

PART 8



Auxiliary Equipment



CONTENTS PART **8** AUXILIARY EQUIPMENT

SYSTEM DESIGN MANUAL

SUMMARY OF PART EIGHT

This part of the system Design Manual presents practical data for selection and application of auxiliary equipment used with air conditioning systems.

The text of this Manual is offered as a general guide for the use of industry and of consulting engineers in designing systems. Judgment is required for application to specific installation, and Carrier is not responsible for any uses made of this text.

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CHAPTER 1. CENTRIFUGAL PUMPS

This chapter sets forth a review of the selection and application of centrifugal pumps used with air conditioning and refrigeration systems.

These are two major categories of pumps:

1. Positive displacement – reciprocating, rotary and screw.
2. Centrifugal – with a variety of impeller designs classified as plain (radial) flow, mixed flow and axial flow, each within a volute casing; also turbine (diffuser) type pumps.

Figure 1 illustrates the two types of centrifugal pumps as well as the four basic types of impellers. The plain impeller has single curvature vanes always curved backwards. Wider impellers have vanes of double curvature with the suction ends twisted. These vanes are called mixed flow (Francis type) vanes. The extreme mixed flow (minimum of radial element) and axial flow impellers have propeller type vanes. While having axial flow, this class of pumps represents hydraulically an extreme in a continuous series of centrifugal pumps.

It is the plain flow impeller centrifugal pump that is used most frequently in air conditioning and refrigeration. They are used to move chilled, warm, hot and refrigerant condensing water, steam condensate, brine, lubricant oil or refrigerant.

A centrifugal pump is distinguished by a continuous steady flow and characteristic performance curves with a smooth rising head and falling power from maximum capacity to shutoff (Fig. 2). The pump presents an easy load for a driver. The starting torque is small and operating load is constant. As a rule a constant speed squirrel-cage induction electric motor (NEMA Design B) with normal starting torque (Chapter 2) is applicable to drive the pump although steam turbines, gasoline or steam engine, and belt and motor drives may also be used.

The centrifugal pump is rated on the basis of capacity, i.e. volume of liquid per unit time or gallons per minute, gpm ($1 \text{ cu ft/min} = 7.48 \text{ gpm}$), against a head, i.e. feet of water required by the fluid transmission system, and the energy required at a given speed.

There are two types of liquid circuits, open and closed. In the open system the pump moves a liquid from a source located above or below the pump but open to atmospheric pressure (Fig. 3a and 3b). A closed system is one in which the liquid circuit is not open to the atmosphere (Fig. 3c and 3d). The most common application in air conditioning and refrigeration systems is the closed water circuit. This is the major subject of the following text.

The rudiments of centrifugal pump behavior are found in the section on *Centrifugal Pump Fundamentals*.

STANDARDS AND CODES

Standards of the Hydraulic Institute (an organization of leading pump manufacturers) define the product, material, process and procedure in the design and testing of any type of pump.

Pump installation should conform to all local codes, rules and regulations.

CENTRIFUGAL PUMP

The centrifugal pump has a unique distinction of simplicity in construction, yet critical in application. There are two major elements in a centrifugal pump assembly – an impeller rotating on a shaft supported in a packed or mechanical seal and bearings, and a casing that is the impeller chamber (volute). The impeller imparts the principal force to the liquid, and the volute guides the liquid from inlet to the outlet, at the same time converting the kinetic (velocity) energy into pressure.*

*In a turbine type centrifugal pump the diffusers perform the major part of the energy conversion task.

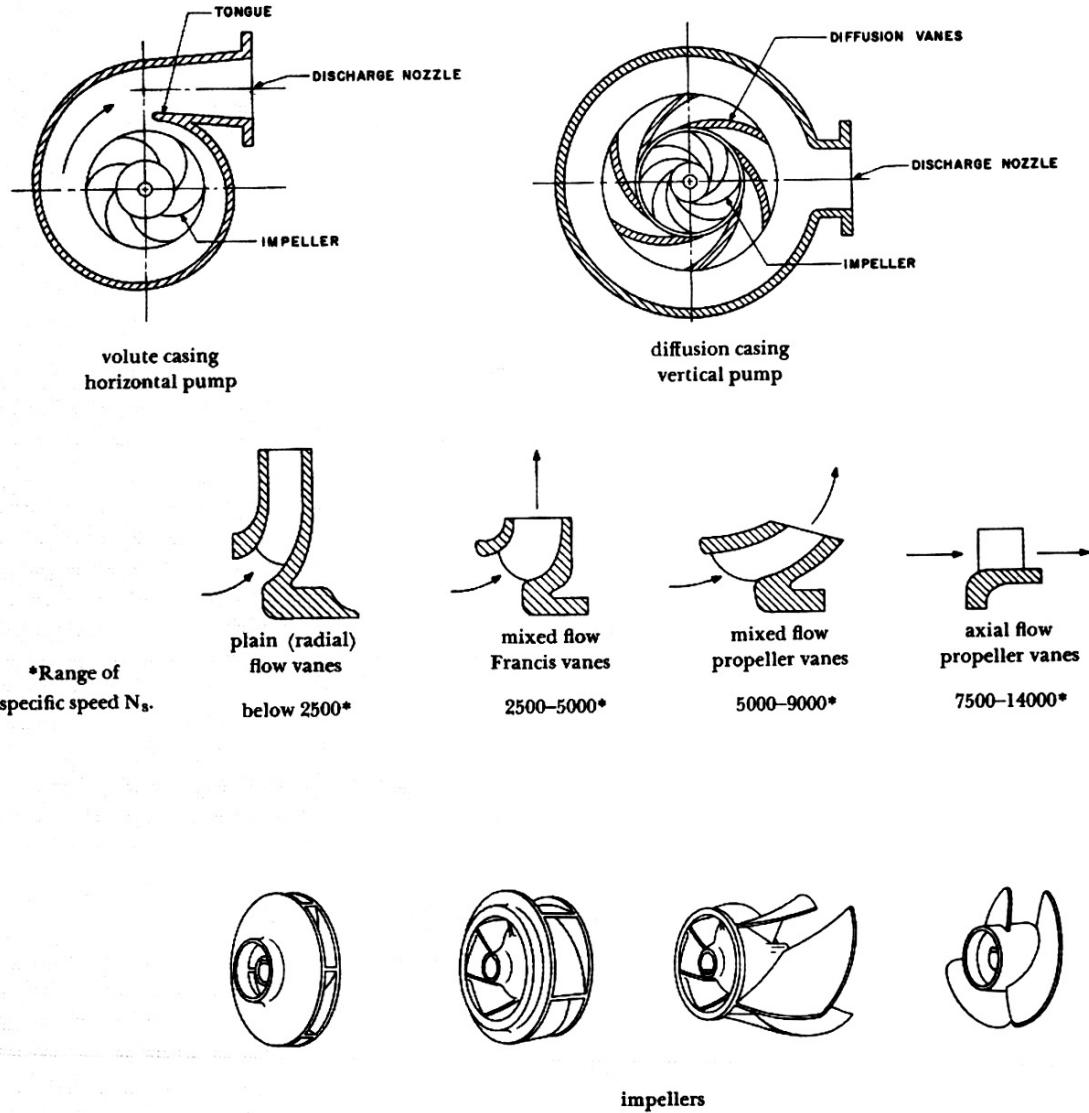


FIG. 1- CENTRIFUGAL PUMP CASINGS AND IMPELLERS

ADVANTAGES

The centrifugal pump is favored because of the following characteristics:

1. Simplicity of construction.
2. Absence of valves and reciprocation parts.
3. Fewer moving parts.
4. Absence of close clearances.
5. Minimum of power transmission losses.
6. Steady, nonsurging flow.

7. Operation at shutoff condition without excessive build-up in pressure.
8. Absence of contact between liquid pumped and lubricant.
9. Compactness; light in weight.
10. Adaptability for direct connection to standard motors (major types of drive).
11. Long life.
12. Ease of maintenance and minimum repair.
13. Reasonable cost.

