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3,407,992

AERODYNAMIC PRESSURE WAVE MACHINE

Filed Jan. 18, 1967

FIG. 1.

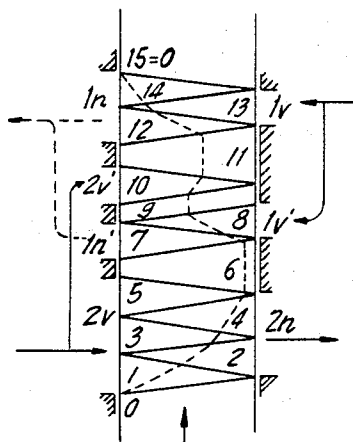


FIG. 3.

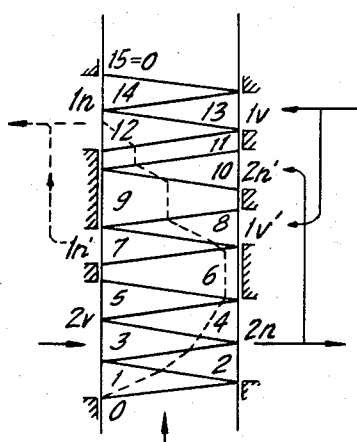


FIG. 2.

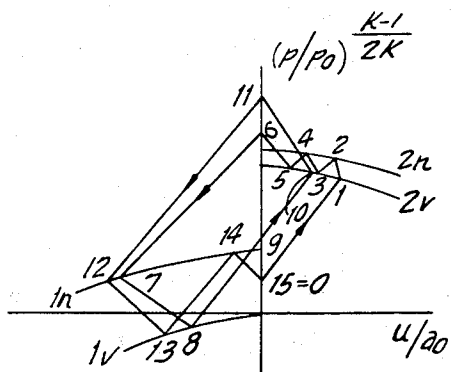
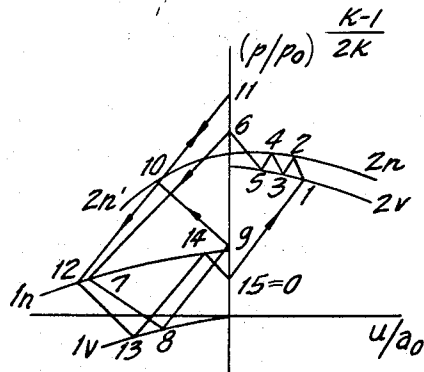


FIG. 4.



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AERODYNAMIC PRESSURE WAVE MACHINE
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Claims priority, application Switzerland, Jan. 28, 1966,
1,221/66

7 Claims. (Cl. 230—69)

ABSTRACT OF THE DISCLOSURE

An aerodynamic pressure wave machine in which the pressure of cold gases at an outlet port (after compression) is equal to or greater than the pressure of the hot gas at an inlet port (before expansion) even though the pressure of the cold gas at an inlet port (prior to compression) is considerably lower than the pressure of low pressure of hot gas discharged from the machine (after expansion). The results are partially achieved by having one of the high pressure gas streams (either hot or cold) subdivided so that a portion of the high pressure gas is utilized to aid scavenging in the low pressure zone or portion of the cycle. Thus, there is an additional inlet port for a portion of either hot or cold high pressure gas of the machine.

This application is based on my Swiss patent application Ser. No. 1,221/66 filed Jan. 28, 1966.

This invention relates to an aerodynamic pressure wave machine and more particularly is directed to a novel arrangement whereby the magnitude of the pressure at the high pressure cold outlet is equal to or greater than the pressure at the high pressure hot inlet even though the pressure of the low pressure cold inlet gas is substantially lower than the pressure of the low pressure hot outlet gas.

My novel arrangement provides for a portion of the gas in the high pressure zone of the cycle of operation to be diverted to the low pressure zone of the cycle of operation.

