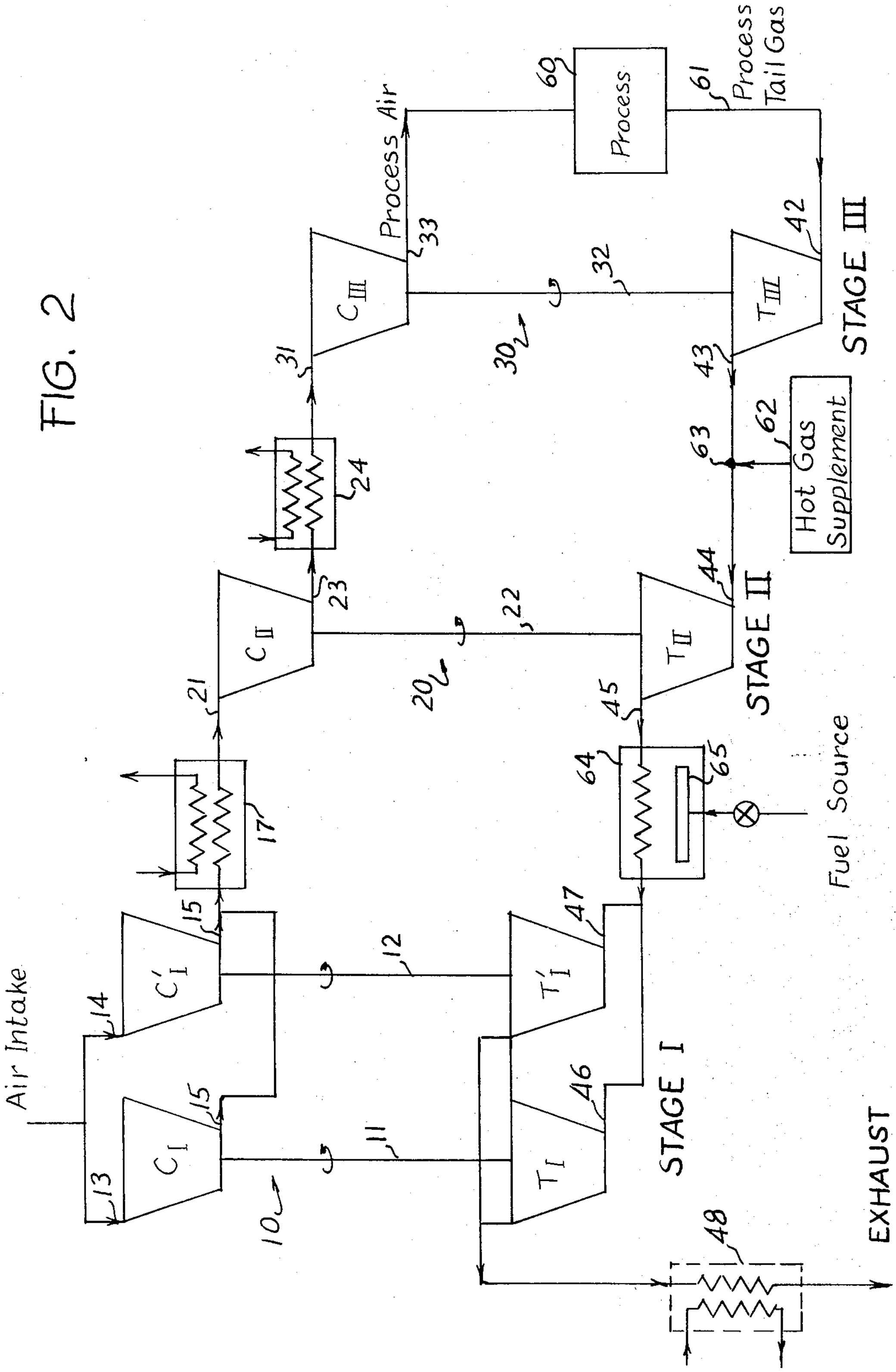

Process
Process Air
Process Tail Gas
Hot Gas Supplement
Fuel Source
Air Intake
STAGE I
STAGE II
STAGE III
EXHAUST

