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(54) ANTI-SURGE SPEED CONTROL

(57) **ABSTRACT**

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The present invention relates to a method and control system to control the speed of a centrifugal compressor operating within a vacuum pressure swing adsorption process to avoid an operation at which surge can occur and directly driven by an electric motor that is in turn controlled by a variable frequency drive. In accordance with present invention an optimal speed for operation of the compressor is determined at which the compressor will operate along a peak efficiency operating line of a compressor map thereof. This speed is adjusted by a feed back speed multiplier when the flow or other parameter referable to flow through the compressor is below a minimum and a feed forward multiplier during evacuation and evacuation with purge steps that multiplies the feed back multiplier to increase speed of the compressor and thereby avoid surge.

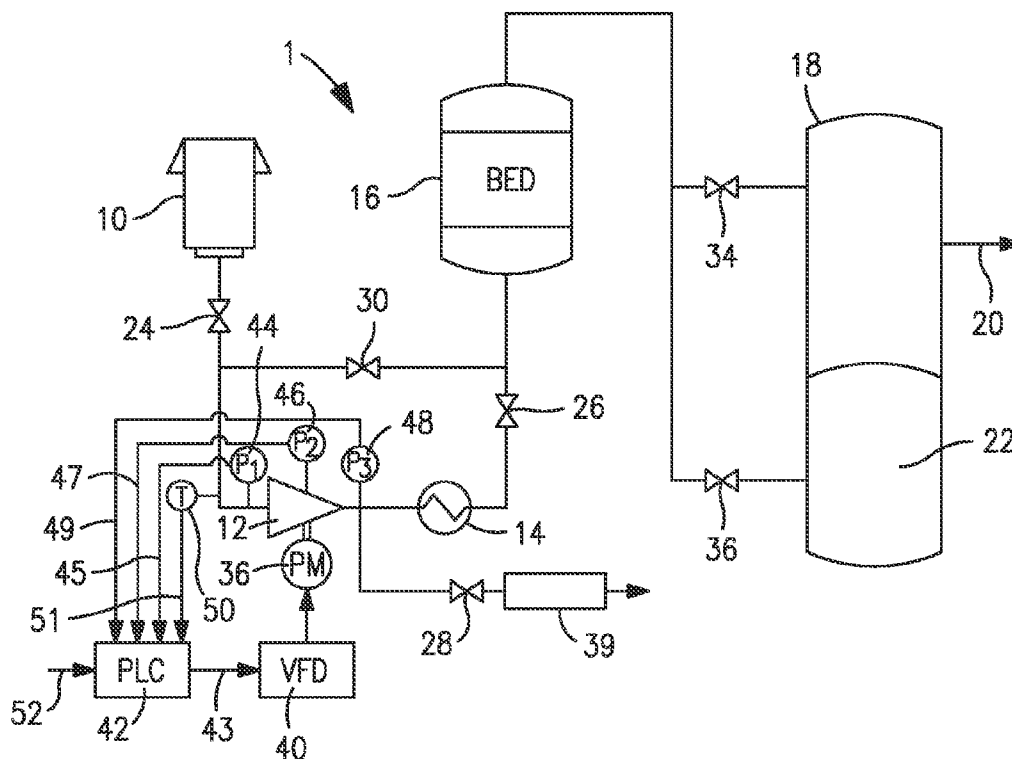


FIG. 2

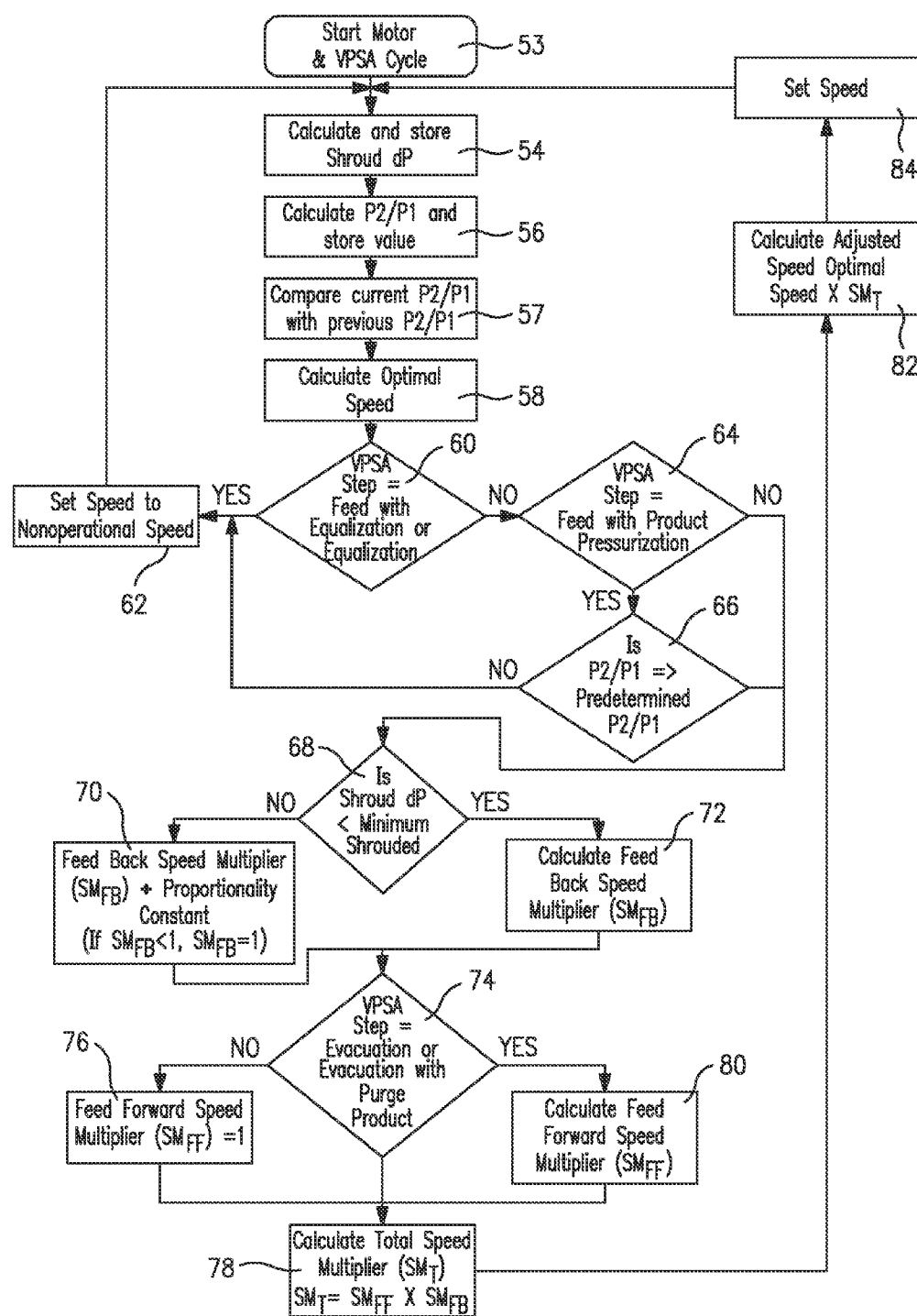
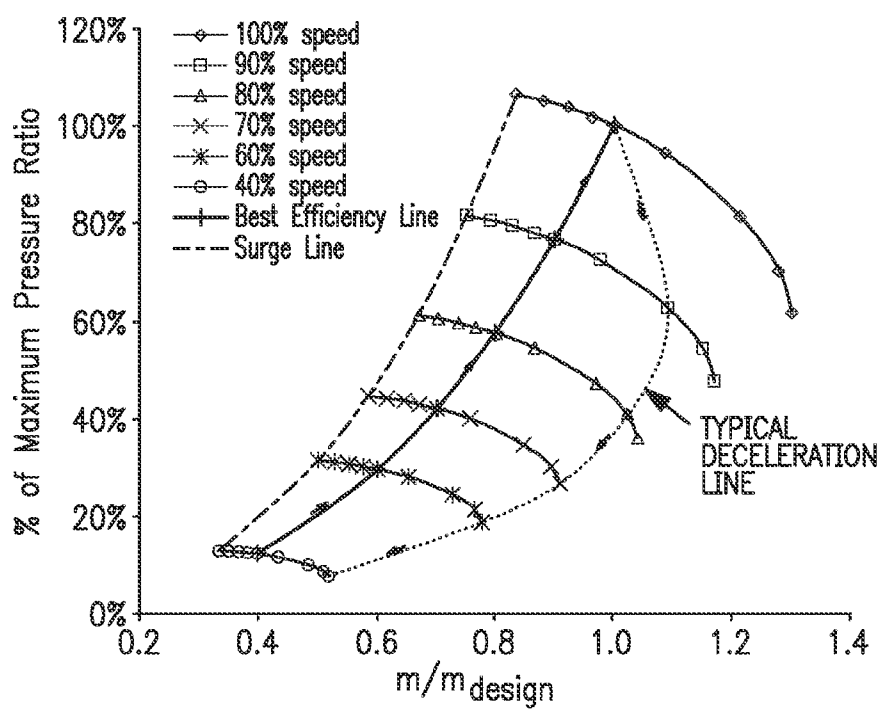
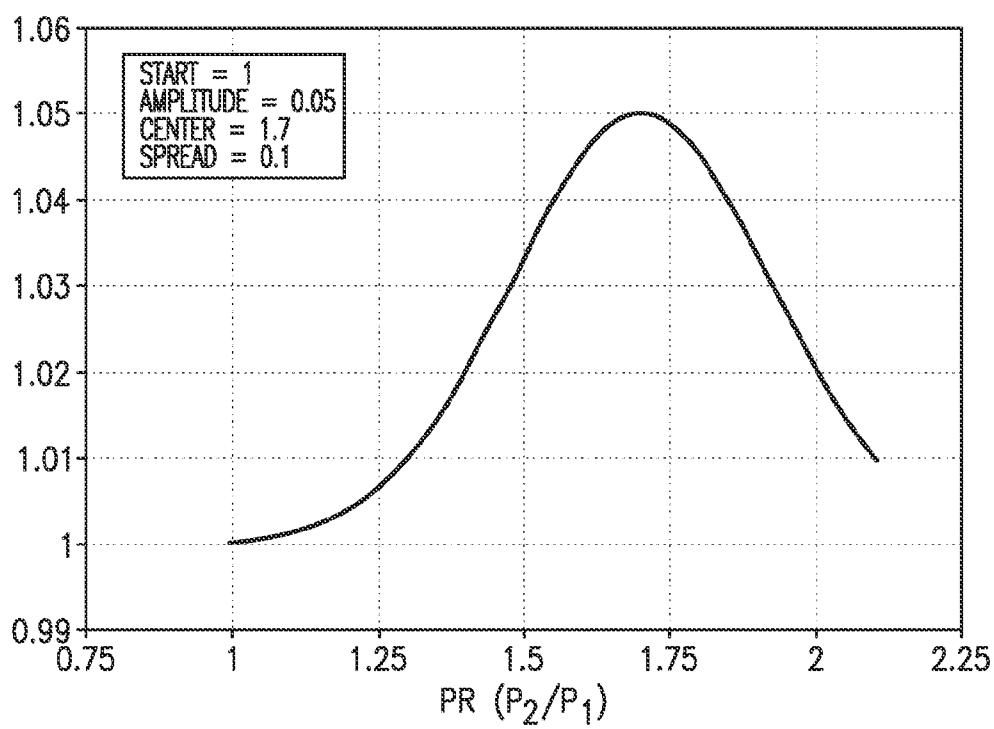


