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Boyce

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[54] **METHOD AND APPARATUS FOR COMPRESSOR SURGE CONTROL**

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[52] **U.S. Cl.** **415/1;** 415/26

[51] **Int. Cl.²** **F04D 27/02;** F04D 27/00

[58] **Field of Search** 415/1, 11, 26, 28; 60/39.29, 39.28

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[57] **ABSTRACT**

A method and apparatus for detecting and controlling impending surge conditions in a compressor. A velocity probe is situated at a compressor outlet adjacent the compressor wall so as to be in the boundary layer of material flowing through the compressor adjacent the wall. Flow reversal in the boundary layer is detected as an indication of an impending surge condition. A bleed line can be connected so as to bleed off a portion of the boundary layer having a reversed flow and feed this portion back to the inlet of the compressor for delaying the onset of surge. The boundary layer flow reversal detection apparatus can also operate a back pressure valve so that the material flow bypasses the compressor when surge conditions are impending in the compressor.

11 Claims, 4 Drawing Figures

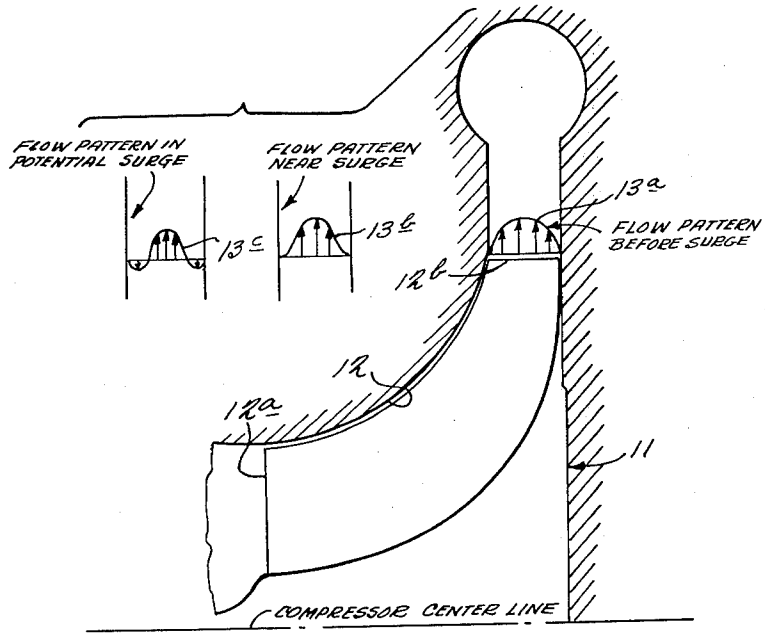


Fig. 1

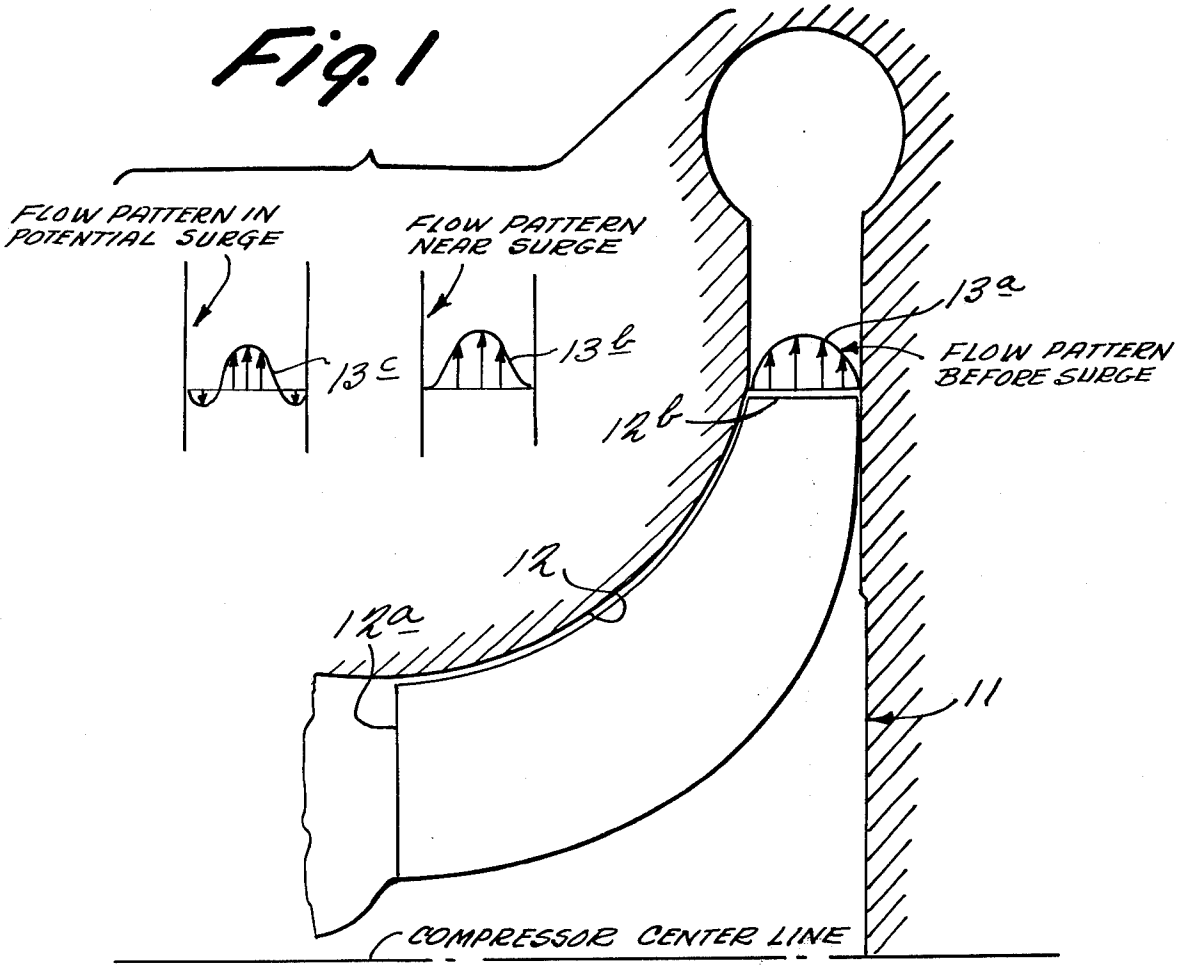

FLOW PATTERN IN POTENTIAL SURGE
FLOW PATTERN NEAR SURGE
13a
13b
13c
FLOW PATTERN BEFORE SURGE
12b
12
12a
11
COMPRESSOR CENTER LINE