FIG. 2

MULTIPLE STAGE GAS COMPRESSION APPARATUS AND METHOD

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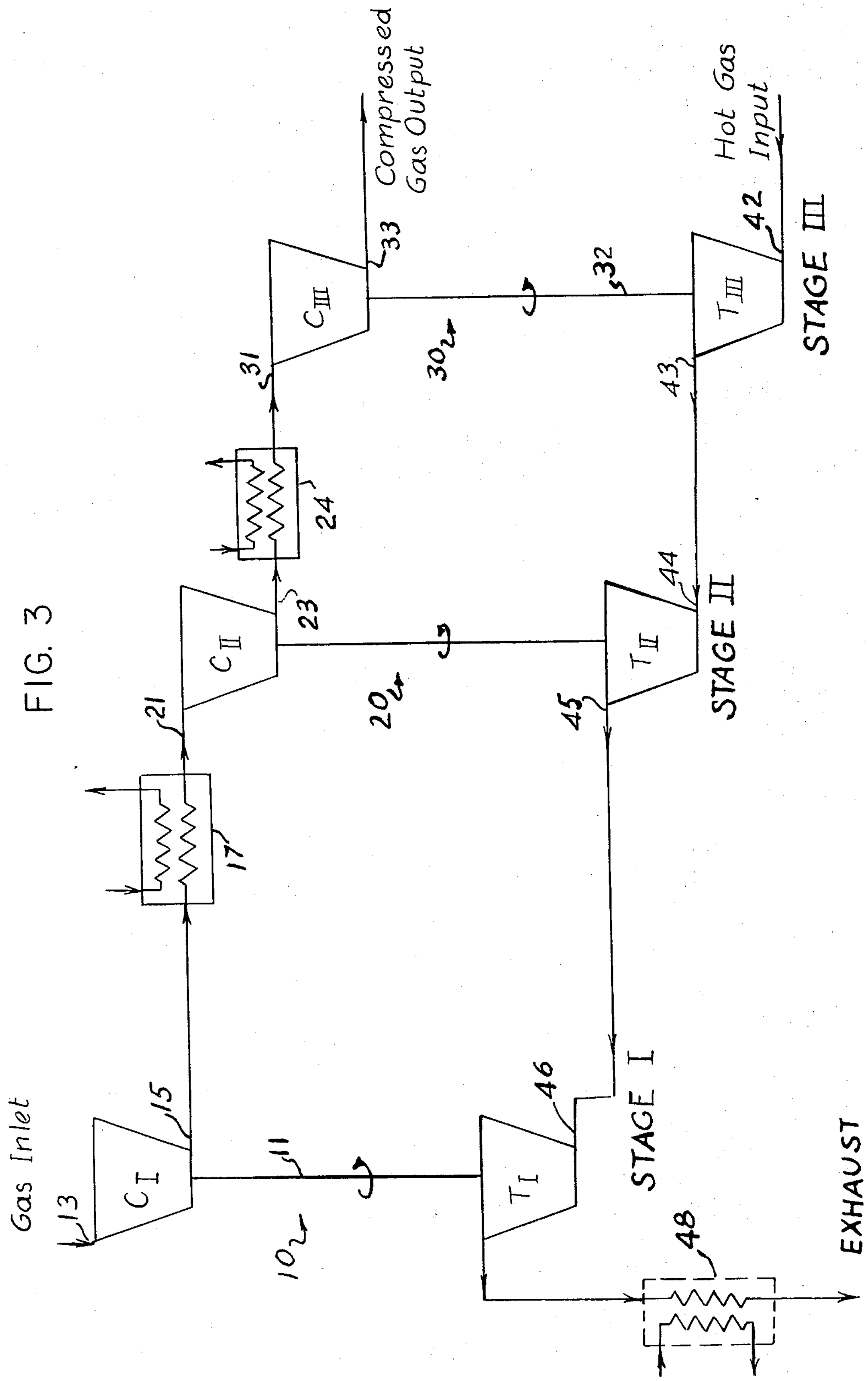