FIG. 3

**FIG. 4****FIG. 5**

ANTI-SURGE SPEED CONTROL

FIELD OF THE INVENTION

[0001] The present invention provides a method and control system for controlling the speed of a centrifugal compressor operating within a vacuum pressure swing adsorption apparatus and directly driven by an electric motor to avoid the compressor from entering surge. More particularly, the present invention relates to such a method and system in which the speed is increased during at least those steps of a repeating cycle conducted by the vacuum pressure swing adsorption apparatus where the compressor may encounter surge and in amounts of increase that vary in accordance with the steps being conducted.

BACKGROUND OF THE INVENTION

[0002] In a vacuum pressure swing adsorption process one or more adsorbents are used to adsorb one or more components of a feed stream and thereby produce a purified product stream. A typical process has a series of continuously executed steps in accordance with a repeating cycle. In the repeating cycle, an adsorbent bed containing the adsorbent is alternately used to produce the purified product and then is regenerated. During regeneration, the adsorbed components are desorbed from the adsorbent and then, the adsorbent bed is brought back into state in which it can be brought back on line and producing the product.

[0003] In a typical vacuum pressure swing adsorption process designed to make product oxygen from feed air, an adsorbent bed is subject to a seven step process conducted in the repeating cycle. For purposes of illustration only, such an adsorption process can be conducted with one bed. In a first step, the bed is simultaneously pressurized from the bottom with feed air and from the top with equalization gas delivered from a recovery tank. Thereafter, high purity product is added to the top of the bed from the oxygen surge tank while feed air is supplied by a compressor or other blower such as a Roots type of blower. In a third step, the bed continues to be pressurized from the bottom via the blower. The bed is now ready to make product and feed air is fed into the bottom of the vessel and product is removed from the top. The product gas is delivered to the oxygen surge tank. After production is complete, the blower is unloaded and the lower purity gas remaining in the top of the pressurized bed is transferred to the recovery tank. In a subsequent evacuation step, waste nitrogen is removed from the bottom of the vessel through the centrifugal compressor while there is no flow exiting or entering the top of the vessel. In the last step, the centrifugal compressor continues to remove nitrogen from the bottom of the vessel while oxygen purge gas is added to the top of the vessel. The pressure remains relatively constant during this step due to the fact that the oxygen purge flow is controlled equal to the evacuation flow. As would be known in the art, such a process could be carried out in multiple beds in which each bed is subjected to the steps outlined above.

[0004] As disclosed in U.S. Pat. No. 7,785,405, centrifugal compressors directly driven by direct drive high-speed permanent magnet motors have been advantageously utilized in vacuum pressure swing adsorption processes. The use of such motors allow for variable-speed operation such that the compressor and high-speed permanent magnet motor combination(s) can accelerate from low-speed to high-speed and decelerate from high-speed to low-speed rapidly, as required

by the process. It has been found that this offers a major improvement over the use of centrifugal compressors driven by conventional induction motor/gearbox systems which due to the high inertia of the induction motor cannot accelerate and decelerate quickly. By continuously varying the compressor speeds to match the pressure ratio requirement for the compressor, which is varying because of the pressurizing and evacuating adsorbent beds, the centrifugal compressor used in such a cycle can be operated near, and preferably at, its peak efficiency from 100% design speed to a substantially lower speed.

[0005] Compressors are designed to operate within an operating envelope that can be plotted in what is referred to as a compressor map of pressure ratio between outlet pressure and inlet pressure versus flow rate through the compressor. On such a plot, a peak or best efficiency operating line is plotted in which for a given flow rate and pressure ratio, the energy consumption of the compressor is at a minimum. This compressor map can be programmed within a controller used in controlling the speed of the motor and therefore, the compressor. Depending upon the specific step in the vacuum pressure swing adsorption process, which would require a specific pressure ratio across the centrifugal compressor, the controller sends a signal referable to the optimal speed as determined from the compressor map to a variable speed drive that controls the speed of the high-speed permanent magnet motor.