Fig. 3

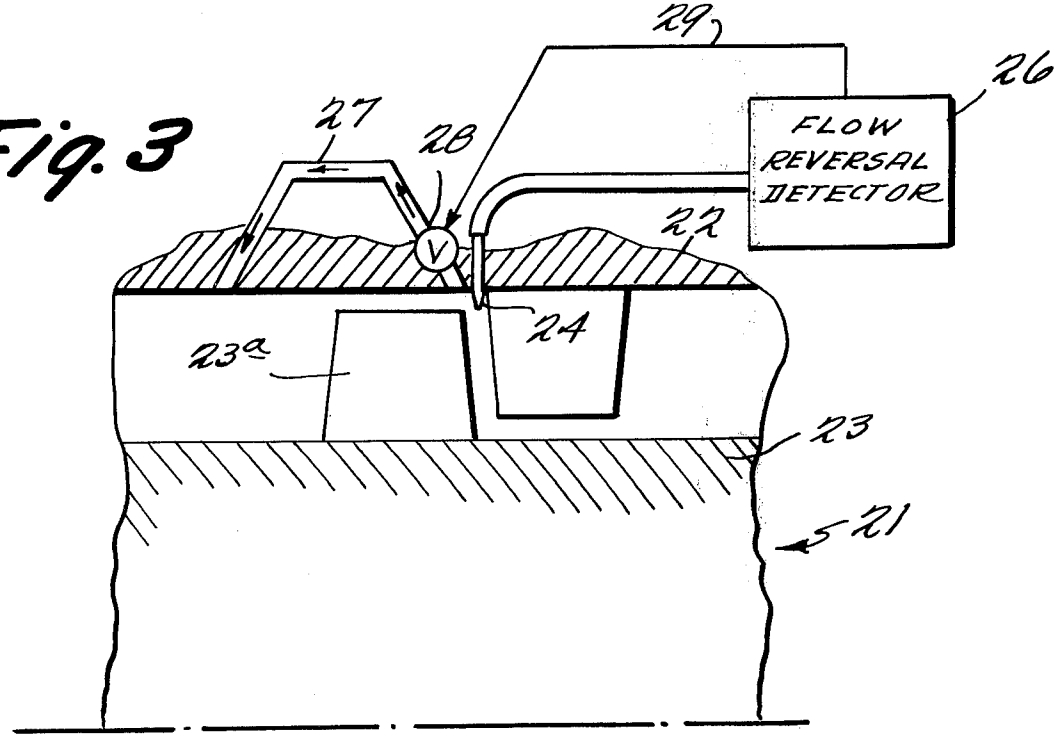
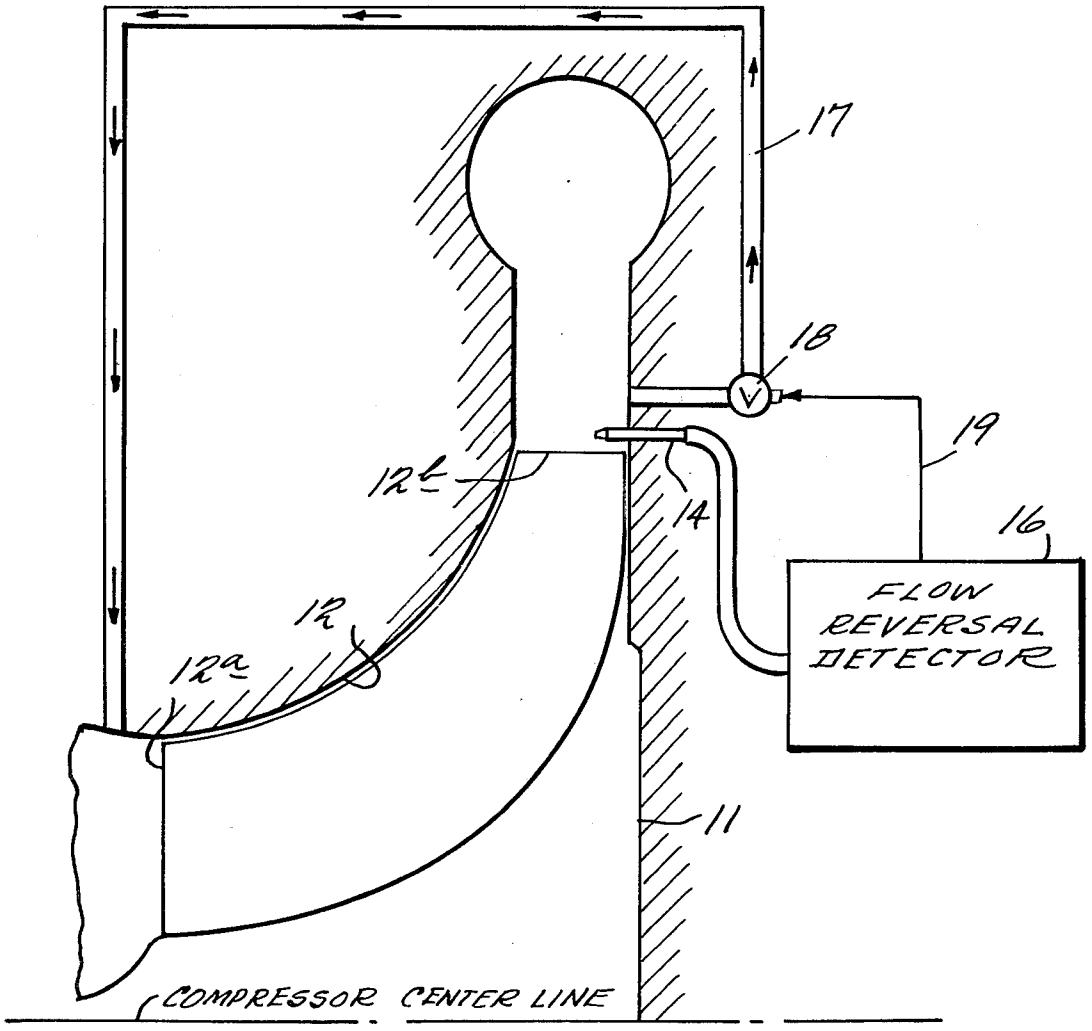

