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CENTRIFUGAL COMPRESSOR OPERATION

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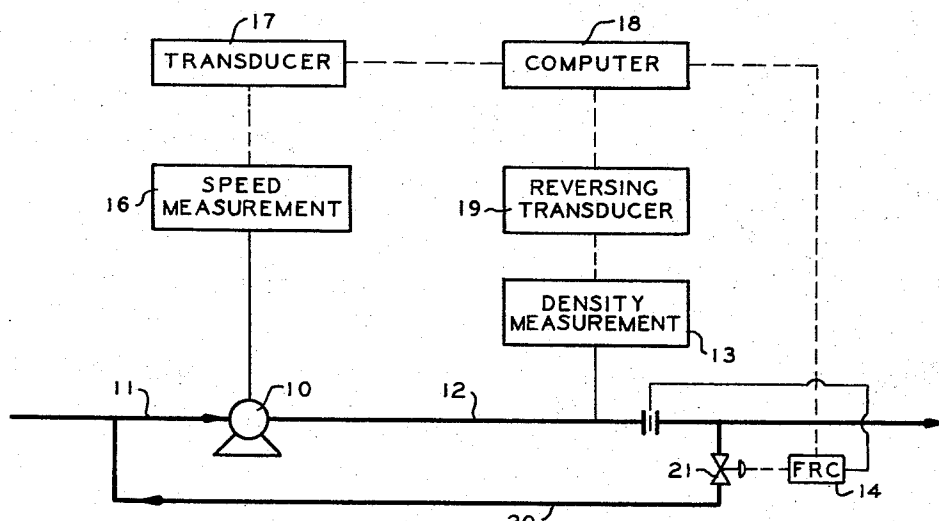


FIG. 2

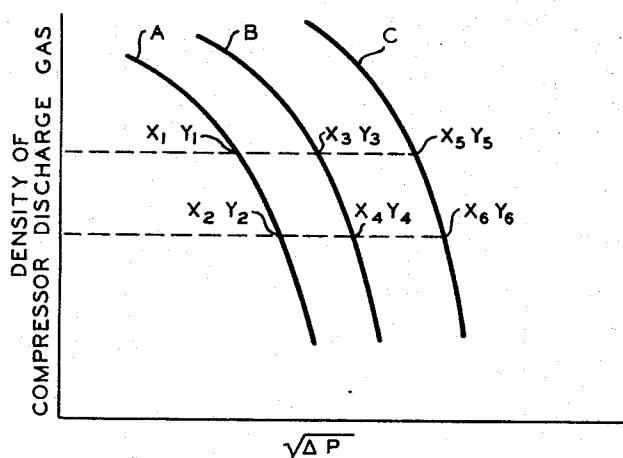


FIG. 1

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CENTRIFUGAL COMPRESSOR OPERATION

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This invention relates to the operation of a centrifugal gas compressor. In another aspect, this invention relates to the operation of a centrifugal gas compressor having fluctuations in the density of the compressed gas, rate of flow of compressor discharge gas, and speed of the compressor.

It is well known by those skilled in the art that a centrifugal gas compressor will go into "surge" if less than a minimum quantity of gas is being compressed for a given compressor speed and pressure drop across the compressor. Surging upon the part of the centrifugal gas compressor will result in excessive compressor vibration and possible destruction of the compressor. The quantity of gas compressed by the compressor is dependent upon the density of the compressed gas, the rate of flow of the discharged compressed gas, and the speed of the compressor. Therefore, if, for example, an attempt was made to operate the compressor so as to prevent surge by recycling a fixed volume of the discharge gas to the suction of the compressor, the compressor could become overloaded at the varying conditions of compressor speed or density of the discharged gas.

Accordingly, an object of our invention is to provide a method and apparatus for operating a centrifugal gas compressor.

Another object of our invention is to provide a method and apparatus for operating a centrifugal gas compressor so as to prevent surge.

Another object of our invention is to provide a method and apparatus for operating a centrifugal gas compressor so as to achieve vibration-free operation of said compressor.

Other objects, advantages and features of our invention will be readily apparent to those skilled in the art from the following description, drawings and appended claims.