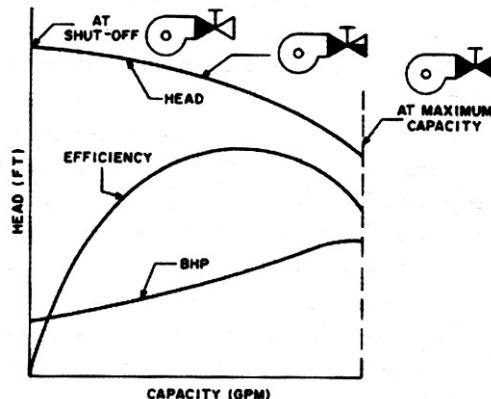


FIG. 2 – TYPICAL PERFORMANCE, PLAIN FLOW VANE CENTRIFUGAL PUMP

There are two shortcomings in a centrifugal pump:

1. It is not self-priming unless specially equipped with a priming device (or a foot valve).
2. It is inefficient for capacities smaller than 10 gpm at heads higher than 30 feet.

CLASSIFICATION AND DESIGNATION

The manner of liquid flow within the impeller and the casing of Centrifugal pumps has already been outlined. The plain radial flow impeller in a volute casing centrifugal pump is the one usually applied in air conditioning and refrigeration applications.

Impeller

The impellers are constructed in three arrangements:

1. Enclosed (vanes within an impeller shroud or side walls).
2. Semi-enclosed (vanes assembled with on side wall).
3. Open (no side walls, casing serving as side walls).

Suction

The liquid approach into the pump may be either:

1. Thru a single inlet with end suction to impeller.
2. Thru a single inlet with double suction, liquid flowing into the impeller along the shaft on two sides (Fig. 4).

Casing

The volute casing (Fig. 5) may be split axially (horizontally, usually with double suction pumps), or

radially (vertically, usually with single suction, end inlet pumps).

Stages

The single stage pump is one with a single impeller; it may have a single or double suction. If the required head is too high for a single impeller to develop, two or more single stage pumps may be used in series, or a set of impellers in series may be put into a single casing. The latter assembly is designated a multi-stage pump.

Assembly

With reference to the axis of rotation of the shaft, centrifugal pumps and drive arrangements are either horizontal or vertical (at times inclined). Horizontal pumps are arranged either with end or side suction inlets; top and bottom suction are also available. Double suction pumps are usually built with side discharge nozzles (Fig. 5)

The single suction pumps are usually made with the end suction inlet (also available in other arrangements) and a variety of discharge nozzle positions (Fig. 6). The discharge nozzle is a size or two smaller than the suction. Centrifugal pumps are often identified by a number corresponding to the size of its discharge; however this does not define its capacity which must be stated concurrently.

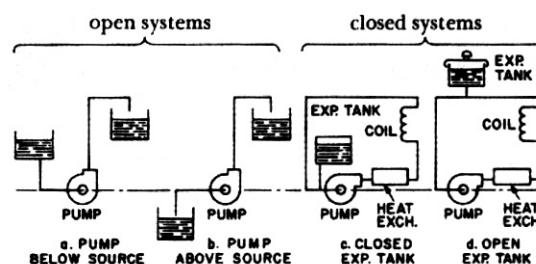


Fig. 3 – LIQUID FLOW SYSTEMS

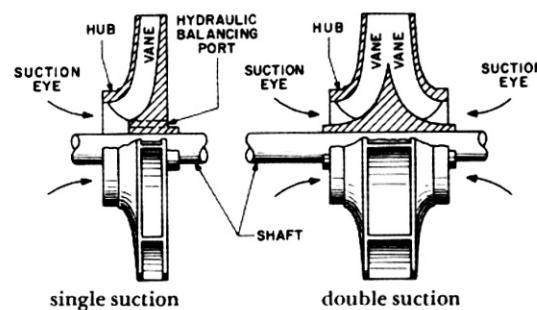


Fig. 4 - IMPELLERS

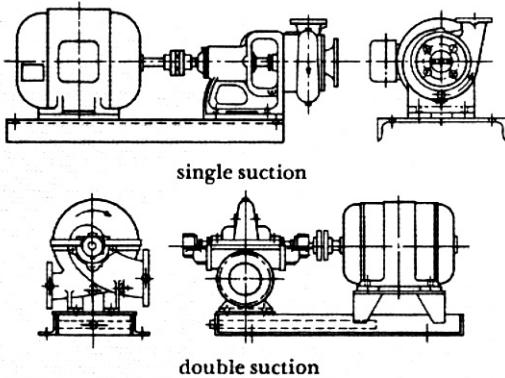
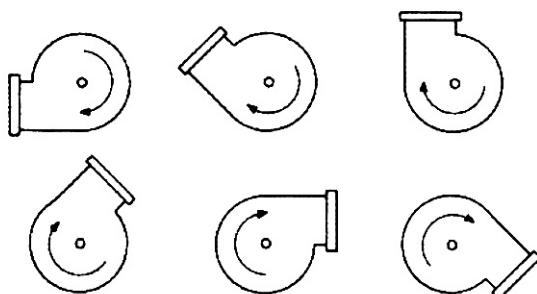


FIG. 5 – SINGLE AND DOUBLE SUCTION CENTRIFUGAL PUMPS



NOTE: Rotation observed from drive end.

FIG. 6 – DISCHARGE NOZZLE ARRANGEMENTS, SINGLE CENTRIFUGAL PUMP

Rotation

Pump rotation is determined when looking from the drive toward the pump. Thus straddling the drive of a horizontal pump or looking down at the motor end of a vertical pump, if the liquid is entering the suction on the right side (double suction) and moves clockwise within the casing towards the discharge, such a pump is designated as having clockwise rotation. With the suction on the left side and the liquid moving within the casing in counterclockwise direction, the pump is designated as having counterclockwise rotation (Fig. 7).

Drive

Motors are the major drivers used to supply energy to centrifugal pumps. Of the single-phase motors the capacitor type are used for small pumps. Of the multi-phase motors the standard squirrel-case induction type (NEMA Design B) are the most popular. Occasionally for

reason peculiar either to power distribution regulations or to the customer's economic situation (Chapter 2) a pump may be driven either by a part-winding, wound rotor or synchronous motor.

The smaller sizes of motor-driven pumps often come in close-coupled assemblies; the impeller is mounted on the projection of the motor shaft. The pump volute and the motor enclosures comprise one unit. Large pumps connect to drivers by a coupling.

The availability of steam may suggest a turbine drive. A situation should not be overlooked where both the chilled and refrigerant condensing water pumps may be driven by a single thru-shaft turbine since both pumps are in operation simultaneously. High speed (3500 rpm and above) pumps are particularly adaptable for direct connection to turbines.

In critical and emergency situations auxiliary drives may be provided; this is another means to drive a pump in case of failure of the regular drive.

SUPPLEMENTARY COMPONENTS

Several components supplementing the impeller shaft and casing are required to complete the centrifugal pump assembly and to provide various protections and accommodations in order to:

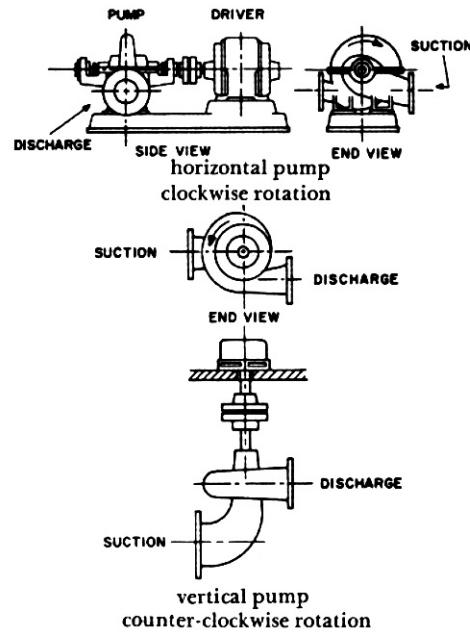


FIG. 7 – ROTATION DESIGNATION, CENTRIFUGAL PUMP

1. Avoid destructive wear to either the total unit of the impeller or the casing; at the same time, provide close-running clearance between the lower pressure inlet and the higher pressure discharge region in the casing (wearing rings).
2. Prevent leakage outward or inward between the inside of the pump and the ambient outside (seal). The direction of leakage depends on whether the pressure within the pump casing is higher or lower than the ambient atmospheric pressure.
3. Support and align the rotating impeller shaft with the casing stationary (bearings).
4. Connect the pump shaft to the driver shaft (coupling) unless the pump impeller is mounted on the extension of the driver shaft as in the end inlet, single suction pumps.
5. Support the total pump-drive assembly (bed-plate).