29
26
27
28
FLOW REVERSAL DETECTOR
22
24
23a
23
21

Fig. 2


17
18
19
16
14
12c
12
12a
11
FLOW
REVERSAL
DETECTOR
COMPRESSOR CENTER LINE

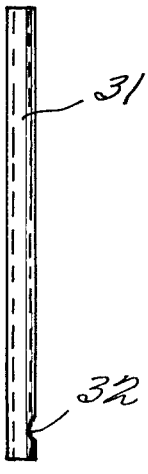

31
32

Fig. 4

METHOD AND APPARATUS FOR COMPRESSOR SURGE CONTROL

BACKGROUND OF THE INVENTION

This invention pertains to a method and apparatus for detecting impending surge conditions in a compressor and for relieving or delaying the onset of surge.

Surge is defined as the lower limit of stable operation of a compressor and consists in the reversal of material flow in the compressor. There are many reasons why surge or flow reversal occur, but predominantly this condition occurs due to high back pressure at the compressor outlet. It is important to be able to detect the onset of surge and initiate corrective action because surge conditions in a compressor can cause great damage to a compressor. One of the methods which has been used in the prior art to detect surge is to detect pressure fluctuations in the compressor in order to indicate the onset of surge. This approach suffers the limitation in that different compressors have different signature patterns of pressure fluctuations and thus it is hard to standardize on any kind of detection apparatus.

OBJECTS AND SUMMARY OF THE INVENTION

Accordingly, it is an object of this invention to provide a method and apparatus for surge detection which give a positive indication of impending surge conditions.

It is another object of this invention to provide such a method and apparatus for detecting impending surge which can be standardized and not vary in characteristics from compressor to compressor.

It is an additional object of this invention to provide a method and apparatus for detecting impending surge and including means for delaying the onset of surge.

Briefly, in accordance with one embodiment of the invention, a velocity probe is positioned at a compressor outlet near the wall of the compressor in the boundary layer of material flowing through the compressor adjacent to the wall. Flow reversal is detected in the boundary layer which is indicative of an impending surge condition.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagrammatic view of a portion of a centrifugal compressor illustrating one impeller and illustrating flow patterns from the exit of the impeller before surge, near surge, and in a potential surge.

FIG. 2 is a diagrammatic illustration similar to FIG. 1 showing a flow reversal detection system in place in a centrifugal compressor and illustrating a bleed line for delaying the onset of surge.

FIG. 3 is a diagrammatic illustration of an embodiment of the invention as applied to axial flow compressors.

