

Dec. 5, 1961

E. W. TANZBERGER ET AL

3,011,322

STABILIZATION OF REFRIGERATION CENTRIFUGAL COMPRESSOR

Filed Aug. 12, 1958

2 Sheets-Sheet 1

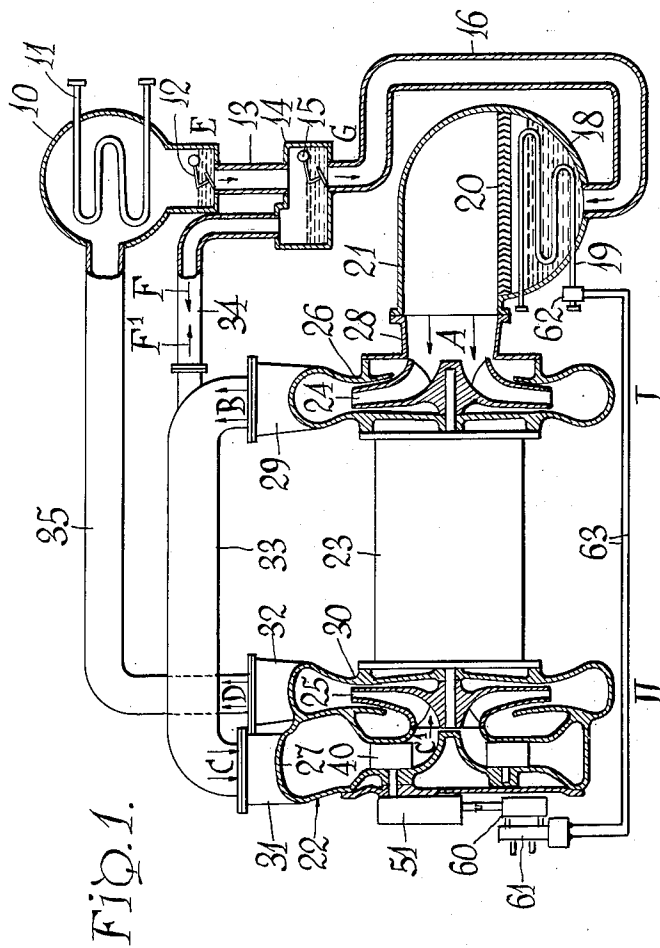


FIG. 1.

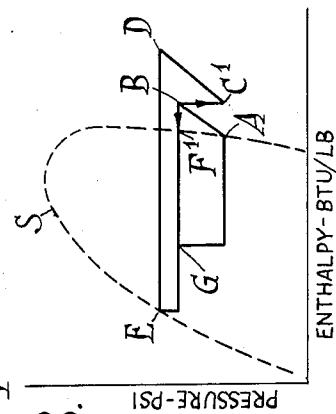


FIG. 2.

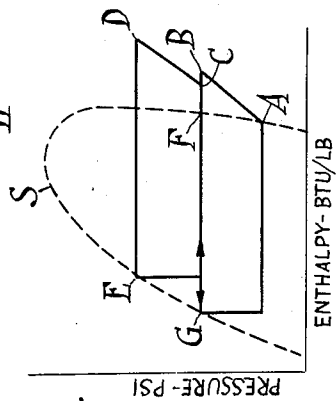


FIG. 3.

INVENTORS
Eric W. Tanzberger,
BY Charles E. Green,
Popp and Sommer
ATTORNEYS.

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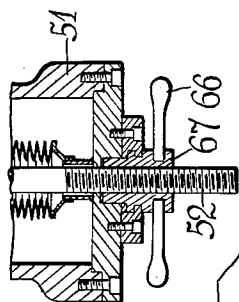


FIG. 6.

FIG. 5.