Wearing Rings

To achieve the first protective provision the impeller hub outer surface at the impeller eye and the adjacent casing surface are variously equipped with wearing rings (Fig. 8). They are respectively the impeller ring and casing ring. When necessary, only the rings are replaced, rather than the total impeller or total casing. A variety of designs and combinations of wearing rings and labyrinth arrangements are available.

Shaft

The shaft, a separate carefully designed entity, is treated in this text together with the impeller as a single rotating element. The standard shaft is protected from wear, corrosion and erosion within a stationary support by a sleeve designed and fitted in many forms. This sleeve covers the shaft thru a stuffing box or a mechanical seal. Very small pumps are frequently built with special wear-resisting shafts to avoid the disadvantages of the diameter enlargement of the fitted shaft.

Stuffing Box

The second protective provision (against leakage between the inside of the pump casing and the ambient atmosphere) is achieved either by a stuffing box (Fig. 9) or by a mechanical seal. With the stuffing box the sealing between the rotating shaft or shaft sleeve and the stationary support is achieved by rings of specially lubricated materials such as asbestos or metal packing, held tight by a gland. When the leakage becomes more apparent, the gland is tightened (within limits).

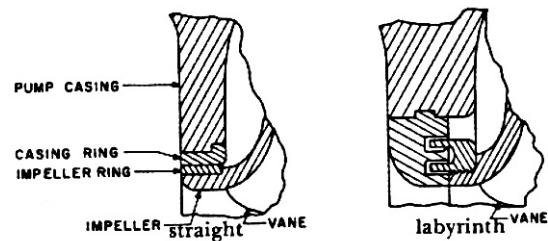


FIG. 8 – WEARING RINGS

The sealing, lubricating and cooling liquid is supplied either from the high pressure region of the casing or from external sources.

Mechanical Seal

When handling expensive volatile or high temperature liquids at varying pressures or when attempting to provide a truly positive seal, a single or double mechanical seal is provided. The mechanical seal differs from the stuffing box with its packing by the orientation of the sealing. The stuffing box packing seals axially along the shaft (Fig. 9); the mechanical seal is formed by contact of two highly polished surfaces of dissimilar material set perpendicular to the shaft. One spring-held inner surface is attached to the shaft, rotating with it; the outer surface is attached to the stationary part of the pump.

It is very important that there is a liquid film between the surfaces to provide lubrication and cooling. Mechanical seals are available in numerous designs that are constantly improved and reduced in cost. They require practically no maintenance.

The zero-leakage wet-winding or "canned" motor-pumps do not need a stuffing box or mechanical seals. They are leakless and sealless close-coupled motor-pump assemblies.

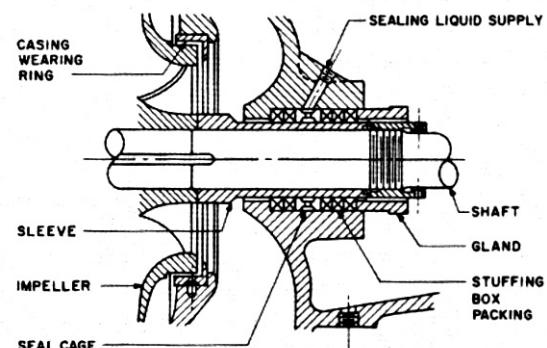


Fig. 9 – SLEEVE, STUFFING BOX,PACKING AND GLAND

Bearings

Bearings are points of shaft support serving to align the shaft. On double suction pumps the bearings are located on either side of the pump casing; the outer bearing is called the outboard, and the bearing between the pump and the driver is called the inboard. On single suction pumps both bearings are between the pump and drive; the one nearest to the pump is called the inboard, and the one nearest the coupling or driver is called the outboard. The bearings are either the sleeve type (minor usage) or the frictionless ball or roller type. The ball bearings are used most frequently. Bearings are often designed to take up thrust resulting from various unbalanced forces exerted within the pump.

Couplings

Except for close-coupled assemblies, pumps are usually connected to the drive thru a coupling. There are two basic classes of couplings, rigid and flexible. The rigid coupling does not permit axial or radial motion. It is a solid connection providing a continuous shaft. The rigid coupling is used for vertical pumps.

While transferring power from driver to pump, the flexible coupling allows a transverse adjustment for a very minor misalignment. However the pump alignment must not be misused; it must be rigidly enforced. Misalignment causes a whipping of the shaft; it adds to pump and driver bearing thrust and may result in excessive maintenance. Misalignment must not be tolerated.

Flexible couplings are effective in providing also lateral adjustments (along the length of the shaft) for either or all of the following: thermal changes, hydraulic float, or shifting of the magnetic center of the motor. A variety of flexible couplings as well as adaptation combinations are available to resolve any particular requirement to accommodate either the behavior peculiarity or ease of maintenance.

Bedplate

The pump and drive assembly must have perfect alignment. Close-coupled pumps are naturally assembled into balanced and aligned units. However pumps that are combinations of drive-coupling-pump units must be assembled either in the field or at the factory. Many pumps come preassembled and pre-aligned on a cast iron bedplate or structural steel support. These pump-on-bedplate assemblies are ready for bolting and dowling for level installation on a foundation. This does not mean that a factory-assembled pump-coupling-drive unit is inviolably perfect; accidents may happen in transit. Therefore, during installation the pump must be rechecked for alignment and level position. Cast iron

bedplates are often equipped with a rim for containing and draining the pump leakages. Otherwise, separate provisions must be made for collecting and disposing of leakage.

MATERIALS

Centrifugal pumps used in air conditioning and refrigeration are usually made of standard materials except in special instances of pumping sea water or corrosive or highly electrolytic brines. The pumps are built of special materials for the case of strenuous hydraulic circumstances or for handling extremely low temperature liquids; in the latter instance the strength and brittleness of standard materials should be examined. For pumps used with high temperature water (HTW) up to 300-350 F, a standard cast iron casing is applicable. With either high temperatures (above 250 F) or low temperatures (below 50 F), the choice of materials for the impeller-shaft-supplementary components assembly becomes critical. The materials must be chosen such that the thermal expansion and contraction of these parts are equal.

According to Hydraulic Institute terminology for a standard fitted pump the standard materials used are: cast iron casing, steel shaft, bronze impeller as well as wearing rings and shaft sleeve (when used). A pump so constructed is termed bronze fitted. When all parts (casing, impeller, various rings, shaft) of the pump that come in contact with the liquid to be pumped* are made of bronze, such a pump is termed all bronze; in the case of all iron parts, the pump is termed all iron. There are many varieties of material deviations to fit the specific needs. Figure 10 shows the major parts of a bronze-fitted pump.

There are two basic approaches in the selection of pump materials:

1. If the engineer is thoroughly experienced for the given application, he dictates the specifications.
2. If the manufacturer has wide experience in selecting the appropriate materials, then the engineer furnishes the manufacturer comprehensive data on the liquid pumped, including the operating temperature, the physical characteristics as this temperature and any peculiarities of the operation.