According to our invention, a centrifugal compressor is operated at minimum horse power and operated so as to prevent surge at the said minimum horse power by recycling a minimum volume of discharge gas to the intake of the compressor, thereby preventing compressor surge while holding to a minimum the power requirements to operate the compressor. The density of the compressor discharge gas is measured, the pressure drop across an orifice in the compressor discharge gas conduit is measured, the speed of the compressor is measured, and a combination of these three measurements employed to manipulate the rate of flow of recycle gas from the discharge of the compressor to the intake of the compressor.

FIGURE 1 is a graph depicting the correlation between the density of the compressor gas and the square root of the pressure differential across an orifice positioned in the compressor discharge conduit below which surge will occur for different compressor speeds.

FIGURE 2 is a schematic representation of one embodiment of the compressor control system of this invention.

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By relating the density of the compressor discharge gas to the square root of the pressure drop across an orifice in the compressor discharge gas graphically a curve can be established for each speed (as measured in revolutions per minute of the impeller) of the compressor below which "surge" or vibration of the compressor will occur. A series of these curves (A, B and C) produced for different compressor speeds and for a particular compressor is illustrated in FIGURE 1. Referring to FIGURE 1, curve A represents the minimum density of the discharge gas permitted for each of multiple discharge pressure differentials at a particular compressor speed and a minimum pressure differential for each of multiple gas densities at said particular compressor speed. Curves A, B and C represent three different compressor speeds. It can readily be seen from FIGURE 1 that in operating with a compressor discharge gas having a density ranging from Y_1 to Y_6 and wherein the square root of the pressure differential ranges from X_1 to X_6 (normal operating range of a centrifugal compressor) that curves A, B and C are substantially parallel.

In operating a centrifugal compressor at a speed, for example, as represented by curve A of FIGURE 1, it is desirable to operate the compressor without recycle of compressed gas so as to have a discharge gas density and square root of pressure differential above curve A. When operating the compressor with recycle so as to prevent surge, it is desirable that the compressor be operated along curve A.

Although, when operating the compressor using recycle to prevent surge, it is within the scope of this invention to operate along a curve, it is preferable to operate along a straight line tangent to the curve. This provides a margin of safety in preventing surge due to rapid changes in density and volume of gas being compressed. It is also within the scope of this invention to operate along a straight line parallel to and slightly above the tangent to the curve for a given speed of the compressor, thus providing an additional margin of safety.

It is within the skill of the art to establish an equation for that portion of curve A laying between points X_2Y_2 and X_1Y_1 and for that portion of curve B laying between X_3Y_3 and X_4Y_4 of curve B. Although not to be limited thereto, for purposes of describing the invention, it will hereinafter be assumed that that portion of curve A laying between points X_1Y_1 and X_2Y_2 is substantially a straight line and is substantially parallel to a straight line joining points X_3Y_3 and X_4Y_4 of curve B. The equation for a straight line tangent to curve A then becomes:

$$(1) \quad y_A = (\text{slope of curve A}) x_A + b_A$$

where slope of curve A is the slope of that portion (straight line) of curve A laying between X_1Y_1 and X_2Y_2 .

The equation of curve B then becomes

$$(2) \quad y_B = (\text{slope of curve B}) x_B + b_B$$

where b_A and b_B are constants. The slopes of curves A and B are identical.

Curve A is for a predetermined speed of a compressor with curves B and C for higher compressor speeds. Intermediate, higher and lower speed curves could be obtained by interpolation and extrapolation. The following derivation, using known values from Equations 1 and 2, provides an equation that can be employed to determine the minimum rate of flow of compressor discharge gas

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for any operable compressor speed and gas density. An equation for a straight line representing a compressor speed is

$$(3) \quad y_D = \text{slope}_D x_D + b_D$$

where slope_D is the slope for any straight line representing any compressor speed (RPM). Then:

$$(4) \quad b_D = (RPM_B - RPM_D) \frac{b_B - b_A}{RPM_B - RPM_A} + b_B$$

Let:

$$(5) \quad \frac{b_B - b_A}{RPM_B - RPM_A} = K_1 \text{ (a constant)}$$

Then:

$$(6) \quad b_D = K_1 (RPM_B - RPM_D) + b_B$$

Substituting in Equation 3 there is obtained:

$$(7) \quad y_D = \text{slope}_D x_D + K_1 (RPM_B - RPM_D) + b_B$$

Solving for x_D there is obtained:

(8)

$$x_D = \frac{y_D}{\text{slope}_D} - \left(\frac{RPM_B}{\text{slope}_D} \right) K_1 + RPM_D \left(\frac{b_B - b_A}{RPM_B - RPM_A} \right) \left(\frac{1}{\text{slope}_D} \right) - \frac{b_B}{\text{slope}_D}$$

Let:

$$(9) \quad RPM_B K_1 + b_B = K_2 \text{ (a constant)}$$

Then:

$$(10) \quad x_D = \frac{y_D}{\text{slope}_D} - \frac{K_2}{\text{slope}_D} + \frac{RPM_D K_1}{\text{slope}_D}$$

Referring to FIGURE 1 and Equation 10, it can readily be seen that by having predetermined the density square root of pressure drop differential relationship for two different compressor speeds, a desired rate of flow (x_D) of compressor discharge gas can be determined for any density measurement (y_D) of the compressor discharge gas and a measurement representative of the speed (RPM_D) of the compressor under operating conditions. Thus, by employing Equation 10, the desired compressor discharge gas rate necessary to prevent compressor surging can be determined by measuring the density of the compressor discharge gas and the speed of the compressor.

Referring to FIGURE 2, there is shown a centrifugal compressor 10 disposed in a flowing gas stream 11, said compressor 10 functioning to compress said gaseous stream. Disposed in compressed gas outlet conduit 12 is a commercially available gas density measuring and transmission device 13, such as the Dynatrol Density Transmitter, Model EC-112F, manufactured by Automation Products, Inc., of Houston, Texas.

Density measuring and transmission means 13 transmits an electrical signal to a conventional reversing transducer 19, such as the Taylor Mili-Volt-to-Pneumatic Transducer, Model 700 TD-1133, illustrated in bulletin 98262. Transducer 19 converts the density signal to a pneumatic signal, reverses the signal, and transmits a pneumatic signal representative of the density signal reversed to computing means 18.

Downstream is a conventional flow recorder-controller 14. The operation of flow recorder-controller 14 will hereinafter be more fully described.

A conventional speed measuring and transmission means 16, such as the Weston Electrical tachometer and bearingless A.-C. generator illustrated in Weston bulletin 03-100-C, is mechanically linked to the impeller of compressor 10 to measure the revolutions per unit time of said impeller. Speed measuring and transmission means 16 produces an electrical signal representative of the impeller speed which is transduced to pneumatic form and properly scaled (as hereinafter described) by conventional transducer 17. A transducer capable of performing the re-

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quired functions is the Moore Products transducer, Model 774-2, manufactured by Moore Products, Inc., Philadelphia, Pennsylvania, in combination with the Moore Pressure Re-Transmitter illustrated in bulletin 17301. Transducer 17 transmits a pneumatic signal to computing means 18, computer means 18 providing a totalizing function as hereinafter described.

A conduit 20 communicates between compressor outlet conduit 12 and inlet conduit 11 for recycling compressed gas from the discharge conduit to the compressor inlet as desired. A conventional flow control means 14 such as a conventional flow recorder-controller operates to open and close valve 21 in conduit 20 responsive to a rate of flow measurement in outlet conduit 12 and a reset signal from computer means 18, as hereinafter described.

Computer means 18 must be capable of solving the following equation: $\text{Output} = a - c + b$, where a and c are input variables and b is a constant. In addition thereto, computing means 18 must be capable of transmitting a signal representative of said output as a reset signal to flow recorder-controller 14. An instrument capable of performing these functions is the Moore Multi-Function Relay, Model 68-1, manufactured by Moore Products Company and illustrated in bulletin 681.

Computer means 18 must become capable of solving for the desired rate of flow of compressor discharge gas for a particular density of the compressor discharge gas as determined by density measurement means 13 and a particular compressor speed as determined by speed measurement means 16, by solving for x_D in Equation 10. Substituting the terms in Equation 10 for the terms in the computer equation, there is obtained:

$$c = \frac{K_1 RPM_D}{\text{slope}_D}, a = \frac{-y_D}{\text{slope}_D}, b = \frac{K_2}{\text{slope}_D}$$

where b is a constant applied continuously to computer 18, slope_D is a constant for the operating range of the compressor and will hereinafter be referred to as K_3 .