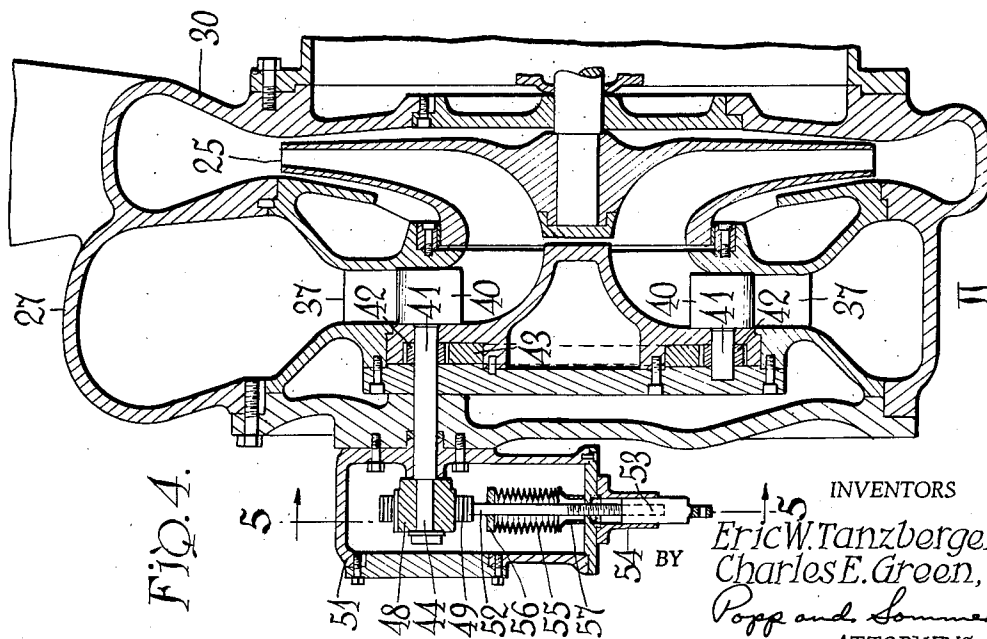
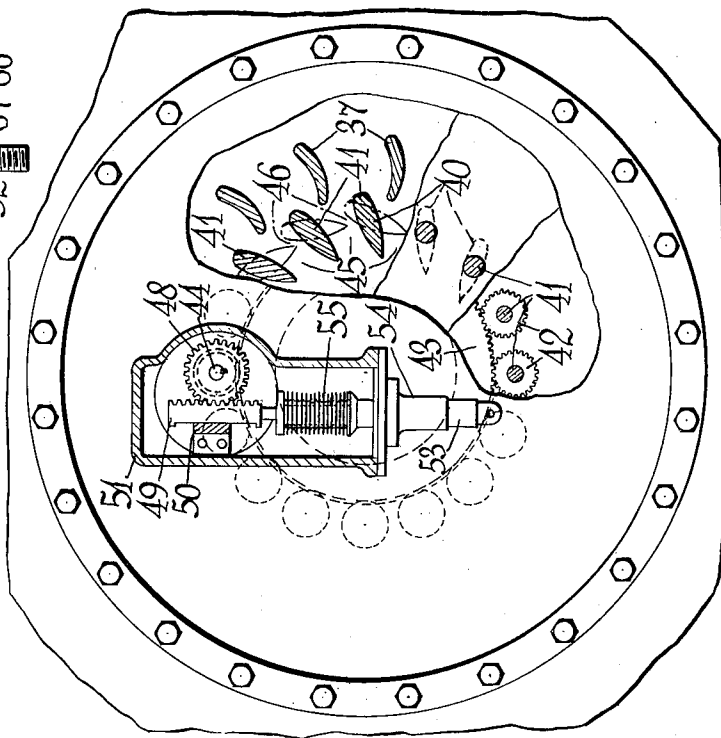


FIG. 4.

INVENTORS
Eric W. Tanzberger,
Charles E. Green,
Popp and Sommer
ATTORNEYS.

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STABILIZATION OF REFRIGERATION
CENTRIFUGAL COMPRESSOR

Eric W. Tanzberger, Olean, and Charles E. Green, Alle-
gany, N.Y., assignors to Dresser Operations, Inc., Whit-
tier, Calif., a corporation of California
Filed Aug. 12, 1958, Ser. No. 754,559
6 Claims. (Cl. 62-196)

This invention relates to the stabilization of a centrifugal compressor used in a refrigeration system.

As is well known, a centrifugal compressor can surge when under light load.

The main object of the present invention is to improve the stability of a compressor of the centrifugal type when used in a refrigeration system where the demand for refrigeration varies and particularly when such demand is low. A reduction in capacity up to 90% has been made without surge occurring in the compressor of the present invention.