Aerodynamic pressure wave machines of the general nature covered by this application are well known in the art and are illustrated and described in U.S. Patent 2,957,304 issued Oct. 25, 1960 to M. Berchtold, entitled "Aerodynamic Wave Machine Used as a Supercharger for Reciprocating Engines"; 2,970,745 issued Feb. 7, 1961 to M. Berchtold, entitled "Wave Engine"; 3,012,708 issued Dec. 12, 1961 to M. Berchtold, entitled "Aerodynamic Wave Machine Port Lead Edge Modification for Extended Speed Range"; 3,145,909 issued Aug. 25, 1964 to F. J. Gardiner, entitled "Pressure Transformer"; all of the aforementioned being assigned to the I-T-E Circuit Breaker Company.

The present invention utilizes substantially the same general arrangement disclosed in the aforementioned U.S. patents but provides for a novel re-arrangement of the ports and a novel reinsertion of a portion of the hot gas to achieve the desired results. Thus, applicant's structure can be comprised of a rotor having a plurality of cells on the perimeter thereof and a stator plate with ports on each side of the rotor in order to control the inlet and outlet of the various gases which are to be or have been compressed or expanded.

As heretofore noted, numerous modifications and variations of aerodynamic wave machines have been proposed. However, my present application is particularly adaptable for use in combination with a gas turbine cycle. Various pressure exchangers or aerodynamic wave machines in the prior art have provided arrangements in which the high pressure cold outlet gas is at a pressure substantially

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equal to the high pressure inlet gas and the pressure of the low pressure hot outlet gas is substantially equal to the low pressure hot outlet gas. That is, the device operates solely as a pressure exchanger in that the usable output of the compressed cold gas is at a pressure equal to the pressure of the available hot gas introduced into the machine. This general arrangement is illustrated in German Patent 724,998 to Claude Seippel. In this arrangement the expansion of the hot gas provides more energy than is needed for the compression of the cold gas. In order to balance the energies, the flow of the compressed cold gas is greater than the flow of the expanded hot gas. This is greater than the flow of the expanded hot gas. This surplus flow of the gas passing through the turbine produces shaft power. Hence, any desired temperature can be obtained by mixing the heated and unheated gases. This temperature will depend on the permissible turbine inlet temperature. However, this mixing is undesirable since it lowers the efficiency of the combination of the units.

Other arrangements of the prior art utilizing aerodynamic wave machine principles have further disadvantages. For example, one such unit is identified as a pressure transformer as illustrated in German Patent 1,000,132. In this arrangement, the device does not equally exchange pressure between the cold and the hot gases. However, there must be in the pressure transformer a substantial difference between the low pressure hot outlet gas and the low pressure cold inlet gas in order to produce a significant large difference between the high pressure cold outlet gas and the high pressure hot inlet gas. Furthermore, there are very distinct limitations with respect to the path that the gas will follow. That is, only part of the gas flow is in fact exposed to the desired change of state.

In the pressure transformer, the compression pressure ratio of the cold gas after and before compression can be larger than the expansion pressure ratio of the hot gas before and after expansion. Such condition can be obtained even though there is equal mass flow of the hot and the cold gas.

In many thermodynamic processes, such as a power producing cycle, it is desirable to have a wave machine in which the high pressure cold outlet gas is equal to or greater than the high pressure hot inlet gas while retaining an arrangement in which the low pressure hot outlet gas is substantially larger than the low pressure cold inlet gas. This permits the expansion of the entire mass flow to take place at as high a temperature as possible.

When one has a combination of a gas turbine powered by an aerodynamic wave machine, the cold gas is compressed in the wave machine after being discharged from the turbine compressor and the hot gas leaving the combustion chamber expands first in the pressure exchanger and then in the turbine. Since the pressure drop in the combustion chamber is relatively small, the pressure of the high pressure cold outlet gas is slightly below the pressure of the high pressure hot inlet gas.

It would be desirable to have all of the hot gas expanded in the pressure wave machine. Under this arrangement, the pressure at which the cold gas would enter the wave machine could be considerably lower than the pressure of the low pressure hot gas being exhausted from the machine. Thus the turbo compressor could be relieved of some of its load and would therefore absorb less power. Therefore the net power output and efficiency of the cycle could be substantially increased.