FIG. 3

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MULTIPLE STAGE GAS COMPRESSION APPARATUS AND METHOD

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U.S. Cl. 60—59 T 10 Claims

ABSTRACT OF THE DISCLOSURE

Gas compression apparatus and method in which gas compression occurs in a series circuit including two or more gas compression stages in which each of the compression stages is independently driven by a corresponding number of separate gas expansion stages which are connected in series to a source of heated gas. Each of the individual compression-expansion stages may comprise a separate turbocharger. The gas expanders obtain power from a source of hot gas applied in series circuit commencing with the expander driving the compression stage having the greatest discharge pressure and ending with the expander driving the compression stage having the lowest discharge pressure.

This invention relates in general to gas compression and in particular to multi-stage compression of a first gas stream with energy derived from a second gas stream.

The need to supply a quantity of gas at a pressure exceeding the normal or ambient pressure of the gas has provided many prior art expedients for accomplishing such gas compression, with the conventional centrifugal gas compressor being but one example of such prior art gas compression devices. The conventional centrifugal compressor generally has a fixed compression ratio expressed as the ratio of the discharge or outlet pressure to the suction or inlet pressure, and it becomes necessary to utilize two or more of stages of compression where it is required to increase the pressure of a gas by an amount which exceeds the compression ratio of the available compressor.

It is conventional in such circumstances to accomplish compression with two or more centrifugal compressors connected in series, so that the pressurized gas discharged by a first compression stage is connected to the inlet of a second compression stage, and so on. Such multi-stage compressors in the prior art have been conventionally driven by a suitable prime mover such as an electric motor, a steam turbine, a hot gas expansion turbine, or the like, with each compressor stage being mechanically linked to the prime mover and thus to every other compressor stage either by being mechanically connected to a common drive shaft or with another type of mechanical interconnection such as a gear drive or the like.

A well known prior art gas compression apparatus is the conventional turbocharger, wherein one or more centrifugal compressor stages or radial flow wheels are mechanically driven by a common drive shaft which is rotated by a turbine or hot gas expander, such turbochargers typically being used in conjunction with gasoline or diesel engines wherein air supplied to the intake manifold of the engine is compressed by means of energy extracted from the exhaust gases of the engine passing through the turbine or expander section of the turbocharger.

When the compression pressure requirements call for two or more stages of compression, multi-stage gas compression has been typically accomplished in the prior art with mechanically connected compression stages

wherein a single prime mover is connected to drive the necessary number of compression stages. Since each one of the multiple compression stages has a particular operating speed of optimum efficiency as determined by the operating parameters of the particular stage, the use of a prime mover common to all of the compression stages forces some or all of the compression stages to be operated at a speed other than the optimum speed for such stages, thus detracting from the overall efficiency of the multi-stage compression system. Prior art efforts to overcome this compromise in the operating speed of commonly-driven multi-stage compressors have generally involved either compressor wheels specially designed for the rotational speed dictated by the prime mover, or else have required variable-speed drive mechanisms interposed between the prime mover and at least some of the compression stages. The added expense, complexity, and other problems associated with such efforts have substantially or completely detracted from the benefits gained by optimizing the operational efficiency of each compression stage.

Accordingly, it is an object of the present invention to provide an improved multi-stage compression apparatus and method.

It is another object of the present invention to provide an improved multi-stage gas compression apparatus and method in which each compression stage operates independently of all other compression stages.

It is yet another object of the present invention to provide an improved gas compression apparatus and method wherein compression of gas in a first stream is accomplished by energy obtained from expansion of gas in a second stream.

It is a further object of the present invention to provide an improved gas compression apparatus and method in which each of the several stages is permitted to assume an independent operating balance within the overall gas compression system.

Other objects and many of the attendant advantages of the present invention will become more readily apparent from the following description of the preferred embodiments of the invention in which:

FIG. 1 is a schematic diagram showing gas compression according to a first embodiment of the present invention;

FIG. 2 is a schematic diagram showing gas compression according to a second embodiment of the present invention; and

FIG. 3 is a schematic diagram showing gas compression according to a third embodiment of the present invention.