In accordance with the present invention a centrifugal compressor for compressing refrigerant gas and having two or more stages is incorporated in a refrigeration system including a condenser, flash cooler or economizer, and evaporator, in such a way as to stabilize the compressor under light load. This is accomplished by arranging the compressor in series with the condenser flash cooler and evaporator and providing a by-pass connection between the flash cooler and the inlet of the second stage and incorporating means to control the amount of gas fed to the second stage, whereby under normal load or full capacity the second stage receives gas jointly from the outlet of the first stage and the flash cooler but under low load substantially all of the output of the first stage is by-passed to the flash cooler so as to be recycled through the first stage. The portion of gas not so by-passed is expanded into the second stage to provide sufficient volume to keep the second stage and any subsequent stages out of surge. The means controlling the second stage inlet are provided preferably by movable guide vanes adjusted automatically.

Other objects and advantages of the present invention will be apparent from the following description and accompanying drawings in which:

FIG. 1 is a diagrammatic representation of the various components, including the new compressor of the present invention, forming the refrigeration system.

FIG. 2 is a Mollier type diagram of the refrigerant cycle for the system when under normal or full load.

FIG. 3 is a similar diagram for the system when under a light load representing 10% capacity.

FIG. 4 is an enlarged vertical central sectional view through the second stage of the improved compressor shown in FIG. 1.

FIG. 5 is a fragmentary vertical transverse sectional view thereof, taken on line 5-5 of FIG. 4, and showing certain portions broken away to reveal other parts more clearly.

FIG. 6 is a fragmentary sectional view of a modified and hand control means for adjusting the movable guide vanes.

Referring to FIG. 1, the numeral 10 represents a condenser of any suitable form, the same being shown as of the shell-and-tube type in which cooling water flows through the tubing 11 and the refrigerant is in the shell outside the tubes. The shell of the condenser is shown as formed with a sump in which the condensed liquid refrigerant collects and from which sump the condensate can flow by gravity under control of a float control valve 12. The outlet of the condenser 10 is connected by a conduit 13 to a flash cooler or economizer 14 having an outlet in its bottom through which liquid refrigerant can

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flow by gravity under control of a float control valve 15. The aforesaid outlet of the cooler 14 is connected by a conduit 16 to the bottom of an evaporator 18 which is also shown as being of the shell-and-tube type in which the secondary refrigerant liquid such as water or brine flows through the tubing 19 and the refrigerant is in the shell outside this tubing. The secondary refrigerant liquid circulates between the evaporator 18 and the cooling load served by the refrigeration apparatus to transfer heat from the load to the evaporator 18. In removing heat from the secondary refrigerant, the refrigerant in the evaporator 18 boils forming gas which passes through the liquid eliminator 20 and thence into the suction pipe 21 to the inlet of a multiple stage centrifugal compressor, indicated generally at 22.

The compressor 22 is shown as having first and second stages I and II separated by a hermetically sealed water cooled electric drive motor 23 of conventional form. The impellers 24, and 25 of the first and second stages, respectively, of the centrifugal compressor 22 are rotatively driven by the motor 23. The impeller 24 of the first stage is arranged in a casing 26 having an inlet 28 and outlet 29. The impeller 25 of the second stage is arranged in a casing 30 having an inlet 31 and outlet 32. The inlet 31 communicates with an inlet volute 27 forming part of the casing 30 and leading to the annular inlet mouth for the impeller 25. The suction pipe 21 of the evaporator 18 is connected to the inlet 28 of the first stage. The outlet 29 of the first stage is connected to the inlet 31 of the second stage by a cross-over conduit 33. A by-pass conduit 34 is shown as connecting the cross-over conduit 33 to the interior of the cooler 14, entering in the top wall thereof. The outlet 32 of the second stage is connected to the condenser 10 by a conduit 35.

Thus it will be seen that the condenser 10, cooler 14, evaporator 18 and the multiple stage centrifugal compressor 22 are connected in series through which the refrigerant cycle but with a by-pass 34 being provided between the cooler 14 and the cross-over conduit 33 intermediate the first two stages of the compressor.