[0006] There are, however, situations that can cause the compressor to move off the peak efficiency operating line and into a surge condition. For instance, there can be a lag in the control system, transitional steps in the process being conducted by the vacuum pressure swing adsorption apparatus, changes in ambient conditions and transitioning off the minimum speed line. In all of such situations, the mass flow being compressed can fall for a given speed and pressure ratio to drive the compressor into surge. A surge event is therefore, produced by a flow rate through the compressor falling below a minimum flow required at a given speed of the impeller of the compressor that is necessary to maintain stable operation. In a surge event, the head pressure developed by the compressor decreases causing a reverse pressure gradient at the compressor discharge and a resulting backflow of gas. Once the pressure in the discharge line of the compressor drops below the pressure developed by the impeller, the flow reverses once again. This alternating flow pattern has been found to be an unstable condition that can result in serious damage to the compressor impeller, drive mechanism and components. This condition must be avoided.

[0007] In repeating cycles employed in vacuum pressure swing adsorption apparatus, the operational conditions of the compression at which surge can occur will be most critical at high speeds. Additionally, during the evacuation and purge steps and particularly during the transition between the purge and evacuation steps, surge can occur quite unexpectedly. As will be discussed, the present invention provides a speed control that is particularly designed to avoid surge during low speed operation and during the evacuation and purge steps and the transition between such steps.

SUMMARY OF THE INVENTION

[0008] The present invention provides a method of controlling the speed of a centrifugal compressor operating within a vacuum pressure swing adsorption apparatus. The centrifugal compressor is directly driven by an electric motor controlled

by a variable frequency drive. In this regard, the term “electric motor” as used herein and in the claims means either a high speed permanent magnet motor or a high speed induction motor. In connection with such method, a parameter referable to a flow rate of gas entering the centrifugal compressor is measured and calculated. The pressure ratio of outlet to inlet pressure of the compressor is also measured and calculated. An optimal speed of the centrifugal compressor is determined based on the pressure ratio and that lies along the peak efficiency operating line of the centrifugal compressor. Additionally, a minimum allowable value of the parameter at which the centrifugal compressor is likely to enter surge conditions at the optimal speed is also determined. A feed back multiplier is determined that when multiplied by the optimal speed will either increase the speed when the parameter is less than the minimum allowable value or will reduce the speed when the parameter is greater than or equal to the minimum allowable value.

[0009] During steps of a repeating cycle conducted by the vacuum swing adsorption apparatus where the centrifugal compressor is at least likely to encounter surge conditions, other than an evacuation step and an evacuation with purge step thereof, a total speed multiplier is set equal to the feed back multiplier. During the evacuation step and the evacuation with purge step, the total speed multiplier is calculated by multiplying the feed back multiplier by a feed forward multiplier that will increase the speed during the evacuation step and the evacuation with purge step such that centrifugal compressor is not likely to enter the surge conditions. An adjusted speed is calculated at such time by multiplying the optimal speed by the total speed multiplier. A control signal referable at least to the adjusted speed is generated and inputted into the variable frequency drive such that the electric motor and therefore, the centrifugal compressors operates at the adjusted speed.

[0010] It is understood that generally speaking, the present invention contemplates that the total speed multiplier is set equal to the feed back multiplier where the centrifugal compressor is at least likely to encounter surge conditions, other than in the evacuation step and the evacuation with purge step thereof. The present invention specifically contemplates, at points within the repeating cycle where surge conditions are unlikely to be encountered, the control signal that is inputted into the variable frequency drive will have the effect of removing power from the electric motor. In this regard, the repeating cycle can include a feed with equalization step subsequent to the evacuation with purge step, a feed with product repressurization step following the feed with equalization step and an equalization step prior to the evacuation step. During the feed with equalization step, the equalization step and initiation of the feed with product repressurization step, the control signal is referable to a non-operational speed such that when the control signal is inputted into the variable frequency drive, electrical power is not applied to the electric motor. However, when a predetermined pressure ratio of the pressure ratio is obtained during the feed with product repressurization step, the control signal is again referable to the adjusted speed such that the electric motor and therefore, the compressor operates at the adjusted speed. It is to be noted, however, that the present invention also contemplates and intends to cover within the appended claims an embodiment in which in steps of the repeating cycle, other than the evacuation step and the evacuation with purge steps, the total speed

multiplier is always set equal to the feed back multiplier and the control signal is always referable to the adjusted speed.

[0011] Each time the feed back multiplier is determined, the feed back multiplier can be stored. When the parameter is less than the minimum allowable value, the feed back multiplier is determined by adding to a last stored value of the feed back multiplier a speed correction factor. When the parameter is greater than or equal to the minimum allowable value, the feed back speed multiplier is calculated by dividing the last stored value of the feed back multiplier by a proportionality constant. The proportionality constant is set equal to a value greater than 1.0 when the last stored value of the feed back multiplier is greater than or equal to 1.0 or 1.0 when the last stored value of the feed back multiplier is less than 1.0.

[0012] The feed forward multiplier can be a function of the pressure ratio. The function can have a maximum value of the feed forward multiplier at a predetermined pressure ratio at which or directly before which the centrifugal compressor will likely enter surge conditions during a transition between the evacuation step and the purge step. The function will have decreasing values of the feed forward multiplier at pressure ratios greater than or less than maximum value. The maximum value has a magnitude preselected such that when the maximum value is multiplied by the optimal speed at the predetermined pressure ratio the resulting speed will prevent the centrifugal compressor from entering surge conditions. The function can be a Gaussian function.

[0013] The parameter can be a pressure difference measured at two points in the shroud of the centrifugal compressor that are successively closer to an impeller thereof. During each of the time intervals, a pressure difference error is calculated and stored by subtracting the minimum allowable value from the a current value of the pressure difference. The speed correction factor of the feed back multiplier is calculated during each of the time intervals through proportional integral control comprising adding a proportional term to an integral term, the proportional term calculated by multiplying a gain factor by a difference between the pressure difference error and a prior pressure difference error calculated in a prior time interval and dividing the difference by the time interval. The integral term is calculated by dividing the gain factor by an integral reset time and multiplying a resultant quotient thereof by the pressure difference error.

[0014] The present invention also provides a control system for controlling speed of a centrifugal compressor operating within a vacuum pressure swing adsorption apparatus and directly driven by an electric motor controlled by a variable frequency drive. The control system is provided with means for sensing a parameter referable to a flow rate of gas entering the centrifugal compressor. Pressure transducers are positioned to sense pressure at an inlet and an outlet of the centrifugal compressor.

[0015] A controller is provided that is responsive to the parameter sensing means, the pressure transducers and steps of a repeating cycle conducted by the vacuum pressure swing adsorption apparatus. The controller has a control program that is programmed to calculate a pressure ratio of the pressures of the outlet to inlet of the centrifugal compressor. The control program also determines an optimal speed of the centrifugal compressor based on the pressure ratio and that lies along the peak efficiency operating line of the centrifugal compressor. A minimum allowable value of the parameter at which the centrifugal compressor is likely to enter surge conditions at the optimal speed is determined by the control-

ler along with a feed back multiplier that when multiplied by the optimal speed will either increase the speed when the parameter is less than the minimum allowable value or will reduce the speed when the parameter is greater than or equal to the minimum allowable value. A total speed multiplier is set equal to the feed back multiplier during the steps of the repeating cycle where the centrifugal compressor is at least likely to enter surge conditions, other than an evacuation step and an evacuation with purge step thereof. The total speed multiplier is set equal to a mathematical product of the feed back multiplier and a feed forward multiplier during the evacuation step and the evacuation with purge step, that will increase the speed such that centrifugal compressor is not likely to enter surge conditions. An adjusted speed is calculated by multiplying the optimal speed by the total speed multiplier.