Unfortunately, none of the prior art constructions had a solution available to solve this problem. My present invention is specifically directed to a novel port arrange-

ment including a reinsertion of a portion of the high pressure gas in order to achieve this result. My invention has a substantial modification of the prior art design which can attain the desired operating conditions aforementioned by dividing at least one of the high pressure gas flows. That is, the main high pressure flow of either hot gas to be expanded or cold gas which has been compressed, has a portion of the flow diverted to assist in the scavenging of the cells in a low pressure zone or stage of the cycle. Thus, my pressure wave machine is designed to have at least one additional inlet port in the low pressure zone or portion of the cycle for the purpose of providing full scavenging.

Accordingly, a primary object of my invention is to provide a novel aerodynamic wave machine in which the pressure of the cold gas at the high pressure outlet port is equal to or greater than the pressure of the hot gas at the high pressure inlet port even though the pressure of the cold gas at a low pressure inlet port is considerably lower than the pressure of the hot gas being discharged at the low pressure outlet port.

Another object of my invention is to provide a novel aerodynamic wave machine which is particularly adaptable for use in combination with a gas turbine and provides for maximum efficiency.

Still another object of my invention is to provide a high efficiency aerodynamic wave machine which may be used in combination with a gas turbine and provides an arrangement in which one of the high pressure gas is subdivided so that a portion of the high pressure gas is reinserted in the low pressure zone or cycle of the machine to aid in scavenging.

Another object of my invention is to provide a novel aerodynamic wave machine in which there is an additional inlet port or opening in the low pressure portion of the cycle for introducing a portion of either the hot or cold high pressure gas obtained from the high pressure cycle of the device.

These and other objects of the instant invention will become apparent when reading the accompanying description and drawings, in which:

FIGURE 1 is a schematic developed view of the rotor and ports showing the condition of the gas in each section of the rotor with respect to temperature and pressure for a reverse cycle of operation. In this illustration, a first embodiment of the invention is illustrated in which a portion of the high pressure hot available gas is diverted for insertion into an additional port located in the low pressure cycle.

FIGURE 2 is a state diagram for the wave machine of FIGURE 1 and is a plot of the pressure ratio with respect to the speed of sound for the vertical axis and the flow of velocity for the horizontal axis.

FIGURE 3 is a schematic developed view of the rotor and ports showing the condition of the gas in each section of the rotor with respect to temperature and pressure for a reverse cycle of operation. FIGURE 3 illustrates a second embodiment in which a portion of the high pressure cold outlet gas is diverted to be reinserted in an additional inlet port located in the low pressure cycle of the wave machine.

FIGURE 4 is a state diagram for the wave machine of FIGURE 3 and is a plot of the pressure ratio with respect to the speed of sound for the vertical axis and the flow of velocity for the horizontal axis.

FIGURES 1 and 3 both illustrate the concept of my invention wherein a portion of one of the high pressure gases can be diverted to be subsequently reinserted into an additional inlet port in the low pressure cycle of the machine but each of these figures illustrate a different embodiment for carrying out the common concept. However, the high pressure zone or portion of the cycle for the two embodiments are substantially identical in operation. Thus, in FIGURES 1 and 3 the high pressure hot gas enters the rotor cells through the high pressure inlet

port $2v$ and this hot gas leaves the rotor cell through the low pressure ports $1n$ and $1n'$. The cold gas flows into the cells of the rotor at the low pressure ports $1v$ and $1v'$ and is discharged, after compression, through the high pressure outlet port $2n$. Consistent with standard terminology and symbols utilized in the aforementioned U. S. patents, the dotted line represents the interface between the hot and the cold gas. Thus, in the illustration of FIGURES 1 and 3, there is shown a reverse cycle arrangement in which all of the hot gas is confined to the left stator and left portion of the rotor and all of the cold gas is confined to the right stator and right portion of the rotor. Although the reverse cycle is illustrated and described, it will be apparent to those skilled in the art that the concept of this invention can be carried out in a forward cycle, although it presently appears that the reverse cycle would be preferable.

In the embodiment of FIGURES 1 and 3, the direction of rotation of the rotor with respect to the ports is indicated by the arrow at the lower portion, namely up. For the purpose of expansion, each of the various conditions or states of the various gases in the rotor are indicated by a numeral 0-15 and the operation of the device will be expanded in connection with these numerals starting with the numeral 0.

