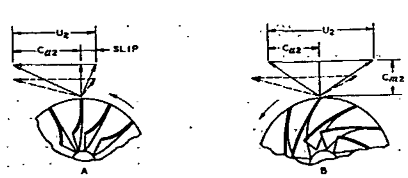

Fig. 11 .... Vector Diagrams Leaving Wheel of a Centrifugal Compressor

purge systems to continually remove noncondensables and impurities from the system. The purge system draws a small flow of vapor from a quiet zone near the top of the condenser, where the noncondensable gases have been concentrated. The refrigerant and any water vapors which may be present are condensed. The noncondensable gases are blown off through a relief valve, and any water accumulating in the purge is periodically drained off, or is collected by a system of weirs. The condensed refrigerant is returned to the evaporator through a float valve.

PERFORMANCE

The centrifugal compressor is basically a relatively constant head, variable capacity machine. The work input per unit mass flow can be derived as a direct function of $U_2C_{u2} - U_1C_{u1}$ *where* U is the peripheral velocity of the impeller and C_u is the tangential velocity of the gas. Subscript 1 is for the conditions entering the impeller, and subscript 2 is for the conditions leaving the impeller. In the simple case where no inlet prewhirl is applied, C_{u1} is zero, and the work input is U_2C_{u2}.

Fig. 11 shows the vector diagrams at the tip of two impellers, (a) radial bladed and (b) with backward-curved blades. Note that because C_{u2} is smaller for the backward-curved impeller, U_2 must be larger in order to achieve the same work input. C_{m2} is the through-flow velocity and is approximately proportional to capacity. Thus, at reduced capacity, the dotted vector diagrams will result. By inspection it can be seen that the value of C_{u2} changes only slightly with change in capacity in either case, but the change is more pronounced for the backward-curved, than for the radial impeller. At shutoff or zero flow, C_{u2} must be equal to U in either case. In Fig. 12, theoretical work input per unit mass flow is shown as a function of flow or capacity. The output of the compressor is a function of the work input and the losses. Fig. 13 shows input and output curves for the two impellers. Generally, the radial-bladed impeller has an output characteristic that is not as broad and flat as the backward-curved type, and surge tends to occur at a higher capacity. However, it should be noted that there is no definite line of demarcation between radial and backward-curved impellers, since any degree of backward curvature may be selected. The illustrated comparisons are between a radial and a highly backward-curved impeller in order to show the extremes.

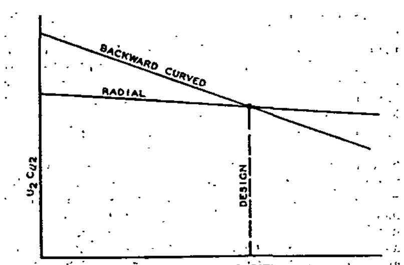

Fig. 12 .... Basic Work Input Curves for a Centrifugal Compressor

Another point to be noted is that the slope of the work input curve for the backward-curved impeller is steeper than that for the radial impeller. The result of this characteristic, as shown in Fig. 13, is that the horsepower for the backward-curved impeller reaches a peak at a capacity somewhat higher than design capacity, whereas the horsepower of the radial-bladed impeller continues to rise because of the slight slope of the work-input curve. This characteristic of the backward-curved impeller is important when electric motor drive is to be used, since it is possible to use this characteristic to prevent overloading of the motor. For the radial-bladed impeller, other means of control must be used to prevent motor overload. This feature is not of particular significance for a turbine drive.

All of the previous discussion has been based on the utilization of constant speed drive and fixed inlet prerotation. Control of capacity and head is normally obtained in this case by throttling (suction damper). However, since both head and capacity are affected by throttling, it is sometimes necessary to use a bypass in order to maintain head at very low loads. Other common means of control are the utilization of variable inlet guide vanes and variable speed. Any or all of these could also be used in combination.

As far as the compressor is concerned, variable speed is a most efficient means of control. However, it has much the same characteristic as throttling and cannot maintain high head at low flow. Also, the efficiency of the driver must be taken into account before any conclusions can be drawn concerning system power consumption. Fig. 14 shows performance with variable speed. Note the significant reduction in horsepower with reduced capacity.

Surge is a characteristic of centrifugal compressors which occurs at reduced capacity. At this flow condition, a sudden breakdown of flow occurs, similar to stalling of an airplane wing. When this happens, the compressor can no longer maintain the condenser pressure and a momentary reversal of flow occurs with an attendant lowering of condenser pressure. At lower condenser pressure, the compressor is again able to function, the gas flows in the normal direction, and at an increased rate, which again allows stable compressor flow. Condenser pressure is again built up, and the flow rate reduces until the stalling point is again reached, at which time the cycle repeats. The frequency of the cycle is determined by the flow characteristics of the entire refrigeration system.

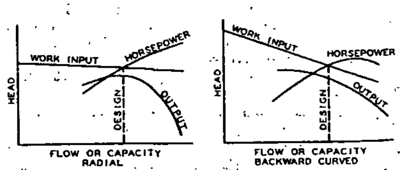

Fig. 13 .... Basic Characteristics of a Centrifugal Compressor

A *steady* surge may occur as often as one or more times a second, or with several seconds between flow reversals. An *intermittent* surge may sometimes be noted, with several minutes between surges.