FIG. 4 is a diagrammatic illustration of one form of suitable probe for detecting flow reversal.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Turning now to a consideration of FIG. 1, there is schematically shown a compressor 11 with one impeller 12 of the compressor being illustrated. The impeller 12 has an eye or entrance 12*a* and has an exit indicated by reference numeral 12*b*. The velocity profile or flow pattern of the material flowing through the compressor is indicated by curve 13*a* at the impeller exit 12*b*. The flow pattern before occurrence of surge is indicated by curve 13*a*. Adjacent to the curve 13*a* there is a curve 13*b*, which indicates the velocity profile or flow pattern of the material flowing through the impeller when a surge condition is nearing. A curve 13*c* is shown disposed adjacent curve 13*b* and curve 13*c* is an indication of the velocity profile or flow pattern of the material flowing out the impeller exit 12*b* where there is a potential surge. A comparison of the curves 13*a*, 13*b* and 13*c* in FIG. 1 shows that as surge is approached, the velocity of the boundary layer changes from positive to zero and then to negative. That is, there is a flow reversal in the boundary layer at the exit of the impeller as a surge condition is approached. The succession of flow patterns as indicated by the curves 13*a* through 13*c* has been confirmed by actual tests on compressors.

Turning now to a consideration of FIG. 2, there is shown apparatus in accordance with the invention and for practicing the method of the invention installed on a compressor. The same reference numerals are used in FIG. 2 to refer to corresponding portions of the compressor as are used in describing the compressor of FIG. 1. Thus the compressor 11 diagrammatically illustrated in FIG. 2 has an impeller 12 with an eye or inlet 12*a* and an exit 12*b*. Situated in the wall of the compressor 11 adjacent the impeller exit is a velocity probe 14. The velocity probe 14 is connected to a flow reversal detector 16. The velocity probe 14, together with the flow reversal detector 16, is adapted to sense the velocity and direction of flow of the boundary layer adjacent the compressor wall at the impeller exit. As described hereinafter, the velocity probe 14 may comprise any suitable conventional velocity probe, such as a pitot tube, hot wire anemometer, etc. As will be appreciated, such conventional probes have a flow direction sensing ability at a predetermined portion thereof which may be positioned within the boundary layer and oriented with respect to the expected downstream boundary flow direction so as to produce an output indication whenever the actual boundary layer flow direction substantially reverses. For example, a simple tube having an aperture therein with the aperture positioned to face downstream (i.e., away from the impeller exit) may be provided for achieving this function as shown schematically in the drawings. At high velocities of the boundary layer (no surge), suction pressure is measured by the probe 14 and the flow reversal detector 16 can, for a simple embodiment, simply be a mercury manometer for providing an indication of the pressure. As the flow pattern of the boundary layer nears surge, the relative pressure (i.e. relative to a static pressure) sensed by the probe 14 would drop to zero; that is, the boundary layer would have zero velocity. As a potential surge then occurs flow reversal takes place within the boundary layer and the probe 14 senses a positive pressure. Thus the probe 14, together with an appropriate flow reversal detector 16, detects flow reversal in the boundary layer to provide an indication of impending surge conditions within the compressor.

FIG. 2 also illustrates another feature in accordance with one embodiment of the invention in which bleed line 17 is provided extending between a position adjacent the impeller exit back to a position adjacent the eye or inlet of the impeller 12*a*. In FIG. 2 a valve 18 is also shown inserted in the bleed line 17. The valve 18

can be controlled through a control circuit **19** actuated by the flow reversal detector **16.**

In operation, flow reversal in the boundary layer is detected by the probe **14** and an indication of flow reversal, which it will be recalled is indicative of impending surge in the compressor, is obtained at the flow reversal detector **16.** The flow reversal detector **16** then actuates through a control circuit **19** the valve **18** which opens the bleed line **17** so that a portion of the flow reversed boundary layer is fed back from the outlet or exit of the compressor back into the eye or inlet of the impeller **12.** Bleeding back this high pressure boundary layer material when flow reversal has occurred back to the inlet of the compressor relieves the high pressure at the boundary layer at the exit of the compressor and thereby stops flow reversal. This has the effect of delaying the onset of surge conditions in the compressor. In accordance with the invention, it is only necessary to feed back through the bleed line a relatively small portion of the high pressure material (air, for example) at the impeller exit. In actual tests in accordance with the invention, it has been found that bleeding back 2 percent to 3 percent of the high pressure material at the impeller exit does have the effect of delaying the onset of surge. Of course, besides the automatic actuation of the bleed line **17** through the valve **18,** the flow reversal detector **16** can also provide an appropriate warning to an operator or control center of impending surge in the compressor.