*Bearings, bearing housings and other parts of the pump external to the liquid passage are not in contact with the liquid pumped, and are made of appropriate industry standard materials.

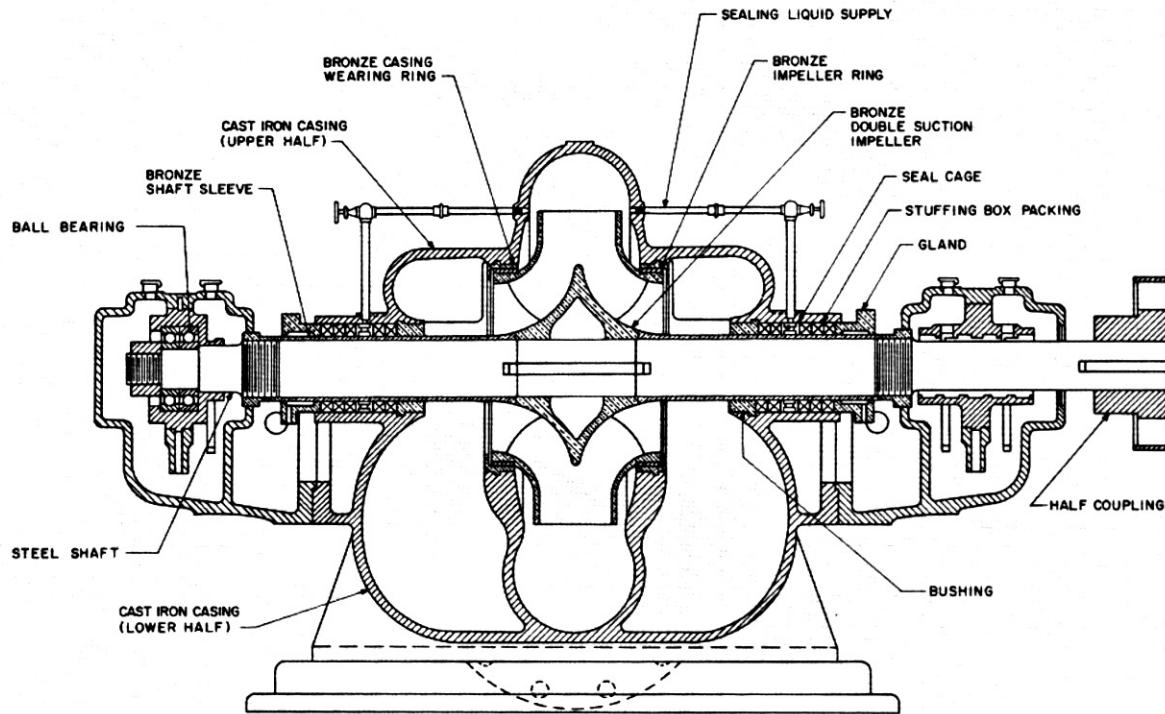


FIG. 10 – MAJOR PARTS OF A PUMP

CENTRIFUGAL PUMP FUNDAMENTALS

Having covered the mechanical aspects of the centrifugal pump and before considering it as part of the liquid circulating system, a discussion of pump behavior is presented.

BASIS THEORY

The rotating impeller imparts to a fluid a centrifugal force, kinetic energy in the form of velocity. The volute converts about 50 percent of the kinetic energy into the pressure head, potential energy measured in feet of fluid handled. As the fluid flows thru the impeller vanes, a reduced pressure zone is created at the inlet to the vanes. The atmospheric or system pressure and the static head of the fluid as available act on the pump suction inlet and force the liquid into the pump. This pressure at the pump suction plus the pressure the flow of the liquid. This is fundamental to the application of the centrifugal pump.

NET POSITIVE SUCTION HEAD

If the pumping is limited only to that normally applied in the air conditioning cold water closed circuit systems,

there is no need to be concerned with sufficiency of the suction pressure to force the liquid into the pump suction. However, the various liquids at any given temperature have a definite saturation pressure at which they turn to vapor. In the field of air conditioning and refrigeration situations exist to handle water, brines and refrigerants at any temperature and pressure level. It is the problem of the process and pump application engineer to be sure that under any set of circumstances there is sufficient pressure on the liquid fed to the pump to prevent the liquid from flashing into vapor.

Between the pump suction nozzle and the minimum pressure point within the pump impeller, there exists in addition to the suction velocity head a pressure drop. This pressure drop is due to velocity acceleration, friction and turbulence losses. The suction head (feet of liquid absolute) determined at the suction nozzle and referred to a datum line less the vapor pressure of the liquid (feet absolute) is called the net positive suction head or NPSH. The suction head necessary to keep liquid flowing into the pump and to overcome the pump internal pressure losses is the required *NPSH* of the pump.

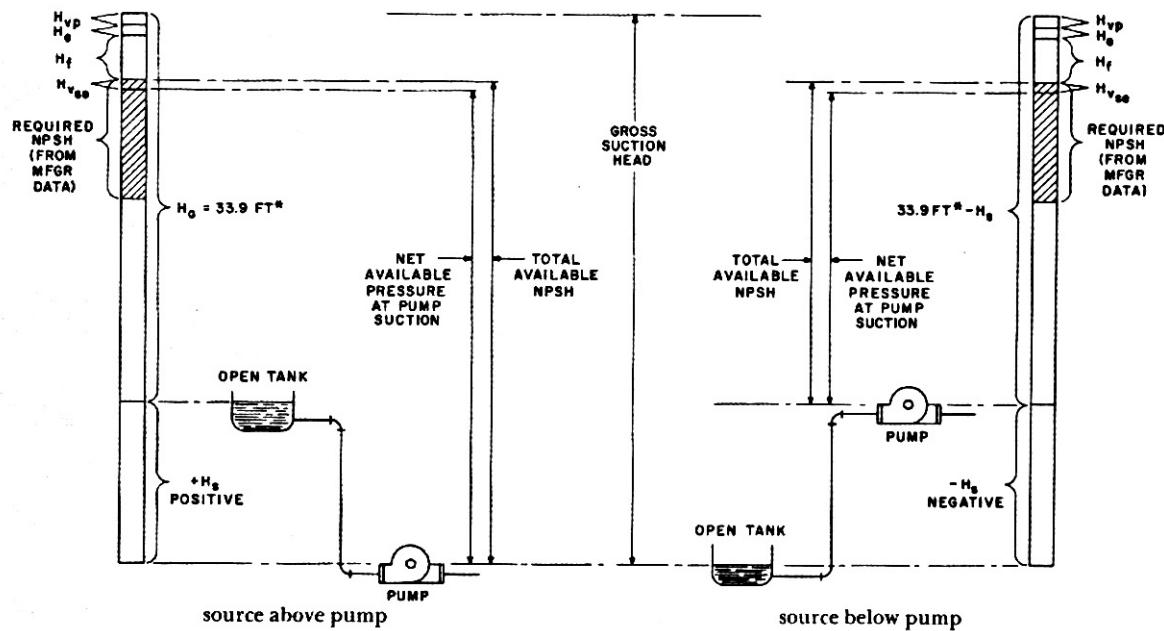


FIG. 11 – NET POSITIVE SUCTION HEAD, OPEN SYSTEMS (COLD WATER)