Surging does not result in an appreciable loss of refrigeration, or in loss of economy, nor is the mechanical function of the machine necessarily affected. The repeated flow reversals will, however, impose higher than normal loads on thrust bearing surfaces. Refrigerant and bearing temperatures can sometimes build up to a dangerous point if a severe degree of surging is maintained for a long period of time. Surge is detected primarily by a significant intermittent change in noise level of the machine. The reduced capacity at which surge occurs varies widely, depending largely on the impeller tip peripheral Mach number. It may be as low as 50 percent of design capacity for low Mach number, and may increase to as high as 100 percent of capacity for very high Mach numbers.

Variable inlet guide vanes in use today perform a suction-throttling function in combination with a variation of the amount of prerotation imparted to the incoming gas. Fig. 15 shows the vector diagrams at the inlet to an impeller. The *design* or peak efficiency occurs at that inlet flow velocity C_{m1} which results in a relative flow angle into the impeller such that the relative vector W, lines up approximately with the leading edge of the impeller blades. If inlet guide vanes are set so as to impart a swirl to the inlet gas in the direction of rotation, the vector diagram (*b*) results, *where* angle α, is obtained with a lower value of C_{m1} than in diagram (*a*). If the inlet guide vanes are set to impart a swirl against rotation, vector diagram (*c*) results *where* C_{m1} to obtain α is larger.

As mentioned, work done on the gas is proportional to $U_2C_{u2} - U_1C_{u1}$, *where* C_u in the direction of rotation is positive. Thus, prewhirl with the impeller rotation will result in some reduction of head as compared to that for no whirl, and prewhirl against rotation will result in some increase in head. Since the velocities at the impeller inlet are low in comparison with the discharge velocities, the change in head is not large even for fairly substantial amounts of prewhirl. Fig. 16 shows the compressor characteristic at constant speed for varying prewhirl. Note that this method of control also effectively lowers horsepower with capacity, but not as rapidly as with variable speed. However, the head is maintained quite well at lowered capacity, in comparison to either simple throttling or speed variation. If variable speed and prewhirl are combined, the compressor will have this type of characteristic at each speed.

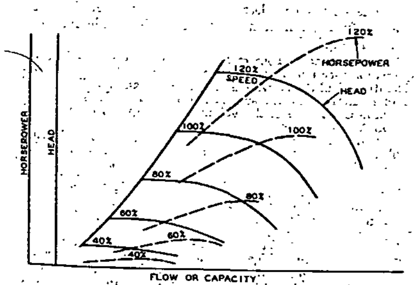

Fig. 14 .... Performance Characteristics of a Centrifugal Compressor Operated at Variable Speed

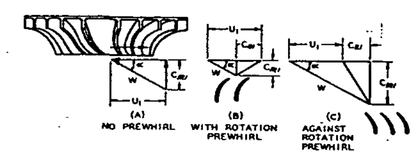

Fig. 15 .... Inlet Vector Diagrams for a Centrifugal Compressor with Inlet Guide Vanes

CENTRIFUGAL REFRIGERATION CONTROLS

Capacity Control

In operation, centrifugal refrigeration machines must accommodate two basic variables, refrigeration load and condenser water inlet temperature. These variables are impressed upon the compressor as flow and head, respectively. The extent and relationship of these variations are functions of the application. The load can be relatively constant in one application or may vary from zero to full load in another application. Condenser water temperature can be virtually constant, vary with the season, or vary with the wet-bulb temperature, depending upon whether well, river, lake, or cooling tower water is used. The head-flow characteristic required from the compressor for a typical water chilling application using cooling towers is shown in Fig. 17. Here, every conceivable means of reducing the head is desirable in order to attain the maximum ability to unload the compressor.

Although the centrifugal compressor is basically a constant head, variable flow device, there remains the problem of matching the compressor output exactly to the load required. An early method of capacity control was to vary the condenser water flow so as to make the load curve coincide with the compressor characteristic. This method limits the stable control range to the fixed speed characteristic of the compressor. Other capacity control means, already described in the section on performance, are variable speed, suction throttling, variable inlet guide vanes, and hot gas bypass. Suction throttling modifies the compressor characteristic in a manner quite similar to that of variable speed, but at somewhat lower efficiency. Fig. 14 indicates that these two methods will not fulfill the complete requirements of Fig. 17. Fig. 16, the characteristic for variable inlet guide vanes, illustrates that this method comes very close to fulfilling the complete

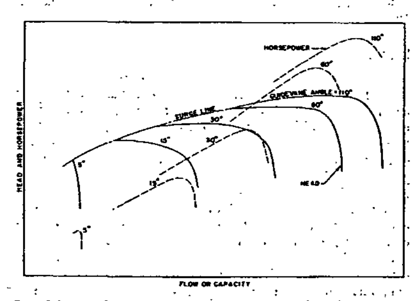

Fig. 16 .... Performance Characteristics of a Centrifugal Compressor with Variable Inlet Guide Vanes