According to the present invention, multi-stage compression of a gas is achieved by using two or more series connected stages of separate gas compressors none of which is mechanically linked to another. Each individual stage of gas compression is separately driven through a mechanical connection with a corresponding individual gas expander, none of which expanders is mechanically linked to any of the other expanders. The gas expanders receive operating power from a suitable stream of hot gas connected to establish a series gas expansion circuit through all of the gas expanders, with the initial expansion stage occurring in the gas expander which drives the gas compressor having the highest discharge pressure in the compression series circuit and with the other gas expanders being similarly arranged in the series circuit so that the final expansion of the hot gas occurs in the gas expander which drives the gas compressor having the lowest discharge pressure in the compression series circuit.

More particularly, and with reference taken to the embodiment of the present invention schematically depicted in FIG. 1, there is shown a three-stage gas compression system having a first stage **10**, a second stage **20**, and a third stage **30**. The first stage **10** includes a compressor C_I, having a compressor inlet **13** and a compressor outlet **15**, and a compressor C'_I having an inlet **14** and an outlet **16**. The inlets **13** and **14** are connected in parallel to a suitable source of gas to be compressed, this source being ambient air in the embodiment of FIG. 1, and the two outlets **15** and **16** similarly are connected in parallel as shown therein, so that compression in the first stage **10** actually occurs through two compressors connected in parallel, this arrangement being for a reason discussed below.

The compressor C_I is a centrifugal compressor which may include one or more compressor wheels mounted for rotation by a drive shaft **11** which in turn is driven by a suitable gas expander T_I, which may be a conventional expansion turbine. Similarly, the compressor C'_I is driven by a drive shaft **12** and a gas expander T'_I. Each of the compressor-expander combinations C_I–T_I and C'_I–T'_I, as well as the other compressor-expander stages used in the embodiments disclosed herein, may be provided by conventional turbochargers in which the compressor stage and the expander or turbine stage are mounted on a single shaft and are contained within a single overall housing, with suitable inlets and outlets for the compression and expansion portions of the turbocharger.

The paralleled gas stream provided by the two compressor oulets **15** and **16**, constituting the output of the first stage in the multi-stage series compression circuit, is connected to pass through a suitable intercooler **17** and is then supplied to the inlet **21** of compressor C_{II} in the second stage **20**. The design and operation of intercoolers such as **17** are known to those skilled in the art and are discussed in detail herein. Compressor C_{II} is driven by a drive shaft **22** and a gas expander T_{II}, and this compressor-expander stage may, as noted above, be provided in actual practice by another turbocharger.

The twice-compressed gas from the second stage **20** leaves the outlet **23** of compressor C_{II} and is connected to flow through a second intercooler **24** and then to be supplied to the inlet **31** of compressor C_{III} of the third stage **30**. The compressor C_{III} is driven by a drive shaft **32** connected to a gas expander T_{III}, and this compressor-expander stage also may be provided by a conventional turbocharger.

It is apparent from the description thus far that the embodiment depicted in FIG. 1 includes a three-stage series gas compression circuit including a low-pressure stage **10**, an intermediate-pressure stage **20**, and a high-pressure stage **30**.

The high-pressure air available at the output **33** of the compressor C_{III} is used in the described embodiment as process air for the operation of a process which is indicated at **40** and which produces a substantial quantity of hot output or tail gas available at outlet **41** of the process. A more detailed example of such a process is set forth below. The tail gas provided by the process **40** is connected to the inlet **42** of the third stage turbine T_{III}, thereby providing the power to drive the high-pressure compressor C_{III}.

The hot gas which is exhausted from the outlet **43** of the expander T_{III} is supplied to the inlet **44** of the second stage expander T_{II}, thereby to provide the power required for driving the second stage or intermediate-pressure compressor. The hot gas exhausted from the outlet **45** of T_{II} then is supplied in parallel connection to the inlets **46** and **47** of first-stage expanders T_I and T'_I, respectively. The gas exhausted from the outlets **48** and **49** of the two paralleled first-stage expanders may be passed through a heat exchanger **50** for useful extraction of the heat remaining in the gas and then passed to a suitable exhaust.