[0016] The controller is configured to generate a control signal in response to the control program and able to serve as an input into the variable frequency drive such that speed of the electric motor and therefore, the centrifugal compressor is controlled in response to the control signal. The control signal referable at least to the adjusted speed such that the electric motor and therefore, the centrifugal compressor operates at the adjusted speed.

[0017] The repeating cycle can include a feed with equalization step subsequent to the evacuation with purge step, a feed with product repressurization step following the feed with equalization step and an equalization step prior to the evacuation step. The control program can be programmed to produce a non-operational speed at which the variable frequency drive will remove electrical power from the electric motor and the control signal is referable to the non-operational speed when produced by the control program. During the feed with equalization step, the equalization step and initiation of the feed with product repressurization step, the control program produces the non-operational speed such that when the control signal is inputted into the variable frequency drive, electrical power is not applied to the electric motor. The control program also programmed such that when a predetermined pressure ratio of the pressure ratio is obtained during the feed with product repressurization step, the control signal is again referable to the adjusted speed such that the electric motor and therefore, the compressor operates at the adjusted speed.

[0018] The control program can be programmed such that each time the feed back multiplier is determined, the feed back multiplier is stored. In accordance with such programming, when the parameter is less than the minimum allowable value, the feed back multiplier is determined by adding to a last stored value of the feed back multiplier a speed correction factor. When the parameter is greater than or equal to the minimum allowable value, the feed back speed multiplier is determined by dividing the last stored value of the feed back multiplier by a proportionality constant. The proportionality constant is set equal to a value greater than 1.0 when the last stored value of the feed back multiplier is greater than or equal to 1.0 or 1.0 when the last stored value of the feed back multiplier is less than 1.0.

[0019] The control program can also be programmed such that the feed forward multiplier is a function of the pressure ratio. Such function has a maximum value of the feed forward multiplier at a predetermined pressure ratio at which or directly before which the centrifugal compressor will likely enter surge conditions during a transition between the evacu-

ation step and the purge step. The feed forward multiplier has decreasing values of the feed forward multiplier at pressure ratios greater than or less than maximum value. The maximum valve has a magnitude preselected such that when the maximum valve is multiplied by the optimal speed at the predetermined pressure ratio the resulting speed will prevent the centrifugal compressor from entering surge conditions. The function can be a Gaussian function.

[0020] The parameter sensing means can include two further pressure transducers situated at two points in the shroud of the centrifugal compressor that are successively closer to an impeller thereof. In such case, the control program is programmed to calculate a pressure difference from pressure measured by the two further pressure transducers. The parameter is the pressure difference. In such case, the control program can be programmed such that during each of the time intervals, a pressure difference error is calculated and stored by subtracting the minimum allowable value from the current value of the pressure difference. The speed correction factor of the feed back multiplier is calculated during each of the time intervals through proportional integral control comprising adding a proportional term to an integral term. The proportional term calculated by multiplying a gain factor by a difference between the pressure difference error and a prior pressure difference error calculated in a prior time interval and dividing the difference by the time interval. The integral term can be calculated by dividing the gain factor by an integral reset time and multiplying a resultant quotient thereof by the pressure difference error.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] While the specification concludes with claims distinctly and particularly pointing out the subject matter that Applicants regard as their invention, it is believed that the invention will be better understood when taken in connection with the accompanying drawings in which:

[0022] FIG. 1 is a schematic diagram of a vacuum pressure swing adsorption apparatus for conducting a process in accordance with the present invention;

[0023] FIG. 2 is an exemplary diagram of the speed and power applied to a permanent magnet motor used in driving a compressor used in FIG. 1;

[0024] FIG. 3 is a logic diagram of speed control programming utilized in a controller employed in FIG. 1;

[0025] FIG. 4 is an exemplary curve of a compressor map illustrating the peak efficiency operating line graphed against pressure ratio versus mass flow through the compressor; and

[0026] FIG. 5 is a Gaussian curve of a feed forward speed multiplier used in control programming of the controller employed in FIG. 1.

DETAILED DESCRIPTION

[0027] With reference to FIG. 1, a vacuum pressure swing adsorption apparatus 1 is illustrated that is designed to produce an oxygen product. Although vacuum pressure swing adsorption apparatus 1 is a single bed design, it is understood that this is for purposes of illustration and the present invention would have equal applicability to a multiple bed design using a single or multiple compressors designed to pressurize and evacuate an adsorbent bed or beds. Furthermore, the present invention is equally applicable to vacuum pressure swing adsorption apparatus designed to produce other products such as carbon dioxide, nitrogen, hydrogen or helium. As

such, the vacuum pressure swing adsorption apparatus 1 is shown and described herein for exemplary purposes only.

[0028] Vacuum pressure swing adsorption apparatus 1 draws air through an inlet 10 that contains a filter to filter out particulates. The resulting air feed stream is drawn by a compressor 12 having an after cooler 14 to remove the heat of compression. The resulting compressed feed stream is introduced into an adsorbent bed 16 that can contain well known LiX adsorbents to produce an oxygen product that is introduced into an oxygen surge tank 18 from which an oxygen product stream 20 can be drawn. It is to be noted that compressor 12 is directly driven by a variable speed permanent magnet motor 38 in which the speed is controlled by a variable frequency drive 40 to be discussed in which an adjusted speed signal is generated by a controller 42, the "PLC", also to be discussed. In this regard, as indicated above, the present invention also has applicability to high speed induction motors.

[0029] The adsorbent bed 16 is subjected to a repeating cycle in the production of the oxygen product stream that has seven steps. In a first of the steps, a feed with equalization step is conducted in which the adsorption bed 16 is simultaneously pressurized from the bottom with the feed air and with the use of the compressor 12 and from the top with equalization gas delivered from a recovery tank 22. In order to accomplish this, valves 24 and 26 are set in open positions, valves 28, 30 and 34 are set in closed positions and a valve 36 is set in a partially open position. With additional reference to FIG. 2, it can be seen that the speed of compressor 12 is falling due to deceleration from a final step seven to be discussed hereinafter. It is to be noted that in FIG. 2, the step number indicates the end of a particular step. In any case, the purpose of such step is to allow the adsorbent bed 16 to be gradually brought up to an operational pressure.

[0030] At the conclusion of Step 1, Step 2 is initiated, a feed with product pressurization step, by closing valve 36 and partially opening valve 34. During this step, high purity product is now being supplied to the adsorbent bed 16 from the oxygen surge tank 18 while the adsorbent bed 16 is pressurized from the bottom with the use of the compressor 12. As can best be seen from FIG. 2, the adsorbent bed 16 at the conclusion of step 2 has been brought up to an operational pressure at which adsorption is commenced in a step 3. During step 2, the compressor speed begins to rise from a minimum as the pressure increases.

[0031] In step 3, a feed only step, valves 28, 30, 34 and 36 are now set in closed positions while the adsorbent bed is further pressurized by the compressor 12 to cause nitrogen to be adsorbed within the adsorbent bed 16. During step 3, the speed of the compressor is gradually increased as is the pressure within the adsorbent bed 16. Step 3 is followed by a feed and production step 4 in which the speed of the compressor 12 is increasing as is the pressure within the adsorbent bed 16. During step 4, valve 34 opens and oxygen product flows into the oxygen surge tank 18.

[0032] After production, the adsorbent bed is regenerated in a series of steps that begins with a step 5 that constitutes an equalization step. Step 5, the equalization step, begins with the compressor 12 in an unpowered state and as such the speed of the compressor 12 begins to fall along with the pressure within the adsorbent bed. Equalization gas is vented from the top of the adsorbent bed 16 to recovery tank 22 by partially opening valve 36. At the conclusion of step 5, step 6 is commenced, an evacuation step, in which the adsorbed bed

begins to be evacuated by closing valve 36 and opening valves 28 and 30. The compressor now is acting as a vacuum pump and is removing waste nitrogen from the adsorbent bed 16 and discharging the waste nitrogen through vent silencer 39. At step 7, evacuation continues with an oxygen purge by partially opening valve 36. This is known as an evacuation with purge step. From step 7, the cycle is continued by commencing step 1 by opening the valves as described above.