Under normal or full load the refrigerant cycle is as depicted in the Mollier type diagram of FIG. 2. Letters have been used to indicate different points on the diagram and these letters have also been applied to FIG. 1. Referring to FIG. 2, S represents the saturation line between liquid and gas and is the characteristic curve for the particular refrigerant under consideration which may be of any suitable type such as one of the Freons. At point A the refrigerant gas enters the inlet of the first stage of the compressor and leaves at point B having a higher pressure and heat content. In passing through the cross-over pipe 33 from the outlet of the first stage (point B) to the inlet of the second stage (point C) the gas loses a slight amount of heat. In passing through the second stage of the compressor the gas is further compressed and heated to the point D which is representative of the condition of the gas at the outlet of the second stage. The gas then passes through the line 35 and condenser 10 in which it is condensed to point E, this requiring the removal of heat without loss of pressure. Inasmuch as the by-pass line 34 is at a lower pressure than the line 35 and condenser 10, the liquid refrigerant leaving point E is partially evaporated, the gas generated moving through the by-pass conduit 34 to point F indicated on the diagram. The portion of the liquid refrigerant remaining liquid passes through the flash cooler with some loss of heat to point G. In moving from point G to point A, completing the cycle, the liquid refrigerant is heated and loses pressure. On the diagram the line connecting points G and A represent the refrigerant effect or cooling load.

In accordance with the principles of the present inven-

tion, the amount of refrigerant gas entering the second stage of the compressor is reduced as the refrigeration load decreases. Assuming that the load has decreased to 10% of normal capacity, the refrigeration cycle depicted by the diagram of FIG. 3 obtains. A reduction in refrigeration or cooling load is effected by a reduction of the temperature differential between the inlet and outlet of the tubing 19 in the evaporator 18.

Referring to the diagram of FIG. 3, at point A the refrigerant gas enters the first stage of the compressor and leaves at point B. Some of the initially compressed gas leaving point B is by-passed through the conduit 34 to the cooler 14, as depicted at point F'. The remaining portion of the first stage output gas flows through the cross-over conduit 33 and enters the inlet of the casing for the second stage. Arranged within this casing are means, later to be described, for throttling the entering gas. As a result of being throttled, the pressure of the gas is reduced to point C'. In passing through the second stage of the compressor the gas is further compressed and increases in heat content to point D. Thereafter the gas flows through the conduit 35 and condenser 10 with loss of heat to point E. The gas entering the cooler 14 through the by-pass conduit 34 is mixed with the liquid refrigerant from the sump of the condenser and then moves to the outlet of the cooler 14 to point G. The reduced refrigeration or cooling load is only diagrammatically represented by the line connecting the points G and A in FIG. 3.

Thus it will be seen that under reduced load conditions a portion of the output of the first stage is by-passed around the second stage and condenser and returns to the flash cooler 14. Sufficient gas, however, is allowed to enter the inlet of the second stage so that after such entering gas is throttled it is expanded in volume sufficiently to keep this second stage from surging.

While any suitable means may be employed for controlling the amount of gas entering the second stage, the means preferred and illustrated include movable inlet guide vanes, indicated at 40. Referring to FIG. 5, a plurality of such movable guide vanes 40 are arranged within the inlet volute 27 in circular fashion at uniform circumferential intervals about the inlet mouth for the impeller 25 of the second stage. Each guide vane 40 is shown as being of air-foil shape in cross-section and as mounted non-rotatably on a stub shaft 41 having an axis parallel to that of the impeller 25. Fast to each of these shafts 41 is a pinion gear 42. All of the pinion gears 42 are engaged by an externally toothed ring gear 43 as best shown in FIG. 4. Each of the shafts 41 is suitably journaled on either side of its pinion gear 42 within the volute 27. The ring gear 43 is also suitably journaled for free rotation within the volute 27. The shaft for the uppermost guide vane is shown as being longitudinally extended as indicated at 44 to extend outwardly through the side wall of the inlet volute 27.

It will be seen that if the extended shaft 44 is rotated the pinion 42 fast thereto will also rotate, causing the ring gear 43 to rotate. Since the teeth of the ring gear 43 engage the teeth of all the other pinion gears 42, the latter are likewise caused to rotate, all resulting in the vanes being rotated about their axes in the same direction and through the same angular displacement, for a given angular motion imparted to the master or extended shaft 44.

If desired, stationary guide vanes 37 may be arranged in the volute 27 radially outwardly of the movable inlet guide vanes 40, as shown in FIG. 5. The movable inlet guide vanes 40 as represented in full lines in FIG. 5 illustrate the positions of these vanes under normal load or full capacity. It will be seen that the space or passage 45 between two adjacent vanes 40 is relatively large. However, if these vanes 40 are adjusted, by turning the shaft 44, they can be caused to assume the dotted line positions shown in FIG. 5 where the space or passage between adjacent vanes, as indicated at 46, is relatively nar-

row. This rather close spacing of the vanes represents their position when the refrigeration load is light. Less gas enters through the restricted passages 46 than through the larger passages 45 when the vanes are open fully, and in passing through the restricted passages 46 the gas is throttled and expanded in volume, of course, with an attending reduction in pressure. However, the expanded volume is sufficient to keep the second stage of the compressor from surging.