It can be seen that the three stages of gas expansion are connected in series circuit with the supply of tail gas which powers these expanders. The highest pressure stage in the series gas compression circuit is driven by the expander which is supplied with gas having the greatest available enthalpy. Thus, the multi-stage series compression circuit, ranging from the low-pressure stage **10**, which receives ambient air for an initial compression, through the intermediate-pressure stage **20**, to the high-pressure stage **30**, is driven by individual gas expanders which are connected in a series circuit in which the first expansion of the available tail gas individually provides power for the high-pressure compression stage **30**, the next expansion of the tail gas individually provides power for the intermediate-pressure compression stage **20**, and the final expansion of the tail gas individually provides power for the low-pressure compression stage **10**. This arrangement of accomplishing multi-stage compression in separate compression stages individually driven by separate corresponding gas expansion stages, with the gas expansion series circuit going from high enthalpy to low enthalpy in a direction inverse to the progression from low pressure to high pressure in the series gas compression circuit, enables each stage of compression to be free to operate at an optimum speed for that stage and permits power balance to be maintained between all stages when a suitable source of gas input is available for the expansion series circuit.

A typical example of air compression according to the embodiment of FIG. 1 is found in the requirement for the manufacture of nitric acid, which can be considered as an example of the process **40**. In a plant designed to produce 220 tons per day (t.p.d.) of nitric acid, there is a requirement for 20,600 s.c.f.m. of process air at a pressure, for example, of not less than 120 p.s.i.g., and at a temperature of approximately 270° F. The waste or tail gas resulting from such manufacture of nitric acid comprises approximately 74,800 pounds/hour of tail gas comprising essentially nitrogen and available at a pressure of approximately 95 p.s.i.g. and a temperature of around 1200° F. Through the use of three independent series-connected stages of compression as described above, ambient air can be compressed to the required pressure and temperature conditions with suitable intercooling between stages. The volume of air required in this example necessitates the use of two parallel-connected compressors in the first stage of compression to enable commercially available turbochargers to be used in place of a more expensive specially designed single compressor unit which would handle the requisite volume of air. Moreover, the entire power requirements for the three-stage compression of ambient air to provide process air for the nitric acid manufacturing process are obtained by extracting energy from the available tail gas through the three-stage expansion of such gas in the expanders T_{III}, T_{II}, and the parallel-connected expanders T_I and T'_I.

Providing a more specific example of gas compression provided by expansion of the tail gas in the above-described nitric acid manufacturing process, the first compression stage **10** is provided by a pair of turbochargers manufactured by the De Laval Turbine Company and designated as model C17–123. The second stage **20** is also provided by a turbocharger model C17–123, while the third stage **30** is provided by a De Laval turbine model C13–060. The following parameters for compression and expansion result from such a system:

COMPRESSOR DATA

	1st stage (two units)	2nd stage	3rd stage
Flow, lbs./sec	25.98	25.98	25.965
Inlet pressure, p.s.i.a	14.6	30.56	63.96
Inlet temperature, ° F	75	100	100
Discharge pressure, p.s.i.a	31.16	64.36	134.7
Discharge temperature, ° F	235	268	268
Speed, r.p.m	14,000	14,000	17,600
Pressure ratio	2.134	2.106	2.106
Moisture, lb./lb. of dry air	0.011	0.011	0.0095
Barometric pressure, p.s.i.a	14.6		
Unit size	C17–123	C17–123	C13–060

EXPANDER DATA

	1st stage (two units)	2nd stage	3rd stage
Flow, lbs./sec	20.64	20.64	20.64
Inlet pressure, p.s.i.a	31.0	59.0	109.7
Inlet temperature, ° F	824	1018	1200
Exhaust pressure, p.s.i.a	15.08	31.2	59.1
Exhaust temperature, ° F	638	824	1018
Speed, r.p.m	14,000	14,000	17,600
Unit size	C17	C17	C13