[0033] The foregoing operation of vacuum pressure swing adsorption system is conventional. However, for reference, the following Table indicates the valve positioning during each of the steps 1-7 outlined above.

TABLE

		STEP						
		1	2	3	4	5	6	7
VALVE NUMBER	24	O	O	O	O	O	C	C
	28	C	C	C	C	O	O	O
	26	O	O	O	O	C	C	C
	30	C	C	C	C	C	O	O
	34	C	P	C	O	C	C	C
	36	P	C	C	C	P	C	P

O = Open

C = Closed

P = Partially open

Although not illustrated, the valves would be controlled by a programmable logic controller that would be programmed to proceed from step to step on the basis of pressure and time. For example, steps 1 and step 2 can be time based steps which conclude upon the elapse of a time interval. The time periods of step 1 and step 2 are set to achieve desired pressures within the adsorbent bed 16 that will bring the adsorbent bed 16 up to an operational pressure at which adsorption will be conducted. Steps 3 and 4 can be pressure based and end when the bed pressure is at an adsorption pressure set point that is an optimal pressure for nitrogen adsorption of the adsorbent. Step 5 can again a time based step in which the time interval is set to achieve a desired low pressure within the adsorbent bed and send a desired amount of gas to recovery tank 22 for later purge and equalization purposes. Step 6 is typically a pressure based step at which the optimal desorption pressure is obtained and step 7 is a time based step that is set to guarantee a sufficient desorption for regeneration of the adsorbent bed 16.

[0034] Although the present invention has been thus far described with reference to a single bed vacuum pressure swing adsorption process, it is equally applicable to a multiple bed process. As would be known to those skilled in the art, where a multiple bed process was conducted, in place of the recovery tank 22, equalization gas would be vented from one adsorbent bed and introduced into another adsorbent bed. Since the production would be continuous, the oxygen surge tank 18 would be of smaller volume than that used with the illustrated single bed apparatus and process.

[0035] In accordance with the present invention, the speed of compressor 12 is controlled by varying the speed of a permanent magnet motor 38 by a variable frequency drive 40 that is responsive to a control signal 43 generated by a controller 42 that can be a programmable logic controller "PLC". It is understood that the controller 42 could be incorporated into the controller that is used in controlling the valve sequence shown in the Table above or could be a separate controller that is responsive to the valve sequence controller

and in particular and for purposes that will be discussed, the exact step that is being executed by the valve sequence controller. The variable frequency drive **40** and the permanent magnet motor **38** can be obtained from a variety of known manufacturers and are readily available.

[0036] Controller **42** can be a Allen Bradley SLC 5/05 processor programmed with RSLogix 500 software or equivalent that can be obtained from Rockwell Automation located in Milwaukee, Wis., USA. The program within controller **42** continually executes during predetermined, repeating time intervals. Controller **42** is responsive to signals generated by pressure transducers **44**, **46** and **48** and preferably a temperature transducer **50** and transmitted by suitable electrical connections **45**, **47**, **49** and **51**, respectively. Additionally, a data input **52** is provided that serves as an input to the controller **42** containing the actual current step that the repeating cycle being conducted by the vacuum pressure swing adsorption apparatus **1**. This data concerning the current step serves as an input to the control program that in a manner to be discussed responds to such data. Data input **52** can be obtained from the controller acting to control the valves in the repeating cycle being conducted by vacuum pressure swing adsorption apparatus **1**.

[0037] With reference to FIG. 3, the control logic is programmed within controller **42** by means of a control program. As a first stage of the programming, as illustrated by logic block **53**, the motor **38** is started along with a repeating cycle conducted by the vacuum pressure swing adsorption apparatus **1** that has been described above with respect to the positioning of the valves. In starting the motor **38**, it is set to run at a minimum speed which constitutes 40 percent of a design maximum speed. At above this speed, power begins to be applied to the motor. The variable frequency drive **40** is responsive to the control signal **43** generated by controller **42** to either control the permanent magnet motor **38** to run at an adjusted speed that will avoid surge or to cut power to the high speed permanent magnet motor **38** and thereby allow the permanent magnet motor **38** and therefore, the compressor **12** to decelerate when required in the repeating cycle.

[0038] After the first step **53**, the controller then commences the continual execution over the predetermined, repeating time intervals which are each preferably less than 1 millisecond. In the step **54** a pressure difference “dP” is calculated at the shroud of the compressor **12** at two points or locations that are situated successively closer to the impeller or at the points measured by pressure transducers **46** and **48**. This pressure difference, between the pressure measured by pressure transducers **48** and **46**, respectively, provide a parameter that is referable to the flow passing through the compressor **12**. In this regard, flow could be directly measured by a flow transducer. In the next logical stage of execution, designated by reference number **56**, a pressure ratio across the compressor is calculated on the basis of the pressures measured by pressure transducer **48** and **44** or in other words, a ratio between outlet and inlet pressure and stored. Following the pressure ratio computation and storage, the current pressure ratio is compared with a previous value in step **57**.

[0039] The optimal speed of the compressor **12** is determined from the pressure ratio calculated in logic block **54** that lies along the peak efficiency operating line. This is determined from compressor performance data for the particular compressor used. With reference to FIG. 4, an example of such data is set forth. The exact determination of this speed

could be from a look up table or a polynomial equation in which the points of the peak efficiency operating line, referred to in the Figure as the “Best Efficiency Line”, are fit in accordance with well known curve fitting techniques. It is understood that this curve will vary slightly based upon the temperature measured by temperature transducer **50**. As such there would be data programmed within the control program that constitutes a family of such curves. Where temperature lies in an intermediate point, the exact speed could be interpolated between curves or multiplied by a correction factor equal to a ratio of the measured temperature to the design temperature from which an operating curve was derived. Alternatively, there could be a single curve that is based upon the expected temperature in which apparatus **1** operates. In such case, there would be no requirement for an input of temperature from temperature transducer **50**. The lines crossing the peak efficiency operating line are specific speeds at which pressure ratio will vary with flow rate through the compressor. As is evident from the graph, at any particular speed, there exists a flow rate through the compressor **12** at which surge will occur.

[0040] After the optimal speed is calculated, execution step **60** is performed in which it is determined whether the vacuum pressure swing adsorption cycle is at the start of step 1 or step 5, namely, at the start of the feed with equalization or the equalization steps. This determination is made from data input **52**. If at the start of such steps, then a non-operational speed is set by the programming, as indicated in step **62**, and the control signal **43** will be referable to such non-operational speed. For instance, this speed could be 40 percent of the design maximum speed of the motor **38**. The variable frequency drive **40** is in turn programmed or set up so that when the control signal **43** is referable to the non-operational speed, energy input to the motor **38** will be disabled, allowing the drive train (motor rotor and compressor impeller) to free-wheel decelerate or coast down to its minimum speed without consuming any power. In this regard, variable frequency drives **40** are typically set up to so function without any modification. This being said, it is equally possible to program the control program executing within controller **42** to generate a signal to control the power supply to the permanent magnet motor **38** to cut power when appropriate in the repeating cycle. With reference again to FIG. 4, the “Typical Deceleration Line” is the path the compressor follows when the repeating cycle conducted by the vacuum pressure swing adsorption apparatus **1** requires the compressor speed to decelerate due to falling head requirements. This is the case in step 1, part of step 2 and step 5.