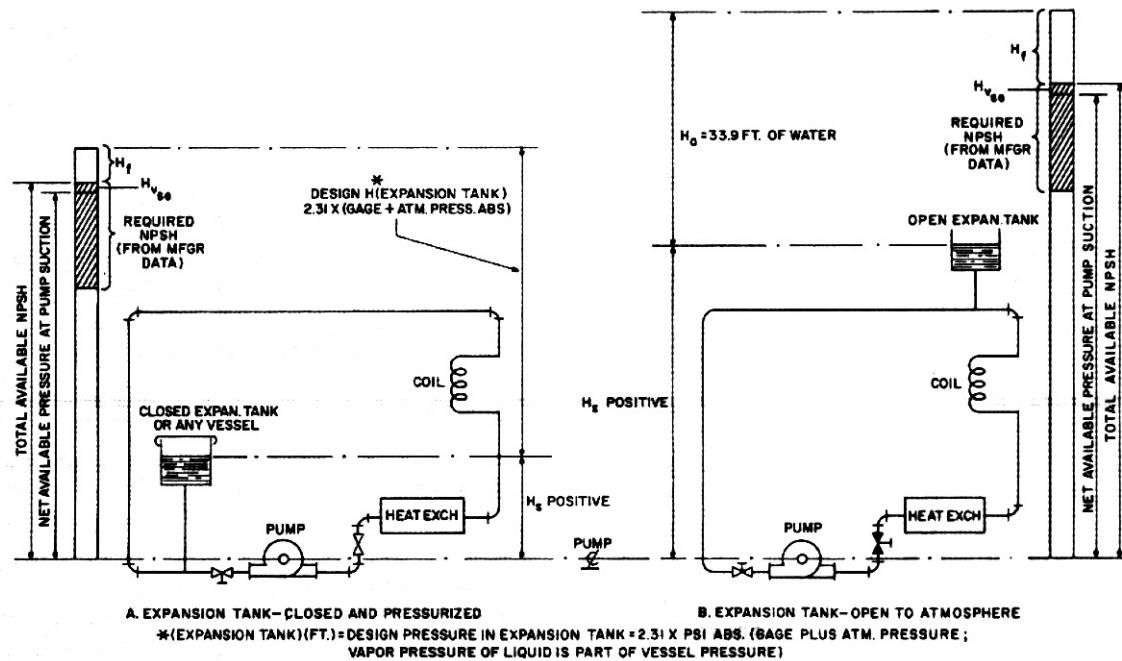


FIG. 12 – NET POSITIVE SUCTION HEAD, CLOSED SYSTEMS (COLD WATER)

The required NPSH of a pump is part of the standard design performance data furnished by the manufacturer or of a design specific to a given process pump.

The net positive suction head (pressure in feet of liquid) of the process liquid system as it exists within the system complex at the entering (suction) side of the pump is called the *available NPSH*. It must be at least equal to or greater than the required NPSH in order to produce a flow thru a pump. A safety factor should be considered to cover a possible excess of required NPSH.

The available NPSH is the algebraic sum determined by the formula:

$$\text{Available NPSH} = \frac{2.31(P_a - P_{vp})}{\text{sp gr}} + H_s - H_f$$

Where:

NPSH = net positive suction head (absolute pressure, ft)

2.31 = conversion factor to change one pound pressure at a specific gravity of 1.0 to pressure head in feet of water (1 inch Hg = 1.134 ft of water).

P_a = atmospheric pressure (absolute pressure, psia) in an open system; or pressure (absolute, psia) within a totally closed system.

P_{vp} = vapor pressure (psia) of the fluid at pumping temperature; in a totally closed system it is part of the total pressure P_a .

H_s = elevation head, static head (ft) above or below the pump center line. If above, positive static head; if below, negative static head, sometimes termed suction lift.*

H_f = friction head (ft) on the suction side of the system including piping, fittings, valves, heat exchangers at the design velocity (V_s in ft per sec) within suction system.

sp gr = specific gravity of liquid handled at operating temperature (Fig. 14).

Figures 11 and 12 illustrate the application of the calculation of available NPSH to the variety of open and closed circuits. Three additional terms are introduced in these figures:

H_{vp} = vapor pressure (ft) of the fluid at pumping temperature.

H_e = entrance head (ft), suction pipe entrance loss in open systems.

H_{ve} = pump suction eye velocity head (ft), $(V_{se})^2/2g$. This term is usually very small as shown in the following tabulation:

Velocity (ft/sec)	3	4	5	6	7
Velocity head (ft)	.14	.25	.39	.56	.76
Velocity (ft/sec)	8	9	10	11	12
Velocity head (ft)	.99	1.26	1.26	1.88	2.23

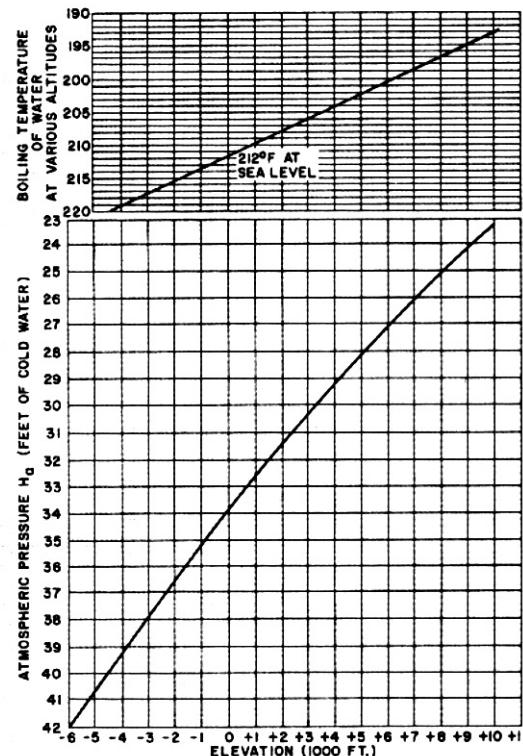


FIG. 13 – EFFECT OF ALTITUDE ON ATMOSPHERIC PRESSURE

A pressure selected to be maintained above atmospheric pressure in the top circuit of a closed piping system determines the design $H_{(expansion tanks)}$ pressure (Fig. 12).

On examining Fig. 11 and 12, it is evident that the available NPSH may vary, especially with critical fluids. The variables that may be either fixed or adjusted are:

1. Altitude of the system location above or below sea level; Fig. 13 Shows the change of atmospheric pressure (feet of cold water) with the altitude. The greater the altitude, the lower is the available atmospheric pressure (P_a in psia or H_a in ft) which influences an open system. The totally closed system pressure P_a may be regulated.
2. Vapor pressure of the liquid (Fig. 14) pumped at operating temperature P_{vp} (psia) or H_{vp} (ft); Figure 14 shows the vapor pressure of water at various temperatures. This pressure may or may not be adjusted.
3. Friction losses of the pump suction piping system; the larger the pipe, the less are the friction losses H_f (ft) for a given fluid flow.

*It must be remembered that a pump does not lift the liquid it moves; a pump must have pressure to produce the flow.