It will be understood from the foregoing description of the embodiment depicted in FIG. 1 that gas compression according to the present invention is not limited to the three stages of gas compression depicted therein, but generally includes gas compression having two or more independent compression stages each of which is independently driven by a separate gas expander, with the expanders connected in a series gas expansion circuit progressing from the expander to which the high-pressure hot gas is applied and which is connected to drive the highest-pressure compressor stage, to the final expander in the series gas expansion circuit which is connected to drive the lowest-pressure compression stage. It will similarly be apparent that the use of two (or more) compression-expansion stages in parallel to constitute a particular compression stage is employed for the specific requirements of the foregoing embodiment and is not considered to be a limitation on the present invention.

Although the foregoing embodiment was described in the context of providing a source of process air for a process which generated tail gas sufficient to provide the entire power requirements for the air compression, a modification of the present invention may be used to provide compression of air or other gases used in a process the tail gas output of which is insufficient to provide the entire compression power requirements. Referring now to FIG. 2 of the drawing, there is shown a three-stage air compression series circuit which is substantially identical on the compression side with the apparatus of FIG. 1 and which provides process air to a process which is indicated at **60** and which is assumed to provide an output **61** of tail gas inadequate to provide the entire power requirements for driving the several compression stages. The enthalpy in the expansion series circuit may be supplemented, for example, by applying an auxiliary source of hot gas as shown at **62** to the junction **63** located upstream of the inlet **44** to the expander T_{II}. The source **62** of supplemental hot gas can be any suitable source, such as tail gas from another process or gas from a gas generator provided expressly for supplementing the series expansion gas stream, which provides gas at a temperature and pressure compatible with the gas stream exhausted from the outlet **43** of expander T_{III}.

Further by way of example in supplementing the enthalpy of the expansion series circuit for driving the compressors, the gas exhausted at the outlet **45** of the expander T_{II} passes through a suitable reheating apparatus **64** including a burner **65** fed by an appropriate fuel source to add heat energy to the series expansion gas stream supplied to the inlets **46** and **47** of the expanders T_I and T'_I.

Although augmentation of the energy available in the series expansion gas circuit is shown in FIG. 2 as being applied to two of the three stages therein, it will be understood that such augmentation may be required at only a single one of these stages or at all expansion stages, depending upon the power requirements of each compression stage and the enthalpy of the tail gas output from the process **60**, to enable all stages of the system to operate in an independent balanced manner. Moreover, it will be apparent that the illustrated use of different techniques for augmenting the enthalpy of the gas stream flowing in the gas expansion circuit of the embodiment depicted in FIG. 2 is by way of example only, and that the same type of augmentation, such as the hot gas sup-

plement **62**, could be used to provide expansion gas augmentation to the turbine inlets **46** and **47** as well to the turbine inlet **44**.

While the present invention has been described thus far in conjunction with operating processes which produced an output or tail gas having sufficient enthalpy to supply partial or complete power requirements for gas compression, the present invention as shown in the embodiment depicted in FIG. 3 may also be used in applications where the hot gas input to the expansion series circuit is derived independently of the gas compression circuit. The compression circuit in the embodiment of FIG. 3 may, for example, be used as part of a refrigeration system to compress gaseous ammonia. The first stage **10** of the FIG. 3 embodiment is shown as requiring only a single compression-expansion unit since, as described above, the use of two (or more) parallel-connected units is a function of the volume requirements of the gas being compressed.

The compressed gas exiting the outlet of high-pressure compressor C_{III} is available as the compressed gas output to be furnished to a suitable utilization apparatus, such as the next operational stage in a refrigeration system. Similarly, the inlet **42** of the first expansion turbine T_{III} is supplied with hot gas from a hot gas input which may, for example, be provided partially or completely by tail or waste gases from some process unrelated to the compressed gas provided by the compression series circuit. The enthalpy of the gas stream supplied to the other turbines T_{II} and T_I in the series expansion circuit may be augmented as necessary.