[0041] Eventually, the drive train will have to power up during step 2 or in other words, the feed with product pressurization step. It begins with falling pressure. Consequently, at the initiation of step 2, the control signal **43** remains referable to the non-operational speed. However, with reference again to FIG. 2, pressure over a portion of such step begins to rise due to requirements of the repeating cycle and the application of power to the permanent magnet motor **38**. In order to execute appropriate control to effectuate the foregoing operation, if the logic in step **60** is answered in the negative, then the program proceeds with execution of the test indicated in logic block **64** in which it is determined whether the step of the repeating cycle, the “VPSA Step” is at the feed with product pressurization, namely step 2, discussed above. Again this test is performed on the basis of the data input **52**. If this test is answered in the affirmative, execution of the control pro-

gram proceeds to execution of a further test shown in logic block 66 and the current pressure ratio “P2/P1”, as measured by pressure transducers 48 and 44, is compared with a predetermined pressure ratio of “Predetermined P2/P1” which has previously being programmed within the control program. If the current pressure ratio is less than the predetermined pressure ratio, then again the program proceeds to the execution stage of the programming shown in block 62 and the permanent magnet motor 38 is allowed to continue to decelerate. As illustrated, where power to motor 38 is cut, the control program loops back to execution stage 54. If, however, the tests performed in the programming as set forth in logic blocks 60 and 64 are in the negative or the test performed in logic block 66 is in the affirmative, then the repeating cycle is not on steps 1 or 5 and is possibly in step 2 where power must be applied to the permanent magnet motor 38. At such point in the repeating cycle being conducted by vacuum pressure swing adsorption cycle, the compressor is being powered and therefore, there is a possibility or likelihood that surge conditions could be encountered in the operation of compressor 12. In order to avoid operation of compressor 12 where surge conditions could be encountered, the programming logic proceeds to the remainder of its execution starting with logic block 68.

[0042] In the execution of the programming as shown by logic block 68, the calculated pressure difference in logic block 54 “Shroud dP” is compared with a minimum dP. This minimum dP which is a value that is experimentally determined to be the minimum value over the entire cycle at which the compressor 12 will surge with a factor of safety. For instance, if compressor 12 will surge at any time during the repeating cycle conducted by the vacuum pressure swing adsorption apparatus 1 at a dP equal to 2 inches of water, the 2 inches of water is multiplied by 15 percent to obtain the minimum. An alternative to this is to determine at dP in step 58 along with the calculation of the optimal speed from the compressor map of the compressor as show as an exemplar in FIG. 4 to be discussed.

[0043] The execution of logic block 68 is a critical step because if the flow rate through the compressor is less than a minimum, then there exists a danger that the compressor 12 will enter surge. If, however, the calculated current pressure difference dP obtained in logic block 54 is greater than or equal to the minimum, there exists a lower probability of the compressor entering surge. In cases, however, that the calculated pressure difference from logic block 54 is not less than such minimum, as indicated in step 70 a feed back speed multiplier is calculated by dividing the last stored value of the feed back multiplier, “(SM_{FB})” that has been determined in a previous execution of the control program, by a proportionality constant. The proportionality constant is set equal to a value greater than 1.0, for instance 1.04 when the last stored value of the feed back multiplier is greater than or equal to 1.0. The exact value of such proportionality constant is determined through experimentation and can be considered as a tuning factor. When, however, the last stored value of the feed back multiplier is less than 1.0, the proportionality constant is simply set to 1.0. When such a feed back multiplier is multiplied by the optimal speed calculated in the execution stage illustrated by logic block 58, the effect of this will be to decrease speed slightly by use of the proportionality constant or to further decrease the speed by the factor of the last stored feed back multiplier when such last stored feed back multiplier is less than 1.0. If, however, the pressure difference

measured in step 54 is less than the minimum pressure difference, then, as indicated in logic block 72, a new feed back multiplier will be calculated that will have the effect of increasing the speed. The calculation contemplated in logic block 72 is to add to a last stored value of the feed back multiplier, a speed correction factor. While such speed correction factor could be a constant, preferably, the speed correction factor contains proportional and integral terms. During each execution of the program, a pressure difference error is calculated and stored by subtracting the minimum allowable value from the current value of the pressure difference calculated in logic block 54. The proportional term is calculated by multiplying a gain factor by a difference between the pressure difference error and a prior pressure difference error calculated in a prior time interval or a prior execution of the control program and dividing the difference by the time interval. This prior pressure difference error is obtained from the stored value read from logic block 54 before calculation and storage of the current pressure difference error. The integral term is calculated by dividing the gain factor by an integral reset time and multiplying a resultant quotient thereof by the current pressure difference error.

[0044] The foregoing can be illustrated by the following equation:

$$SM_{FBi} = SM_{FBi-1} + K_c * \frac{(\epsilon_i - \epsilon_{i-1})}{t} + \frac{K_c}{\tau_I} * \epsilon_i;$$

where: SM_{FBi}=Feed Back Speed Multiplier; SM_{FBi-1}=The previous stored value of the Feed Back Speed Multiplier, K_c is the gain; ϵ_i is the pressure difference error; ϵ_{i-1} is the last stored value of the pressure difference error; τ_I is the integral reset time and t is the execution time interval of the control program. Thus, proportional—integral speed control is being exercised here and the “gain” and the “integral reset time” are simply known tuning factors that will be experimentally determined in a manner known in the art.

[0045] The program execution next proceeds to a step 74 in which the program tests where the current step of the repeating cycle conducted by the vacuum pressure swing adsorption apparatus 1 mentioned above is either in an evacuation or evacuation with purge step, or in other words, whether it is in steps 6 or 7 involving evacuation or evacuation with a product purge. If the vacuum pressure swing adsorption process is not in either of these steps, the a feed forward speed multiplier is set at 1.0 as indicated in the logic block of program designated by reference number 76 and a total speed multiplier is calculated in step 78 by multiplying the feed back speed multiplier determined in either steps 70 and 72 by 1.0. In other words, in such case, the total speed multiplier is equal to the feed back speed multiplier.

[0046] In case the test perform in logic block 74 is in the affirmative, then a feed forward speed multiplier is calculated in step 80 that will prevent surge during the evacuation or evacuation with purge steps and in particular at a point during the vacuum pressure swing adsorption cycle that lies near or at a transition between these two steps. While not well understood by the inventors herein, it has been found in practice that there exists a particular danger of the compressor 12 entering surge at that point of operation. In any case, with reference to FIG. 5, depending upon the current pressure ratio value calculated in step 56, a feed forward multiplier will be determined that is dependent upon such pressure ratio that

will prevent surge. When this feed forward multiplier is multiplied by the feed back speed multiplier, the effect will be to increase the total speed multiplier calculated in step 76 over that which would be obtained from the feed back speed multiplier alone.

[0047] After the total speed multiplier has been calculated in step 78, an adjusted optimal speed is calculated in logic block 82 by multiplying the optimal speed calculated in step 58 by the total speed multiplier (“SM_T”) to obtain an adjusted speed. This adjusted speed is then used to set the speed in the variable frequency drive 40 as shown in step 84. In this regard, the controller 42, in response to the value of the adjusted speed determined by the control program, generates the control signal 43 that is referable to such adjusted speed. This control signal 43 will then serve as an input that would revise the speed set in variable frequency drive 40. Another possibility would be for the variable frequency drive being programmed to read the output of adjusted speed that is generated by the controller 42. In any case, the programming proceeds to the next execution thereof after the elapse of the re-occurring execution time by looping back to execution step 54.