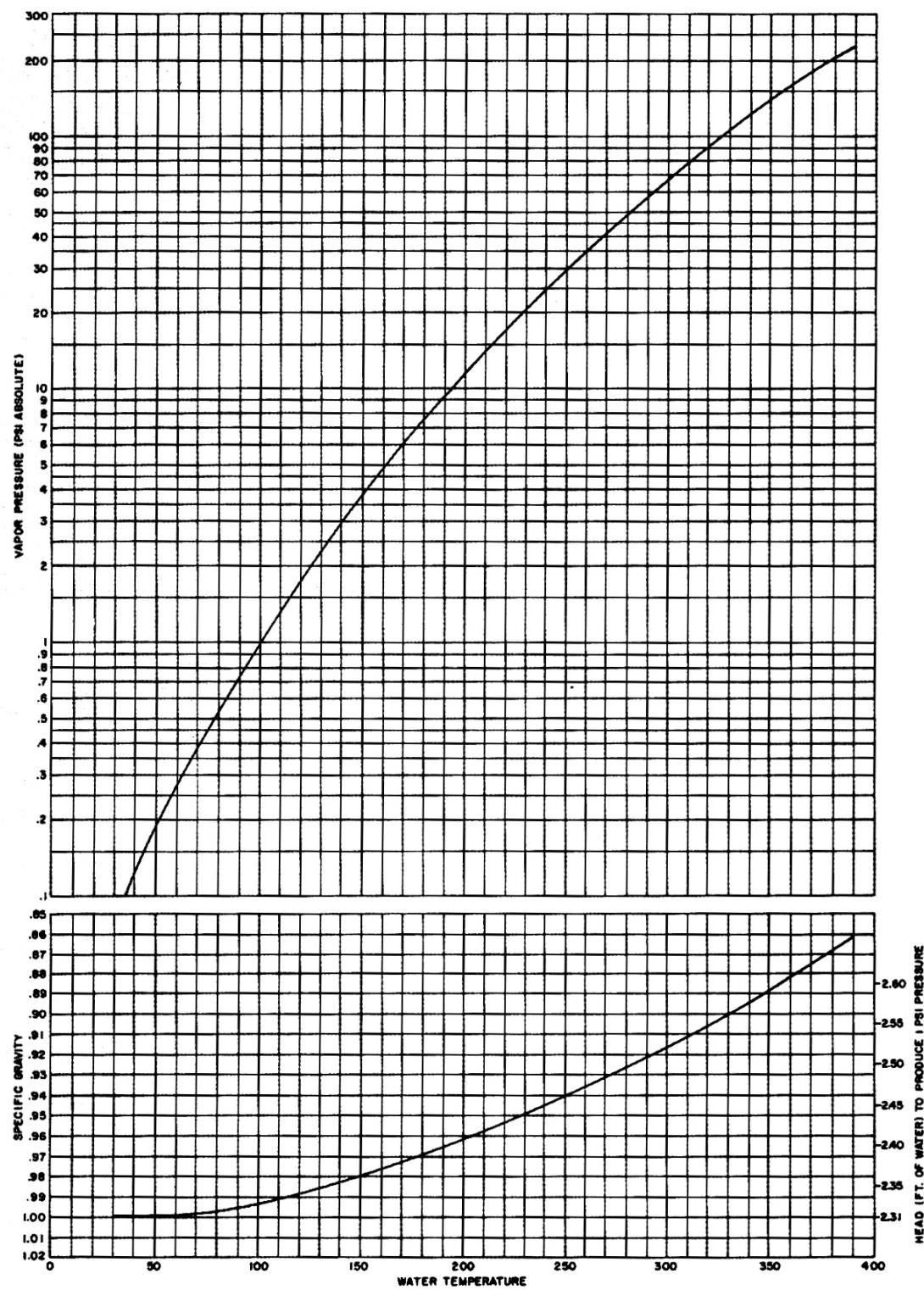


FIG. 14-PROPERTIES OF WATER AT VARIOUS TEMPERATURES

- Elevation of the source of liquid static head H_s (ft, positive or negative); pump location may be altered to increase or reduce static head. There are limitations to the negative head (suction lift).

SUCTION LIFT

The suction lift of open systems is not too frequent a factor in the design of air conditioning and refrigeration systems. Basically a pump does not lift; to operate, it must have pressure at its suction. Thus the maximum lift is determined by the required NPSH and limited by the available NPSH pressure.

The atmospheric pressure at sea level is 33.9 feet of water. For cold water at normal temperatures H_{vp} equals approximately one foot; therefore the gross suction pressure may be considered as 33 feet. Based on an operating rule that available NPSH should at least equal the required NPSH, normal suction lift should be limited. The limitation is the amount of available NPSH remaining after deducting from the gross suction pressure the H_e , H_f and the required NPSH (Fig. 11b) of the pump plus a safety factor, to allow for possible vagaries and to prevent appearance of cavitation and consequent vibration of the pump. There must be pressure at the suction for the pump to do normal work.

To quote from paragraph B-44 of the Hydraulic Institute Standards, "Among the more important factors affecting the operation of a centrifugal pump are the suction conditions. Abnormally high suction lifts (low NPSH) beyond the suction rating of the pump usually cause serious reductions in capacity and efficiency, often leading to serious trouble from vibration and cavitation.

SPECIFIC SPEED

Paragraph B-45 of the Hydraulic Institute Standards states: "The effect of suction lift on a centrifugal pump is related to its head, capacity and speed. The relation of these factors for design purposes is expressed by an index number known as the specific speed."

This number is used by pump designers to arrive at an optimum efficiency, expressed as follows:

$$\text{Specific speed } N_s = \frac{g \text{ rpm}^{0.5}}{H^{0.75}}$$

Where:

H = head (ft) * based on the maximum diameter impeller at the design capacity.

gpm = capacity at best efficiency.

rpm = mechanical speed at which the gpm and head are obtained.

*In case of a multi-stage pump, head of each stage.

The specific speed may be defined as the rpm at which a pump of a particular design would have to operate to deliver on gpm against a head of one foot. Specific speed is an index to the type of impeller (Fig. 1). The lower the specific speed, the more the blades of the impeller are of an arrangement to deliver a strictly radial flow; the higher the delivery head, the smaller the required NPSH. Excessive reduction in required NPSH may lead to cavitation. The radial flow impellers afford more regulated flow thru the impeller vanes.

CAVITATION

The lack of available NPSH show up particularly in pump cavitation. If the pressure at any point inside the pump falls below the operating vapor pressure of the fluid, the fluid flashes into a vapor and forms bubbles. These bubbles are carried along in the fluid stream until they reach a region of higher pressure. Within this region the bubbles collapse or implode with a tremendous shock on the adjacent surfaces. Cavitation accompanied by low rumbling or sharp rattling noise and even vibration causes mechanical destruction in the form of pitting or erosion.

Remedies to eliminate cavitation are apparent from the tabulation of variable elements in an evaluation of available NPSH. The first two factors are fixed; the system is installed at a definite altitude, and the temperature of the fluid is fixed by the process. Therefore, only the two remaining adjustments can be made; decrease the friction loss and/or change the elevation of the pump to increase the static head.

Do not tamper with the pump suction inlet; do not request the pump manufacturer to enlarge the pump suction in order to decrease the required NPSH. The pump efficiency falls off and the whole performance of the impeller is upset.

VORTEX

A whirling fluid forming an area of low pressure at the center of a circle is called a vortex. This is caused by a pipe suction placed too close to the surface of the fluid. Such a vortex impairs the performance of a pump and may cause a loss of prime.

In the case of pump suction in a shallow water sump such a vortex may be prevented by placing a plate close to the intake at a distance of one-third diameter from the suction inlet. The plate should extend $2\frac{1}{2}$ diameters in all directions from the center of the inlet.

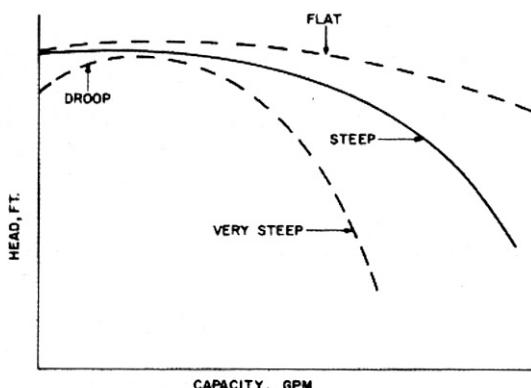


FIG. 15 – DESIRABLE HEAD-CAPACITY CURVE

PERFORMANCE

When a pump designer has established the specific speed of a pump, its capacity-head curve is then defined. The pump operates on this curve (Fig. 2 and 22) unless some physical change is effected.

Head-capacity curves should not droop at shutoff conditions; this leads to a surging operation when the flow is throttled into this range. Neither should the curves be too flat. The steepness in the pump head-capacity curve (Fig. 15) most desirable for an air conditioning and refrigeration application is shown by the solid line.

The performance characteristics of a centrifugal pump as expressed by a head-capacity curve are influenced in several ways:

1. Variation in speed-proportionally raises or lowers the head and capacity. The whole head-capacity curve shifts up or down.
2. Varying impeller diameter – varies the capacity and head proportionally, as in Item 1.
3. Varying impeller width – proportionally varies the capacity.
4. Varying the pitch and number of vanes within the impeller changes the shape of the head-capacity curve. Spoke-like vanes or more vanes usually produce a flat curve.
5. Varying impeller and vane designs produce variations in head-capacity relationships. Narrow impellers with larger impeller-to-eye diameter ratios develop larger heads. The wide impellers with low diameter ratios are used for large flows at low heads.