Any suitable means may be employed for controlling the adjustment of the movable inlet guide vanes 40. The automatic means shown in FIGS. 1 and 4 are preferred, although the manual means shown in FIG. 6 may be used, if desired.

Referring to FIG. 4, the extended shaft 44 extends laterally outwardly through the outer side wall of the inlet volute 27, being suitably sealed with respect thereto. The outer end of this shaft has fast thereto a pinion gear 48 which engages with a vertically movable gear rack 49. The rack 49 is shown as being guided for rectilinear vertical movement by the guide 50 arranged within the box 51 mounted on the outer side wall of the volute 27. Depending from the lower end of the gear rack 49 is an actuating rod 52, which extends downwardly through an opening provided in the bottom of the box 51. The lower extremity of the rod 52 is externally threaded to receive a cylindrical slide member 53 received in a tubular extension 54 attached to the bottom of the box 51 and extending downwardly therefrom.

The exit of the actuating rod 52 from the box or housing 51 is sealed against leakage of gas. For this purpose, a bellows 55 surrounds the rod 52 within the box 51. At its upper end the bellows 55 is connected to a collar 56 welded to the rod, and at its lower end the bellows is connected to a sleeve 57 surrounding the rod 52 in spaced relation thereto. The lower end of the sleeve 57 is welded to the bottom of the box 51. In this manner, the rod 52 can move in and out of the box 51 with a constant seal being maintained.

Referring to FIG. 1, slide member 53 is connected to the piston rod of a piston and cylinder device 60 which may be of any suitable construction. Such piston and cylinder device 60 has a suitable connection with a supply of pressurized fluid (not shown) and is shown as having a solenoid valve 61 to control the direction and extent of movement of the piston rod of the device 60. In order to render the operation of the piston and cylinder device responsive to the temperature of the secondary refrigerant passing through the tubing 19 of the evaporator 18, a suitable temperature sensing device 62, such as a thermocouple unit, is shown as being operatively associated with the inlet end of the tubing 19 and connected by the electrical control lines 63 to the solenoid control valve 61.

In this manner, the position of the movable inlet guide vanes 40 can be automatically adjusted in direct response to the refrigeration load as sensed from the secondary refrigerant passing through the tubing 19. For example, if the temperature of the secondary refrigerant passing through the leg of the tubing 19 in which the temperature sensing device 62 is arranged, is relatively high, indicating a refrigeration demand, the solenoid valve 61 is actuated so as to cause the piston and cylinder device 60 to operate to move the actuating rod 52 and hence gear rack 49 upwardly. This rotates the pinion 48 in a clockwise direction as viewed in FIG. 5, thereby rotating the extended shaft 44 likewise in a clockwise direction. The pinion 42 on the extended shaft 44 is similarly caused to rotate in a clockwise direction, but by reason of its engagement with the ring gear 43, the latter is caused to move in a counter-clockwise direction. This in turn causes the other pinions 42 and the various other guide vanes 40 to rotate about their respective axes in a clockwise direction to a more fully open position as shown typically by full lines in FIG. 5.

However, assume now the temperature of the secondary refrigerant entering the tubing 19 lowers in value, indicating a decrease in refrigeration demand. The temperature sensing device 62 sends a command signal to the solenoid of the solenoid control valve 61 thereby causing the piston and cylinder device 60 to pull down on the actuating rod 52 and hence also move the gear rack 49 downwardly. This causes a reversed direction of rotation of the various pinions 42. They now move in a counter-clockwise direction so as to close the gaps between adjacent guide vanes 40, for example, to the restricted spacing 46 shown in FIG. 5.

The restricting of the passages through which the refrigerant gas entering the second stage of the compressor must pass changes the refrigeration cycle to that typically depicted in FIG. 3. Under such conditions of operation some of the output of the first stage of the compressor is by-passed back to the flash cooler 14 to be recycled through this cooler and evaporator 18, the gas not so by-passed passing through the restricted passages, as illustrated by the space 46 in FIG. 5. In passing through these spaces the gas is throttled or expanded. This has the effect of increasing its volume although lowering its pressure which operates to keep the second stage of the compressor, and any additional stages that may be employed in the multi-stage compressor, from surging.