[0048] With reference again to FIG. 2, the strategy behind the speed control of the present invention is basically to obtain a speed based upon pressure ratio that will in most cases operate the compressor 12 upon its peak efficiency operating line shown in FIG. 3. Specifically, at the conclusion of the seventh step in the vacuum pressure swing adsorption process, the pressure ratio developed across the compressor 12 will be, in the embodiment described herein, about 2. The adsorbent bed will, however, be at a negative pressure. As, equalization gas flows into adsorption bed 16 from equalization tank 22, bed pressure rises rapidly from step 7 in which the bed has been evacuated to remove the nitrogen and conclude regeneration of the adsorbent. However, as far as the pressure ratio across the compressor 12 is concerned, during at least a portion of the pressure rise, power will be removed from the permanent magnet motor 38 and as shown, in FIG. 2, now power is being applied for part of the step and the speed of the compressor 12 is decelerating. During step 2, pressurization continues with product gas and a point is reached in which the pressure ratio as sensed by pressure transducers 48 and 44 increases due to the increase in bed pressure such that the speed of the compressor 16 must be increased to maintain operation along the peak efficiency operating line as shown in FIG. 3. During either of these steps, if the compressor 12 does not accelerate quickly enough the flow rate through the compressor as sensed by pressure transducers 46 and 44 may not be sufficient to avoid surge. In such case, this would be a situation in which an affirmative answer for the test in program execution block 68 would be in the affirmative and a feed back multiplier would be computed that necessarily increase the speed of the compressor to avoid surge. As steps 3 and 4 take place, the pressure ratio across the compressor increases due to the increase in bed pressure. The compressor therefore, speeds up to obtain the increase along the peak efficiency operating line. At such time, it is unlikely that the compressor will be at a mass flow anywhere near a condition at which surge would occur; and the inquiry in block 68 would be answered in the negative. This would result in a reduction of compressor speed back towards the peak efficiency operating line by either further reducing the feed back speed multiplier with the proportionality constant if the last value

were 1.0 or greater or by reducing the speed further with the last value of the feed back speed multiplier.

[0049] After the conclusion of step 4, the adsorbent bed 16 needs to be regenerated. At this point gas is allowed to escape from the adsorbent bed 16 into the equalization tank 22. The pressure ratio falls rapidly and preferably, as described above, the variable frequency drive 40 reacts to the control signal 43 referable to the nonoperational speed produced in logic block 62 and ceases to apply power to the permanent magnet motor 38. Given that the motor is unloaded it is unlikely that a surge event would occur. However, at the beginning of the sixth step, the compressor 12 is acting as a vacuum pump and as the pressure decreases within adsorbent bed 16, the pressure ratio starts to rise. If the mass flow through the compressor is not sufficient, surge could occur. However, now an aggressive feed forward speed multiplier is calculated with the aid of FIG. 5. As the pressure ratio increases across the compressor as measured by pressure transducers 48 and 44, the feed forward speed multiplier increases to a peak value at a pressure ratio of about 1.7. This pressure ratio is experimentally determined to be that pressure ratio at which surge is likely to occur and the feed forward speed multiplier is selected to be that value that will sufficiently increase the speed of the compressor to avoid surge. As the pressure ratio further increases due to the evacuation of the adsorbent bed 16, the pressure ratio further increases. However, the feed forward speed multiplier decreases. The reason for this is that the motor and compressor combination will not react immediately due to aerodynamic drag and inertial effects. Consequently, as the pressure ratio increases, the speed of the compressor is gradually increased and after the peak, the speed is gradually decreased to allow the compressor to decelerate and return to peak efficiency so that the next step 1 can take place at which power to the permanent magnet motor is removed.

[0050] With specific reference to FIG. 5, preferably the response of the feed forward speed multiplier is obtained with a Gaussian function in which the feed forward speed multiplier is given by the equation:

$$\text{START} + \text{Amplitude}^{[F/\text{spread}]},$$

where $F = (P_2/P_1 - \text{Center})$. “Start” will shift the curve shown in FIG. 4 up or down, “Amplitude” will move the peak up or down. “Center” will shift the pressure ratio where the peak occurs and “Spread” controls the rate at which the curve fans out from the center. Thus, the curve itself could be programmed within the control program or data points within a look up table could likewise be programmed. This being said, rather than the illustrated Gaussian curve, the curve could be triangular. Less preferred, but possible, would just be to use the peak of the curve for the feed forward speed multiplier. Likewise, it would be possible to use a fixed factor of increase for the feed back speed multiplier so that the compressor speed would be increased if the flow rate through the compressor dropped below an allowable point and reduced by a fixed factor if the flow rate remained above the allowable point. Why neither of these are preferred is that a greater percentage of operation of the compressor will be off the peak efficiency operating line and therefore, the apparatus 1 will consume more power.

[0051] As mentioned above, the programming of the variable frequency drive 40 to remove power at very low speeds is also optional, but as could be appreciated, such operation also saves power. All of the foregoing being said, it is possible to conduct an embodiment of the present invention in which

power is never removed from the motor **38**. In other words, an embodiment without execution stages **60**, **62**, **64** and **66**. However, if power to the motor were not disabled, then the variable frequency drive **40** will attempt to ramp down the speed along a preprogrammed path by inputting power to the motor **38**, thus consuming more power. However, at the very least, the present invention does contemplate programming logic of the type shown in the subsequent logic blocks **68-84** where compressor **12** is at least likely to encounter surge operational conditions, namely, in the present cycle, part of step 2 where pressure ratio across the compressor **12** is rising and thus, power needs to be applied to permanent magnet motor **38**, steps 3-4 and steps 6 and 7.

[0052] While the present invention has been described with reference to a preferred embodiment as will occur to those skilled in the art, numerous, changes, additions and omission can be made without departing from the spirit and scope of the invention as set forth in the appended claims.

We claim:

1. A method of controlling speed of a centrifugal compressor operating within a vacuum pressure swing adsorption apparatus and directly driven by an electric motor controlled by a variable frequency drive, said method comprising:

measuring and calculating a parameter referable to a flow rate of gas entering the centrifugal compressor;
measuring and calculating a pressure ratio of outlet to inlet pressure of the compressor;

determining an optimal speed of the centrifugal compressor based on the pressure ratio and that lies along the peak efficiency operating line of the centrifugal compressor;

determining a minimum allowable value of the parameter at which the centrifugal compressor is likely to enter surge conditions at the optimal speed;

determining a feed back multiplier that when multiplied by the optimal speed will either increase the speed when the parameter is less than the minimum allowable value or will reduce the speed when the parameter is greater than or equal to the minimum allowable value;

during steps of a repeating cycle conducted by the vacuum pressure swing adsorption apparatus where the centrifugal compressor is at least likely to encounter surge conditions, other than an evacuation step and an evacuation with purge step thereof, setting a total speed multiplier equal to the feed back multiplier;

during the evacuation step and the evacuation with purge step, calculating the total speed multiplier by multiplying the feed back multiplier by a feed forward multiplier that will increase the speed during the evacuation step and the evacuation with purge step such that centrifugal compressor is not likely to enter the surge conditions;

calculating an adjusted speed by multiplying the optimal speed by the total speed multiplier; and

generating a control signal referable at least to the adjusted speed and inputting the control signal into the variable frequency drive such that the electric motor and therefore, the centrifugal compressor operates at the adjusted speed.

2. The method of claim 1, wherein:

the repeating cycle includes a feed with equalization step subsequent to the evacuation with purge step, a feed with product repressurization step following the feed with equalization step and an equalization step prior to the evacuation step; and

during the feed with equalization step, the equalization step and initiation of the feed with product repressurization step, the control signal is referable to a non-operational speed such that when the control signal is inputted into the variable frequency drive, electrical power is not applied to the electric motor; and

when a predetermined pressure ratio is obtained during the feed with product repressurization step, the control signal is again referable to the adjusted speed such that the electric motor and therefore, the compressor operates at the adjusted speed.

3. The method of claim 1, wherein:

each time the feed back multiplier is determined, the feed back multiplier is stored;

when the parameter is less than the minimum allowable value, the feed back multiplier is determined by adding to a last stored value of the feed back multiplier a speed correction factor; and

when the parameter is greater than or equal to the minimum allowable value, the feed back speed multiplier is calculated by dividing the last stored value of the feed back multiplier by a proportionality constant, the proportionality constant set equal to a value greater than 1.0 when the last stored value of the feed back multiplier is greater than or equal to 1.0 or 1.0 when the last stored value of the feed back multiplier is less than 1.0.