Assuming that the state or condition 0 is the start of the cycle, it is noted that the cell of the rotor is completely filled with cold gas at a low pressure and is stationary as illustrated in the state diagrams of FIGURES 2 and 4. The left hand of the cell of the rotor initially reaches the leading edge of the high pressure hot inlet port $2v$ and thereafter the right-hand end of the cell is opened by the leading edge of the high pressure cold outlet port $2n$. Thereafter, the right-hand end of the cell is first closed by the leading edge of the low pressure outlet port $2n$ and, subsequently, the left-hand edge is closed by the trailing edge of the high pressure hot inlet port $2v$.

The conditions 1, 3 and 5 represent the flow of the hot gas entering the cell at a cold pressure of P_{2v} and compresses the cold gas to a total pressure of P_{2n} shown at conditions 2 and 4. In the conditions 2 and 4, the hot gas which enters through the high pressure hot inlet port $2v$, displaces the cold compressed gas which is then discharged through the high pressure cold outlet port $2n$.

As illustrated in the state diagram of FIGURES 2 and 4, the pressures P_{2v} and P_{2n} are substantially equal with the pressure P_{2n} being slightly greater than the pressure P_{2v} . This condition is indicated by the proximity of the two ellipses illustrated in the state diagram of the numerals $2v$ and $2n$.

The high pressure cold outlet port $2n$ closes the cell before the high pressure hot inlet port $2v$ so that the high pressure of the gas in field 6 is maintained in the rotor following the extraction of the compressed cold gas from the high pressure cold outlet port $2n$. Thus, the hot gas at high pressure retained in the rotor can be discharged through the low pressure port $1n'$ located at field 7 and, since the right-hand end of the cell of the rotor is thereafter opened by the low pressure inlet port $1v'$, cold gas will be drawn into the rotor through the low pressure port $1v'$ at field 8 as a result of the discharge of the hot gas through the port $1n'$. Since the pressure in field 8 is lower than the pressure in field 7, reflected waves could reverse the flow direction of the fresh cold gas and thus upset the cycle. In order to prevent this from happening, the cell is immediately closed at its left end by the trailing edge of the outlet port $1n'$ and thereafter immediately closed at its right end by the trailing edge of the cold inlet port $1v'$. Thus, the pressure in the field 9 is between the extremes of the high and low pressure of the machine as clearly indicated in the state diagrams of FIGURES 2 and 4.

All of the operation heretofore described in connection with the condition in fields 0-9 are identical for both the embodiments of FIGURES 1 and 3. This can

best be appreciated by the comparison of the state diagrams of FIGURES 2 and 4.

Because of the different modes of operation between the embodiments of FIGURES 1 and 3, even though they have the same basic concept or principle of operation, the remaining states 10 and 11 differ somewhat in condition.

In the embodiment of FIGURES 1 and 2 there is illustrated an arrangement whereby a portion of the available high pressure hot gas entering the hot inlet port 2v is divided to enter the machine at an additional inlet port 2v'. The additional inlet port 2v' in fact is a significant contribution of the present invention. Thus, the gas entering the additional inlet port 2v' is at the same pressure as the hot gas entering the main hot inlet port 2v. Since the gas entering the additional inlet port 2v' is at the high pressure of P_{2v} , the pressure of the gas in the cell is raised so that the gas at field 11 is higher than the pressure of the gas in field 9. This elevated pressure, created in the low pressure zone of the cycle of operation is now sufficiently high to permit a desirable level of scavenging in the low pressure zone so that all of the hot gas which has been expanded can be exhausted from the rotor. Thus, in the fields 12 and 13, all of the remaining expanded hot gas will be exhausted through the low pressure hot outlet port 1n. It is noted that soon after the hot gas starts to be discharged from the rotor, the right-hand end of the rotor is opened to the low pressure cold inlet port 1v. Thus, in the field 13 the cold gas enters the cell so that it can be subsequently compressed in the high pressure zone of the cycle of operation. It is noted that in the event that additional scavenging is required in order to exhaust all of the expanded hot gas from the cell, a second high pressure port 2v'' (not shown) could be incorporated into the machine. However, in the illustration of FIGURES 1 and 2, the second high pressure port 2v'' is not required since all of the expanded hot gas has been discharged through the low pressure hot outlet port 1n as indicated by the interface dotted line representation. Thus, the cycle can start all over again in that the field 15 is in fact the same as the field 0 in which the description of the cycle of operation started. That is, the entire cell is filled with fresh cold gas at low pressure ready to be compressed as it enters the high pressure zone of the cycle.