Instead of the automatic means for controlling adjustment of the movable inlet guide vanes 40 shown in FIGS. 1 and 5, the manually adjusting means shown in FIG. 6 may be employed. The only modification made is the elimination of the slide member 53 and associated apparatus 60-63, cylinder member 54, and the substitution of the hand wheel means shown in FIG. 6. As there shown, a hand wheel 66 is mounted on a hub 67 internally threaded to receive the external thread on the lower end portion of the actuating rod 52. The hub 67 is shown as being suitably rotatably mounted on the bottom of the box 51 but in such manner as to prevent any axial displacement of this hub. It will be seen that by turning the hand wheel 66 in one direction the actuating rod 52 and also the gear rack 49 to which this rod is connected, are moved in one direction. When the hand wheel is turned in the opposite direction the actuating rod 52 and gear rack 49 moves in the opposite direction.

It is an important feature of the present invention to note that there are no flow control means, such as guide vanes, at the inlet to the first stage of the compressor. The flow control means, such as the movable inlet guide vanes 40, are provided only at the inlet to the second stage of the compressor. Such an arrangement, including the by-pass conduit 34 interposed between the crossover conduit 33 between the first two stages of the compressor and the flash cooler 14, has been found in actual practice to be highly effective in preventing the compressor from surging under light load conditions, even to the extent of a reduction of 90% of load capacity.

We claim:

1. In a refrigeration system having a condenser, flash cooler and evaporator connected in series, the combination therewith of a centrifugal compressor having at least two stages, the inlet of the first stage being connected to said evaporator, the outlet of the last stage being connected to said condenser, a first conduit connecting the outlet of the first stage with the inlet of the second stage, a second conduit connecting said first conduit with said cooler, and flow control means only for the second one of the stages and arranged downstream of the connection between said conduits but upstream of the inlet to the second stage to throttle refrigerant gas entering the second stage thereby to stabilize the compressor under light load.

2. In a refrigeration system having a condenser, flash

cooler and evaporator connected in series, the combination therewith of a centrifugal compressor having at least two stages, the inlet of the first stage being connected to said evaporator, the outlet of the last stage being connected to said condenser, a first conduit connecting the outlet of the first stage with the inlet of the second stage, a second conduit connecting said first conduit with said cooler, movable inlet guide vane means only for the second one of the stages and arranged to control the flow of refrigerant gas into the second stage, and control means arranged to move said guide vane means to throttle the refrigerant gas entering the second stage when the compressor is under light load thereby to stabilize the compressor.

3. A centrifugal compressor according to claim 2 in which said control means are manually actuated.

4. In a refrigeration system having a condenser, flash cooler and evaporator connected in series, the combination therewith of a centrifugal compressor having at least two stages, the inlet of the first stage being connected to said evaporator, the outlet of the last stage being connected to said condenser, a first conduit connecting the outlet of the first stage with the inlet of the second stage, a second conduit connecting said first conduit with said cooler, movable inlet guide vane means only for the second one of the stages and arranged to control the flow of refrigerant gas into the second stage, and automatic control means responsive to refrigeration load variation and arranged to move said guide vane means to throttle the refrigerant gas as the refrigeration load decreases and vice versa, thereby to stabilize the compressor.

5. In a refrigeration system having a condenser, flash cooler and evaporator connected in series, the combination therewith of a centrifugal compressor having at least two stages, the inlet of the first stage being connected to said evaporator, the outlet of the last stage being connected to said condenser, a first conduit connecting the outlet of the first stage with the inlet of the second stage, a second conduit connecting said first conduit with said cooler, movable inlet guide vane means only for the second one of the stages and arranged to control the flow of refrigerant gas into the second stage, and automatic control means responsive to refrigeration load variation and arranged to move said guide vane means to throttle the refrigerant gas as the refrigeration load decreases and vice versa, thereby to stabilize the compressor, said automatic control means including a temperature sensing device operatively associated with said evaporator, fluid operated actuating means controlled by said device and means actuated by said actuating means for effecting movement of said guide vane means.

6. In a refrigeration system including a centrifugal compressor having at least two stages for compressing refrigerant gas, the improvement of stabilizing the compressor under light load to prevent surging, comprising flow control means only for the second one of the stages and arranged upstream of the inlet to the second stage to throttle the refrigerant gas entering the second stage and received from the first stage, and means arranged upstream of said flow control means for bleeding-off some of the refrigerant gas discharged by the first stage for recirculation through the first stage.

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