Referring again to FIGURE 2, speed measuring and transmission means 16 transmits a signal representative of $K_1 RPM_D / K_3$ to transducer 17. Transducer 17 transduces the electrical signal received from speed measuring and transmitting means 13 into a pneumatic signal and expands the operating scale so as to provide an input c having a high sensitivity to changes in the compressor speed.

Transducer 17 thus provides signals for transmission to computer means 16 having the proper signal level (zero) and sensitivity to speed changes (span) representative of the required rates of flow of computer discharge gas for changing compressor impeller speeds.

Transducer 19 converts the millivolt signal received from density measuring and transmission means 13 to an air signal and reverses the signal. The zero and span adjustments of transducer 19 are employed to provide air output signals equivalent to the required rate of flow y_D / K_3 of the discharged compressor gas for changing gas density—at the proper signal level (zero) and sensitivity to changes (span).

Computer means 18 transmits a signal to flow recorder-controller 14 representative of the required pressure drop across an orifice positioned in the compressor discharge gas for the measured density of the compressor discharge gas and the measured speed of the compressor. This reset signal received by flow recorder-controller 14 is compared with a signal representative of the measured pressure drop across the orifice positioned in the compressor discharge gas and valve 21 is opened or closed responsive to this comparison so as to maintain the rate of flow of compressor discharge gas through conduit 12 at or above the minimum to prevent surge.

Although the computing means employed in FIGURE 2 was pneumatic, it is within the scope of this invention to utilize an electrically operated computing means, there-

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by eliminating the transducing steps of transducers 17 and 19.

As will be evident to those skilled in the art, various modifications of this invention can be made, or followed, in the light of the foregoing disclosure, without departing from the spirit or scope thereof.

We claim:

1. A method of operating a centrifugal compressor having a recycle line between the discharge and the intake which comprises measuring the density of said discharge gas, measuring the speed of said compressor, and then manipulating the rate of flow of recycle gas from the discharge of said compressor to the intake of said compressor responsive to said density and speed measurements to maintain a flow through said compressor sufficient to prevent surging of said compressor.

2. A method of operating a centrifugal compressor having a recycle line between the discharge and the intake which comprises measuring the density of said discharge gas, passing a signal representative of said measurement to a computing zone, measuring the speed of said compressor, passing a signal representative of said speed measurement to said computing zone, and passing a signal representative of the minimum rate of flow of said discharge gas for the speed and density of discharge gas measured to prevent surging of said compressor to a means for manipulating the rate of flow of recycle gas from the discharge of said compressor to the intake of said compressor, and manipulating said recycle flow rate responsive to said density and speed measurements to thereby maintain said minimum rate of flow of said discharge gas to prevent surging of said compressor.

3. The method of claim 2 wherein said computing zone solves the equation

$$\text{output} = a - c + b$$

where a is representative of density/ K_3 , c is representative of

$$K_1 \left(\frac{\text{speed of compressor}}{K_3} \right)$$

and where K_1 , K_3 and b are constants.

4. Apparatus comprising a centrifugal compressor, means for recycling a portion of discharge gas to the intake to the compressor means for measuring the density of the discharge gas, means for measuring the speed of said compressor, and means for manipulating the rate of flow of recycle gas from the discharge of said compressor to the intake of said compressor responsive to said density and speed measurements to maintain a rate of flow of said discharge gas sufficient to prevent surging of said compressor.

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5. Apparatus comprising a centrifugal compressor, recycle means for returning a portion of compressor discharge gas to the compressor intake means for measuring the density of said discharge gas, a computing means, means for passing a signal representative of said density measurement to said computing means, means for measuring the speed of said compressor, means for passing a signal representative of said speed measurement to said computing means, means for manipulating the rate of flow of recycle gas from the discharge of said compressor to the intake of said compressor, and means for passing a signal representative of the minimum rate of flow of said discharge gas for the speed and density measured to said means for manipulating.

6. The apparatus of claim 5 wherein said computing means solves the equation

$$\text{output} = a - c + b$$

where a is representative of density/ K_3 , c is representative of

$$K_1 \left(\frac{\text{speed of compressor}}{K_3} \right)$$

and where K_1 , K_3 and b are constants.

7. The apparatus of claim 6 wherein said computing means is a pneumatic computing means, said means for passing a signal representative of said density measurement includes a means for transducing and reversing an input electrical signal representative of said density, and said means for passing a signal representative of said speed measurement includes a means for transducing an electrical input signal representative of said speed measurement.

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