As heretofore noted, the mode and cycle of operation of embodiments 1 and 3 are identical for fields 0-9. However, in the embodiment of FIGURES 3 and 4, I have illustrated the manner in which the high pressure cold gas can be utilized, instead of the high pressure hot gas, to be reinserted into the low pressure zone or cycle. That is, the high pressure compressed cold gas at the outlet port 2n is bypassed from the main flow and reinserted into the cycle at the additional inlet port 2n' located in the low pressure zone. Thus, in the embodiment of FIGURES 3 and 4, cold gas, which had previously been compressed in the high pressure zone, enters the cells at field 10 at pressure P_{2n} and furnishes the necessary energy required for scavenging the expanded hot gas out of the rotor. It is apparent, of course, that the main portion of the compressed cold gas can be utilized in any desirable arrangement required for the wave machine.

Thus, the introduction of the compressed cold gas at the additional inlet port 2n' raises the pressure of the gas at field 9 to an elevated pressure at field 11 so that the hot gas can be easily and readily scavenged or exhausted through the low pressure hot outlet 1n. Thus, at fields 13 and 14, the cell is thoroughly scavenged, as illustrated by the interfaced dotted line, so that the cold fresh gas completely fills the rotor. Since some of the cold fresh gas may also be discharged through the outlet port 1n the efficiency of the cycle shown in FIGURES 3 and 4 is lower than the efficiency of the cycle illustrated in FIGURES 1 and 2. However, even though the efficiency may be lower, utilization of the compressed cold

gas for scavenging, permits the hot gas to be discharged or pushed out of the cell faster, thus producing better scavenging results and furthermore providing more effective cooling of the walls of the cell of the rotor.

It will be apparent to those skilled in the art that in the event that additional scavenging is required and that a second additional high pressure inlet port 2n'' (not shown) could be utilized as a bypass of additional gas from the main high pressure cold outlet port 2n. However, in the illustration shown in FIGURES 3 and 4, it is apparent that such second additional high pressure cold inlet port is not required. Thus, the state 15 represents the cold gas completely filling the rotor. Since the explanation of the cycle of operation for FIGURES 3 and 4 started at field 0, it will be apparent that the cycle can thereafter be repeated since the field 15 and 0 are the same.

As previously noted, the embodiment of FIGURES 1 and 2 illustrates a bypass of the high pressure hot gas for subsequent reinsertion into cycle and the embodiment of FIGURES 3 and 4 illustrates a bypass of the high pressure cold gas for subsequent reinsertion into the low pressure zone of the cycle of operation.

However, it will be apparent to those skilled in the art that in some installations it may be desirable to combine the embodiments of FIGURES 1 and 3 into a single cycle of operation so that there is a bypass and an additional inlet port for both the high pressure hot and cold gas.

It is furthermore noted that in both of the embodiments of FIGURES 1 and 3 the interface, represented by the dotted line, does not reach the right-hand end of the cell of the rotor in field 6. This is considered advantageous since the low temperature in the proximity of the interface would lower the temperature of the walls of the cell. However, if desirable, it is possible to design the porting arrangement so that the interface reaches the extreme right-hand end of the cell. That is, during the conditions set forth in field 6, the entire cell could be filled with hot gas.

In the embodiment of FIGURES 1 and 3, I have illustrated a preferred cycle of operation for my invention in which the cycle incorporates a reverse flow arrangement. That is, all hot gas is confined to one side and all cold gas to the other side. However, if required or desirable, it would be apparent to those skilled in the art that the arrangement could be modified for a forward cycle arrangement, that is, the gas flowing directly through the rotor and always being exhausted from a side opposite the side in which it was introduced.