Referring now to FIG. **3,** there is shown a schematic embodiment of application of the invention to an axial flow compressor. Thus, the axial flow compressor **21** schematically illustrated in FIG. **3** includes a stator **22** and a rotor **23.** In FIG. **3** a probe **24** is shown placed in the wall of the compressor adjacent the rotor tip **23***a*. The purpose of the probe **24** is exactly the same as for the case of the centrifugal compressor illustrated in FIGS. **1** and **2**; that is, the probe **24** detects reversal of flow in the boundary layer at the exit side of the rotor blade tip **23***a*. The probe **24,** as before, is connected to a flow reversal detector **26.** As was the case in the previous embodiment discussed herein, the velocity probe **24** may comprise a pitot tube, hot wire anemometer, or other conventional device having a flow direction sensing ability at a predetermined portion thereof. For example, a simple tube may be used having a hole therein facing downstream with the flow reversal detector in its simplest form being a pressure manometer. In accordance with one embodiment of the invention, as applied to axial flow compressors, a bleed line **27** is provided having a valve **28** therein. The valve **28** may be actuated through a control circuit **29** by the flow reversal detector **26.** Thus, when the flow reversal detector **26** detects a flow reversal in the boundary layer adjacent the exit side of the rotor blade tip **23***a*, the valve **28** is opened so that the high pressure material at the exit side of the rotor blade tip is bled back through bleed line **27** to the inlet side of the rotor blade tip **23***a*. This relieves the high pressure at the exit side of the rotor blade tip, stops flow reversal, and therefore delays the onset of surge. As before, the bleed line **27** may be of such a diameter so that 2–3 percent of the high pressure material at the exit side of the rotor blade tip is fed back into the inlet side of the rotor blade tip. Of course, the valve **28** may be an adjustable valve so that varying amounts of feedback are provided depending upon the extent of flow reversal as detected by the probe **24.**

Referring to FIG. **4,** there is illustrated one simple form of probe for use in the apparatus described for practicing the method of the invention. Thus, in FIG. **4,** a probe is shown which comprises a simple tube **31** having an aperture **32** in one side thereof. The probe is positioned in the compressor such that the aperture faces downstream in the direction of desired flow through the compressor. Thus, any positive pressure (relative to a static pressure) detected as being exerted through the aperture **32** is an indication of flow reversal. The velocity probe gives an indication of flow direction. In accordance with the invention the probe is adjacent the exit of a compressor stage are situated so as to be in the boundary layer of the flow at the compressor stage exit. Thus, in accordance with one particular embodiment of the invention, for a centrifugal compressor having a 2-inch throat or impeller exit, a probe was provided which extended 0.2 inch into the compressor throat. This placed the probe in the boundary layer of the material flow at the compressor throat. Of course, there are larger boundary layers for compressors having larger throats and smaller boundary layers for compressors having smaller throats. The size of the boundary layer is also dependent upon the pressures and speeds at which the compressor is operated. It is considered within the skill of those knowledgable in the art to determine for a particular instance where a probe should be placed so as to be within the boundary layer of the material flow at a compressor stage exit.

Other arrangements are also possible for assisting in preventing surge conditions in a compressor utilizing the method and some apparatus of the present invention. Thus, it is typical for high pressure compressors that a back pressure valve be provided with the compressor. The back pressure valve can either actuate a complete bypass so that the compressor is bypassed to prevent surge, or the back pressure valve can exhaust air, for example, from the outlet side of the compressor to the atmosphere through a blow off system so that there is always enough air passing through the compressor to keep it in its stable range away from surge conditions. Typically, a back pressure valve is operated by means of a static pressure probe placed some place adjacent the exit side of the compressor. Thus, when the static pressure probe detects a build-up of high pressure to an extent that might be deleterious to the compressor, the back pressure valve is actuated to either bypass the compressor completely or to exhaust the high pressure air at the outlet side of the machine to the atmosphere so as to lower the pressure on the outlet side of the machine. In accordance with one aspect of the present invention, such a back pressure valve can be operated through the flow reversal detecting mechanism of the present invention. That is, the back pressure valve is actuated dependent upon flow reversal detected in the boundary layer adjacent the exit side of the machine rather than the static pressure build-up detected by some variety of static pressure probe. Detecting flow reversal for operating the back pressure valve is a much more accurate means for preventing surge conditions than depending upon a static pressure condition, which can vary from compressor to compressor.