4. The method of claim 1, wherein:

the feed forward multiplier is a function of the pressure ratio;

the function having a maximum value of the feed forward multiplier at a predetermined pressure ratio at which or directly before which the centrifugal compressor will likely enter surge conditions during a transition between the evacuation step and the purge step and decreasing values of the feed forward multiplier at pressure ratios greater than or less than maximum value; and

the maximum value has a magnitude preselected such that when the maximum value is multiplied by the optimal speed at the predetermined pressure ratio the resulting speed will prevent the centrifugal compressor from entering surge conditions.

5. The method of claim 4, wherein the function is a Gaussian function.

6. The method of claim 1, wherein the parameter is a pressure difference measured at two point in the shroud of the centrifugal compressor that are successively closer to an impeller thereof.

7. The method of claim 3, wherein:

the parameter is a pressure difference measured at two points in the shroud of the centrifugal compressor that are successively closer to an impeller thereof;

during each of the time intervals, a pressure difference error is calculated and stored by subtracting the minimum allowable value from the a current value of the pressure difference; and

the speed correction factor of the feed back multiplier is calculated during each of the time intervals through proportional integral control comprising adding a proportional term to an integral term, the proportional term calculated by multiplying a gain factor by a difference between the pressure difference error and a prior pressure difference error calculated in a prior time interval and dividing the difference by the time interval and the integral term calculated by dividing the gain factor by an

integral reset time and multiplying a resultant quotient thereof by the pressure difference error.

8. The method of claim 7, wherein:

the feed forward multiplier is a Gaussian function of the pressure ratio;

the Gaussian function having a maximum value of the feed forward multiplier at a predetermined pressure ratio at which or directly before which the centrifugal compressor will likely enter surge conditions during a transition between the evacuation step and the purge step and decreasing values of the feed forward multiplier at pressure ratios greater than or less than maximum value; and the maximum valve has a magnitude preselected such that when the maximum valve is multiplied by the optimal speed at the predetermined pressure ratio the resulting speed will prevent the centrifugal compressor from entering surge conditions.

9. A control system for controlling speed of a centrifugal compressor operating within a vacuum pressure swing adsorption apparatus and directly driven by an electric motor controlled by a variable frequency drive, said control system comprising:

means for sensing a parameter referable to a flow rate of gas entering the centrifugal compressor;

pressure transducers positioned to sense pressure at an inlet and an outlet of the centrifugal compressor;

a controller responsive to the parameter sensing means, the pressure transducers and steps of a repeating cycle conducted by the vacuum pressure swing adsorption apparatus and having a control program programmed to:

calculate a pressure ratio of the pressures of the outlet to inlet of the centrifugal compressor;

determine an optimal speed of the centrifugal compressor based on the pressure ratio and that lies along the peak efficiency operating line of the centrifugal compressor;

determine a minimum allowable value of the parameter at which the centrifugal compressor is likely to enter surge conditions at the optimal speed;

determine a feed back multiplier that when multiplied by the optimal speed will either increase the speed when the parameter is less than the minimum allowable value or will reduce the speed when the parameter is greater than or equal to the minimum allowable value;

set a total speed multiplier equal to the feed back multiplier during the steps of the repeating cycle where the centrifugal compressor is at least likely to enter surge conditions, other than an evacuation step and an evacuation with purge step thereof;

set the total speed multiplier equal to a mathematical product of the feed back multiplier and a feed forward multiplier during the evacuation step and the evacuation with purge step, that will increase the speed such that centrifugal compressor is not likely to enter the surge conditions; and

calculate an adjusted speed by multiplying the optimal speed by the total speed multiplier; and

the controller configured to generate a control signal in response to the control program and able to serve as an input into the variable frequency drive such that speed of the electric motor and therefore, the centrifugal compressor is controlled in response to the control signal, the control signal referable at least to the adjusted speed

such that the electric motor and therefore, the centrifugal compressor operates at the adjusted speed.

10. The control system of claim 9, wherein:

the repeating cycle includes a feed with equalization step subsequent to the evacuation with purge step, a feed with product repressurization step following the feed with equalization step and an equalization step prior to the evacuation step;

the control program is programmed to produce a non-operational speed at which the variable frequency drive will remove electrical power from the electric motor and the control signal is referable to the non-operational speed when produced by the control program;

during the feed with equalization step, the equalization step and initiation of the feed with product repressurization step, the control program produces the non-operational speed such that when the control signal is inputted into the variable frequency drive, electrical power is not applied to the electric motor; and

the control program also programmed such that when a predetermined pressure ratio of the pressure ratio is obtained during the feed with product repressurization step, the control signal is again referable to the adjusted speed such that the electric motor and therefore, the compressor operates at the adjusted speed.

11. The control system of claim 9, wherein the control program is programmed such that:

each time the feed back multiplier is determined, the feed back multiplier is stored;

when the parameter is less than the minimum allowable value, the feed back multiplier is determined by adding to a last stored value of the feed back multiplier a speed correction factor; and

when the parameter is greater than or equal to the minimum allowable value, the feed back speed multiplier is determined by dividing the last stored value of the feed back multiplier by a proportionality constant, the proportionality constant set equal to a value greater than 1.0 when the last stored value of the feed back multiplier is greater than or equal to 1.0 or 1.0 when the last stored value of the feed back multiplier is less than 1.0.

12. The control system of claim 9, wherein the control program is programmed such that:

the feed forward multiplier is a function of the pressure ratio;

the function having a maximum value of the feed forward multiplier at a predetermined pressure ratio at which or directly before which the centrifugal compressor will likely enter surge conditions during a transition between the evacuation step and the purge step and decreasing values of the feed forward multiplier at pressure ratios greater than or less than maximum value; and

the maximum valve has a magnitude preselected such that when the maximum valve is multiplied by the optimal speed at the predetermined pressure ratio the resulting speed will prevent the centrifugal compressor from entering surge conditions.

13. The control system of claim 12, wherein the function is a Gaussian function.

14. The control system of claim 9, wherein:

the parameter sensing means is two further pressure transducers situated at two points in the shroud of the centrifugal compressor that are successively closer to an impeller thereof;

the control program is programmed to calculate a pressure difference from pressure measured by the two further pressure transducers; and

the parameter is the pressure difference.

15. The control system of claim **11**, wherein:

the parameter sensing means is two further pressure transducers situated at two points in the shroud of the centrifugal compressor that are successively closer to an impeller thereof;

the control program is programmed to calculate a pressure difference from pressure measured by the two further pressure transducers;

the parameter is the pressure difference; and

the control program is programmed such that;

during each of the time intervals, a pressure difference error is calculated and stored by subtracting the minimum allowable value from the a current value of the pressure difference; and

the speed correction factor of the feed back multiplier is calculated during each of the time intervals through proportional integral control comprising adding a proportional term to an integral term, the proportional term calculated by multiplying a gain factor by a difference

between the pressure difference error and a prior pressure difference error calculated in a prior time interval and dividing the difference by the time interval and the integral term calculated by dividing the gain factor by an integral reset time and multiplying a resultant quotient thereof by the pressure difference error.

16. The control system of claim **15**, wherein the control program is programmed such that:

the feed forward multiplier is a Gaussian function of the pressure ratio;

the Gaussian function having a maximum value of the feed forward multiplier at a predetermined pressure ratio at which or directly before which the centrifugal compressor will likely enter surge conditions during a transition between the evacuation step and the purge step and decreasing values of the feed forward multiplier at pressure ratios greater than or less than maximum value; and the maximum value has a magnitude preselected such that when the maximum value is multiplied by the optimal speed at the predetermined pressure ratio the resulting speed will prevent the centrifugal compressor from entering surge conditions.

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