The changes in speed and impeller diameters are reflected in pump performance as follows:

$$\frac{rpm_1}{rpm_2} \text{ or } \frac{impeller}{impeller} \frac{dia_1}{dia_2} = \frac{gpm_1}{gpm_2} = \left(\frac{head_1}{head_2} \right)^{\frac{1}{4}} = \left(\frac{bhp_1}{bhp_2} \right)^{\frac{1}{3}}$$

or

Capacity varies directly,

Head varies as the square,

Bhp varies as the cube or impeller diameter change.

The performance of a centrifugal pump is affected when handling viscous fluids. The effects are a marked increase in brake horsepower and decrease in head, capacity and efficiency (Fig. 16).

POWER AND EFFICIENCY

In pump operation two power requirements may be evaluated, liquid power and actual power (brake horsepower that takes into account the pump efficiency). Liquid power is the product of the weight of the liquid pumped (gpm), pump head (ft), and the conversion factors. Brake horsepower is the actual power output of the driver, pump input, or liquid power divided by pump efficiency. Pump efficiency is the relation between the liquid (theoretical) power and the actual mechanical power input (a greater amount due to machine losses). The efficiency is expressed as a decimal. This should not be confused with driver efficiency since the latter is the relation between the output of the driver and the energy input to produce the power to drive the pump and compensate for losses within the driver.

$$Bhp = \frac{U.S.gpm \times \text{pump H (ft)} \times \text{sp gr}}{3960 \times \text{percent pump eff}}$$

where:

3960 = 33,000 (ft lb)/ 8.33 (lb/gal water at 1.0 sp gr), used to convert to horsepower.

Sp gr = specific gravity of liquid.

Viscosity* of the liquid pumped affects the friction losses and therefore the pump horsepower requirements.

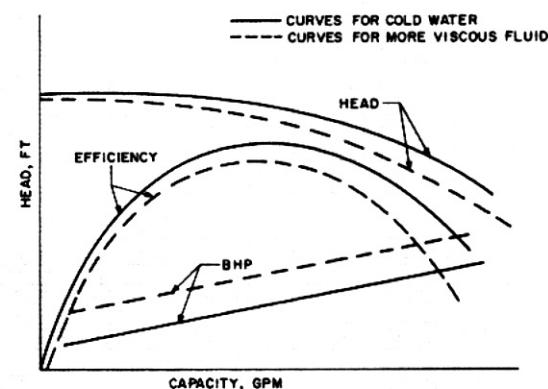


FIG. 16 – INFLUENCE OF VISCOSITY ON PUMP PERFORMANCE

*Viscosities and specific gravities for various brines at meanbrine temperatures are found in Part 4. Viscosities must be expressed in consistent units.

CENTRIFUGAL PUMP AND SYSTEM SYSTEM HEAD

A flow of liquid within any system of piping including fittings, valves and heat exchangers requires a system head consisting of a velocity head (usually insignificant) and friction head, and must overcome a static head. Thus in any piping system the system head is the algebraic sum of the static head on the pump discharge minus the static head on the pump suction plus the friction losses thru the entire system of fluid flow. With an increase in flow the friction losses increase approximately as the square of the flow; when plotting head against capacity flow, a parabolic head curve is formed (Fig. 17).

OPERATION IN A SYSTEM

A given centrifugal pump operates along its own head-capacity curve. At full capacity flow the operating point falls at the crossing of the pump head-capacity curve and the system head curve (Point 1, Fig. 17). If the pump is throttled, the operating point moves up the head-capacity curve (Point 2); if it is desired to obtain greater flow to operate down the head-capacity curve (Point 3), the path of flow in the system must be eased to reduce the friction losses. Otherwise the pump must be either speeded up or the impeller increased in diameter. Then a new head-capacity curve is established (Point 4). The engineer must carefully analyze the system and select the pump from the manufacturer's performance head-capacity curves.

If the system head is overestimated and the pump is selected with a high head-capacity curve, unfortunate results may follow. The pump will operate on its head-capacity curve to produce an increased flow at decreased head and increased horsepower demand (Fig. 18). The system head should always be calculated

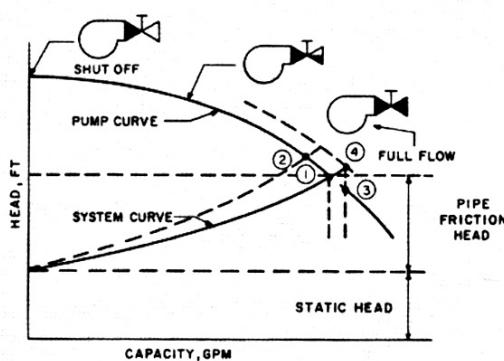


FIG. 17 – CROSSOVER POINT OF PUMP AND
SYSTEM CURVES

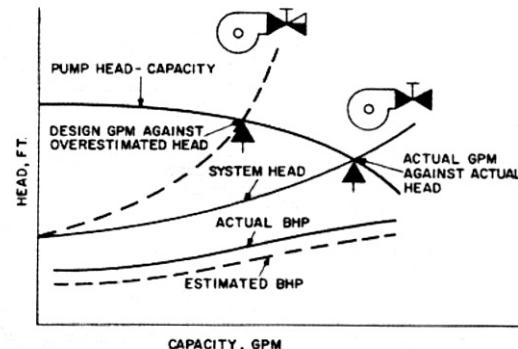


FIG. 18 – EFFECT OF OVERESTIMATING PUMP HEAD

without undue safety factor extention or as close as practical to the true values to eliminate possible waste of horsepower or possible overload of pump motor with an unvalved system.

The true evaluation of system head is specially important when designing a system with pumps in parallel or in series.

PARALLEL OPERATION

The operation of pumps in parallel results in multiple capacity against a common head (Fig. 19). This type of application is for a system requiring high capacity with a relatively low head or for variable systems where a number of small pumps handle the load with one or more pumps shutting down as required. The pumps should have matched characteristics. Drives should have ample power to avoid overloading when operated singly.

SERIES OPERATION

The operation of pumps in series results in multiple head with a common capacity (Fig. 20). This type of application is for systems requiring a high head and a relatively low capacity. Careful consideration of fluid flow must be made to safeguard the booster pump. Normally a series flow is provided for by a multi-stage pump.

HIGH BUILDINGS

The operation of pumps at the base of high buildings requires an analysis of pressures on the discharge and suction sides of the pump. The static head of the fluid in the piping system plus the head developed in the pump may necessitate the use of 250 lb pipe and fittings and even a reinforced pump casing.