It should be understood, of course, that the foregoing disclosure relates only to preferred embodiments of the present invention and that numerous modifications or alterations may be made therein without departing from the spirit and the scope of the invention as set forth in the appended claims.

What is claimed is:

1. Apparatus for the simultaneous compression of a first gas stream and expansion of a second gas stream, comprising in combination:

at least a pair of separate individually operative compressor-expander means, each of said compressor-expander means having a compressor portion operative to receive and to compress gas in said first gas stream and also having an expander portion operatively coupled to operate said compressor portion and operative to receive and to expand gas in said second gas stream;

a first one of said compressor-expander means having the input of the compressor portion connected to receive the first gas stream and having the output of such compressor portion connected to the input of the compressor portion of the second one of said compressor-expander means; and

the input of the expander portion of said second compressor-expander means being connected to receive the second gas stream and the output of the expander portion of said second compressor-expander means being connected to the input of the said expander portion of said first compressor-expander means.

2. Apparatus as in claim **1**, wherein each of said separate compressor-expander means comprises compressor wheel means separately driven for rotation by an expansion turbine means so that each compressor wheel means and expansion turbine drivingly associated therewith rotates at a speed independent of the speed of rotation of the other of said compressor wheel means and driving turbine means.

3. Apparatus as in claim **1**, wherein all of the power required to operate said compressor portions is obtained from expansion of said second gas stream.

4. Apparatus as in claim **1**, wherein said first gas stream is connected to receive air for compression, means connecting the compressed air output of said compressor portion of said second compressor-expander means to supply a process which produces a quantity of heated gas, said quantity of heated gas constituting said second gas stream.

5. Apparatus for accomplishing multi-stage compression of a first gas by extracting energy from a second gas, comprising in combination:

a plurality of separate compressor-expander means each of which includes a compressor wheel means and a turbine means operatively connected to rotate said compressor means, each of said compressor means being interconnected in series by first conduit means to establish a first series fluid circuit in which each of said compressor means increases the pressure of the first gas in an ascending order from a low-pressure inlet to a high-pressure outlet;

each of said turbine means being interconnected in series by second conduit means to establish a second series fluid circuit;

said second series fluid circuit having an input to receive the second gas;

said series interconnection to said turbine means being in the reverse order of said series interconnection of said compressor means so as to establish a descending order of expansion of the second gas in said second series circuit in which the initial expansion of the second gas takes place in the turbine means which rotates the compressor means supplying the first gas to said high pressure outlet of the first series circuit, and in which the final expansion of the second gas takes place in the turbine means which rotates the compressor means accomplishing the first stage of compression of the first gas received from said low pressure inlet; and

the compressor wheel means and operative turbine means of each separate compressor-expander means being free to rotate at a speed independent of the rotational speed of the other compressor-expander means.

6. Apparatus as in claim 5, wherein each of said separate compressor-expander means comprises a turbocharger means.

7. Apparatus as in claim 5, wherein said first series circuit is connected to receive air at the low pressure inlet and to deliver pressurized air from the high pressure outlet to a process which utilizes pressurized air in the production of a quantity of heated gas; and means connecting said quantity of heated gas to the input of said second series circuit.

8. Apparatus as in claim 7, further comprising additional means for supplying heat energy into said second series fluid circuit.

9. The method of accomplishing multistage compression of a first gas stream by extracting energy from a second gas stream, comprising the steps of:

compressing the gas in the first gas stream to a first pressure level;

compressing the gas at said first pressure level in the first gas stream to a second level greater than said first pressure level;

expanding the gas in the second gas stream to extract a first amount of energy therefrom;

using said first amount of energy to accomplish said compression of the first gas stream only from said first pressure level to said second pressure level;

again expanding the gas in the second gas stream to extract a second amount of energy therefrom; and

using said second amount of energy to accomplish said compression of the first gas stream only to said first pressure level.

10. The method of claim 9, further comprising the steps of supplying the compressed gas in the first gas stream to a process which produces a quantity of heated gas; and supplying said quantity of heated gas to said second gas stream for said steps of expansion.

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