Thus, while there have been described particular embodiments of the invention by way of example, it is obvious that variations and modifications of the particular disclosed embodiments may be made by those skilled in the art without departing from the true spirit and scope of the invention.

What is claimed is:

1. A method of detecting an impending surge condition in a compressor comprising:

positioning a velocity probe adjacent the wall of the compressor outlet,

said velocity probe having a flow direction sensing ability at a predetermined portion thereof,

positioning said predetermined portion of said velocity probe within the boundary layer of material flowing through the compressor and adjacent the wall of the compressor,

orienting said predetermined portion of said velocity probe at a predetermined orientation with respect to the expected downstream direction of material flow in said boundary layer under non-surge conditions to cause a detectable output indication from said velocity probe whenever said material flow substantially reverses in direction from said expected downstream direction, and

detecting an impending compressor surge condition in response to said output indication from said velocity probe indicating flow reversal in the boundary layer which is, in turn, indicative of impending surge conditions.

2. A method in accordance with claim **1** including the step of bleeding off a portion of the boundary layer at the compressor outlet back into the compressor inlet in response to detected flow reversal in order to delay the onset of surge.

3. A method in accordance with claim **1** including the step of operating a back pressure valve in response to detected flow reversal so that the compressor is bypassed by the flowing material prior to the onset of surge.

4. A method in accordance with claim **1** including the step of operating a back pressure valve in response to detected flow reversal so that high pressures are relieved at the outlet side of the compressor to eliminate flow reversal in the boundary layer and thereby delay the onset of surge.

5. A method in accordance with claim **2** in which **5** percent or less of the output of the compressor is bled back into the input in order to delay the onset of surge.

6. In a compressor including a stage having an inlet and an outlet and adapted for fluid flow through the compressor, a surge detecting system comprising:

a velocity probe mounted to the compressor adjacent a wall thereof near its outlet,

said velocity probe having a flow direction sensing ability at a predetermined portion thereof, said predetermined portion being disposed within the boundary layer of material flowing through the compressor at the compressor outlet adjacent said wall,

said predetermined portion also having a predetermined orientation with respect to the expected downstream direction of material flow in said boundary layer under nonsurge conditions to cause a detectable output indication from said velocity probe whenever said material flow substantially reverses in direction from said expected downstream direction, and indicating means connected with said probe for detecting an impending compressor surge condition in response to said output indication from said velocity probe indicating flow reversal of direction in said boundary layer which is, in turn, indicative of impending surge condition.

7. Apparatus in accordance with claim **6** including a bleed line extending between the compressor stage outlet and the compressor stage inlet, said bleed line having a valve positioned therein, said flow reversal indicating means functioning to operate said valve to bleed back a portion of the fluid at the outlet of the compressor back into the inlet when flow reversal occurs so as to eliminate flow reversal and delay the onset of surge conditions.

8. Apparatus in accordance with claim **6** including means responsive to said flow reversal indicating means for operating a back pressure valve for relieving high pressure conditions at the compressor stage outlet.

9. Apparatus in accordance with claim **6** wherein said velocity probe comprises a pressure sensing tube having an aperture therein oriented facing downstream of the desired flow in the compressor and wherein said flow reversal indicating means comprises a pressure sensing apparatus.

10. Apparatus in accordance with claim **6** wherein said compressor stage is a centrifugal compressor stage and wherein said velocity probe is mounted adjacent the impeller exit of the compressor stage.

11. Apparatus in accordance with claim **6** wherein said compressor stage is an axial flow compressor stage and wherein said velocity probe is mounted adjacent the exit side of the rotor blade tips.

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