It is furthermore noted that the invention is illustrated in connection with a preferred structural arrangement in which the cells are rotated and the ports are stationary in the two stator plates on each side of the rotor. However, if desired, the concept of the present invention could be achieved by an arrangement in which the cells are stationary and the ports are located in rotating casings on either side of the cells.

The pressure or aerodynamic wave machine with the improvements of my present invention could be used in a thermo-cycle with considerable advantages. My invention results in a substantially improved scavenging arrangement with a higher purity of the compressed cold gas. Also, if the pressure wave machine of the present invention is combined with a gas turbine, the rotational speed of the rotor can easily be modified to obtain optimum operating conditions. Furthermore, in order to obtain increased efficiencies, at speeds of the rotor other than at designed speed, gas pockets can be provided in the stator plates of the general type described and illustrated in U.S. Patents 3,120,920 issued Feb. 11, 1964 to Jose Waleffe et al., entitled "Pocket Combination for Extension for Speed and Load Range of AWM Superccharger," assigned to Brown, Boveri & Company, Ltd.; 3,120,339 issued Feb. 4, 1964 to Kurt Muller, entitled

"Cycle for a Wide Speed and Load Range," assigned to the I-T-E Circuit Breaker Company.

It is furthermore noted that the structural arrangement of my present invention could be used in chemical processes as well as in the supercharging of diesel engines.

Although there has been described a preferred embodiment of this novel invention, many variations and modifications will now be apparent to those skilled in the art. Therefore, this invention is to be limited, not by the specific disclosure herein, but only by the appending claims.

The embodiments of the invention in which an exclusive privilege or property is claimed are defined as follows:

1. An aerodynamic wave machine having a rotor and a stator on each side of said rotor; said machine having a high pressure zone and a low pressure zone;
 - said high pressure zone having a first high pressure outlet port for gas which has been compressed and a first high pressure inlet port for gas to be expanded;
 - said low pressure zone having a first and second low pressure inlet port for gas to be compressed, a first and second low pressure outlet port for gas which has been expanded, and a second high pressure inlet port for a portion of the gases divided from at least one of said first high pressure ports in said high pressure zone;
 - said second high pressure inlet port at said low pressure zone being operative to aid the scavenging of the low pressure gas in said rotor through said first low pressure outlet port; said second high pressure inlet port of said low pressure zone being located between one of the sets of said first and second low pressure ports.
2. The device of claim 1 wherein said second high pressure inlet port of said low pressure zone is operatively connected to receive high pressure gas divided from said first high pressure outlet port.
3. The device of claim 2 in which said second high pressure inlet port of said low pressure zone is located be-

tween said first and second low pressure inlet ports; the pressure at said first high pressure outlet port being equal to or greater than the pressure at said first high pressure inlet port and the pressure in said first and second low pressure inlet ports being lower than the pressure in said first and second low pressure outlet ports.

4. The device of claim 3 in which said first high pressure inlet port for the high pressure zone and said first and second low pressure outlet port of said low pressure zone are all located in one stator; and said first high pressure outlet port for the high pressure zone and said second high pressure inlet port for the low pressure zone together with said first and second inlet port are located in the other stator.

5. The device of claim 1 wherein said second high pressure inlet port of said low pressure zone is operatively connected to receive high pressure gas divided from said first high pressure inlet port.

6. The device of claim 5 in which said second high pressure inlet port of said low pressure zone is located between said first and second low pressure outlet ports; the pressure at said first high pressure outlet port being equal to or greater than the pressure at said first high pressure inlet port and the pressure in said first and second low pressure inlet ports being lower than the pressure in said first and second low pressure outlet ports.

7. The device of claim 5 in which said first and second high pressure inlet ports for the high and low pressure zones and said first and second low pressure outlet ports of said low pressure zones are all located in one stator; and said first high pressure outlet port for the high pressure zone as well as said first and second low pressure inlet port are located in the other stator.

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ROBERT M. WALKER, *Primary Examiner*.