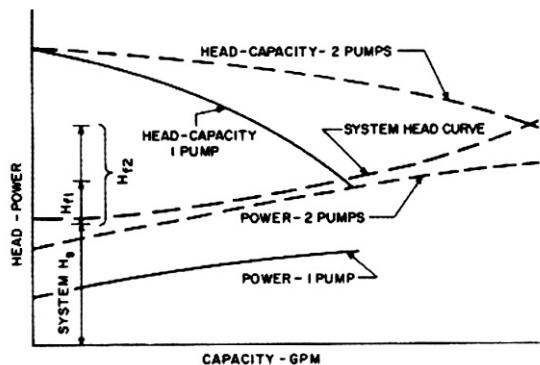


FIG. 19 – TWO EQUAL CAPACITY PUMPS, PARALLEL OPERATION

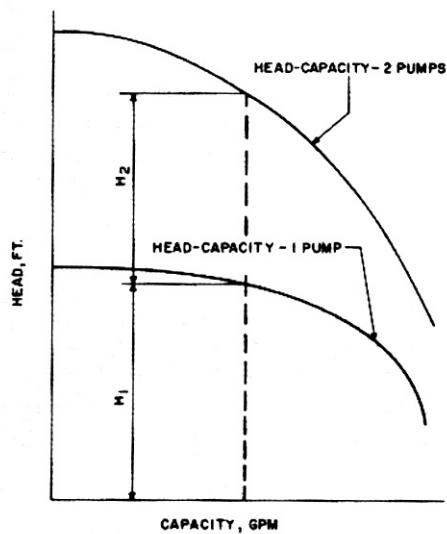
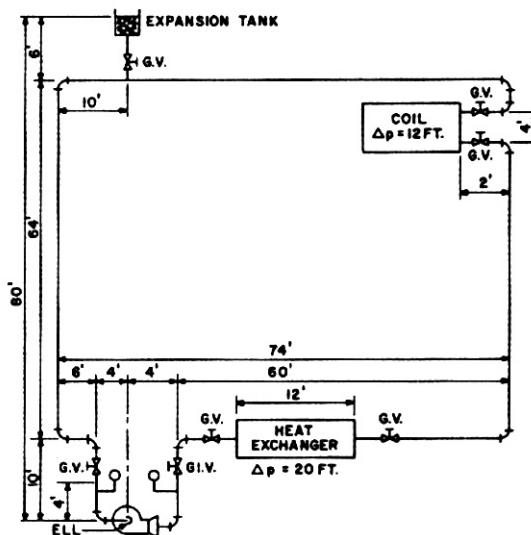


FIG. 20 – TWO EQUAL CAPACITY PUMPS, SERIES OPERATION

WORKING PRESSURE

Pump casing working pressure is the total head developed by the pump to overcome friction losses of the system plus the suction static head minus the friction losses in the pump suction line, from the junction of the expansion tank line to the pump suction. The problem outlined in *Fig. 21* and its solution serve as an example.



Given:

600 gpm of water
6 in. steel pipe, standard weight
Ells, long radius, R/D = 1.5

Find:

Total pump head (ft)
Pump casing working pressure (psig)
Suction pressure (psig)
Discharge pressure (psig)

FIG. 21 – PUMP SYSTEM TOTAL HEAD AND PUMP CASING WORKING PRESSURE

Example 1 – Calculation of Total Head and Working Pressure

Solution:

(based on data in *Part 3, Chapter 2, Water Piping*)

Friction head H_f , suction line
(from expansion tank to pump)

$$\begin{aligned}
 \text{Straight pipe} &= 94 \text{ ft} \\
 \text{Five ell} &= 50 \text{ ft} \\
 \text{One gate valve} &= 7 \text{ ft} \\
 \text{Suction head total} &= 151 \text{ ft} \times 2.35 \text{ ft } H_f / 100 \text{ ft} \\
 &= 3.54 \text{ ft}
 \end{aligned}$$

Friction head H_f , discharge line
(from pump to expansion tank)

Straight pipe	= 190 ft
One $\frac{2}{3}$ enlargement	= 9 ft
Six ells	= 60 ft
Four gate valves	= 28 ft
One globe valve	= 170 ft
Discharge head total	= $457 \text{ ft} \times 2.35 \text{ ft } H/100 \text{ ft}$ = 10.75 ft

Pump system total friction losses H_f

Suction piping	= 3.54 ft
Discharge piping	= 10.75 ft
Heat exchanger	= 20.00 ft
Coil	= 12.00 ft
Pump head total	= 46.29 ft

Pumps casing working pressure

Static head	= 80.00 ft
Less suction line H_f	= 3.54
Subtotal	= 76.46 ft
Plus system H_f	= 46.29 ft
Working pressure	= $122.75 \text{ ft} \times 2.31 \text{ ft per psi}$ = 53.1 psi

Suction pressure gage reading

Static head	= 80 - 4	= 76.00 ft
Less H_f of straight pipe*	=	86 ft
3 ells	=	30 ft
1 gate valve	=	7 ft
86 + 30 + 7 = 123 ft		

$$\text{Less suction head} = 123 \text{ ft} \times 2.35 \text{ ft } H_f / 100 \text{ ft} = -2.89 \text{ ft}$$

Net = 73.11 ft

$$\text{Suction pressure} = 73.11 \text{ ft}/2.31 \text{ ft per psi} = 31.7 \text{ psi}$$

Discharge pressure gage reading

$$\text{Suction pressure gage plus pump system total } H_f = 73.11 + 46.29 = 119.40 \text{ ft}$$

$$\text{Less } H_f \text{ of straight pipe} = 16 \text{ ft}$$

$$1 \text{ enlargement} = 9 \text{ ft}$$

$$3 \text{ ells} = 30 \text{ ft}$$

$$16 + 9 + 30 = 55 \text{ ft}$$

$$\text{Less discharge head} = 55 \text{ ft} \times 2.35 \text{ ft } H_f / 100 \text{ ft} = -1.29 \text{ ft}$$

Net = 118.11 ft

$$\text{Discharge pressure} = 118.11 \text{ ft}/2.31 \text{ ft per psi} = 51.2 \text{ psi}$$

NOISE

The centrifugal pump is inherently a relatively quiet machine. However, in the case of a motor driven pump there are possible motor disturbances such as motor fan, bearings and magnetic noise (Chapter 2), in addition to the normal hydraulic and mechanical disturbances originating in the pump.

* Distance between expansion tank and gage.

† Distance between gages

A fixed frequency vibration (rpm times the number of blades divided by 60) may be set up by a pump using too large an impeller. Sometimes, to produce quiet operation a recommendation is made to use an impeller diameter 10-15% smaller than the largest size that will fit in a given pump casing.

Operation of the pump under conditions of insufficient NPSH must be avoided to preclude formation or aggravation of cavitation and noise. However a small amount of cavitation in a condensate pump operation is permissible.

Well designed pumps operating at either 1750 or 3500 rpm rotative speed may be used.

A pump frequency may coincide with a corresponding frequency in the piping system or building structure; such telegraphing noise must be avoided.

PUMP SELECTION

Pump are selected from manufacturer's performance curves (Fig. 22). Most standard pumps are de-signed to operate at maximum efficiency about midway on the head-capacity curve. Selecting a pump at the maximum efficiency point or slightly to the left materially assists in minimizing problems of noise and vibration. A selection too far to the right of the efficiency point may lead to cavitation due to an in-crease in required NPSH.

Pump efficiency is not the only selection criterion; quiet operation, lowest first and operating costs and close conformance to actual needs are parallel objectives.

MOTOR SELECTION

The horsepower of the motor selected to drive a given pump must be equal to or greater than the brake horsepower called for at the operating point of the head-capacity curve. There is always the danger of a pump running away from the selected operating point and overloading the motor. In case of a nonoverloading pump-motor combination the selected motor horsepower is always larger than the required brake horsepower;

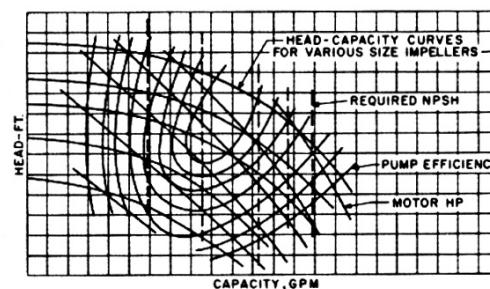


FIG. 22 – TYPICAL PUMP SELECTION CURVES

a safety margin is provided. If the pump is fitted with a nonoverloading impeller, it may be possible to select a motor of smaller horsepower. In either case the brake horse-power is the same.

CENTRIFUGAL PUMP INSTALLATION INSTALLATION

There are several aspects in the application of a centrifugal pump that are external to the pump itself, yet important in the installation.

The suction piping at the centrifugal pump must be designed with care to avoid possible malfunctioning. The precautions to be taken (*Part 3*) are summarized:

1. The suction line approach to the pump should be as straight as possible and all elbows should have large radii.
2. A straight section of pipe should be attached to the suction inlet to allow the fluid to straighten out before entering the pump; this is especially true of double suction pumps.
3. The suction line should be one or two sizes larger than the pump inlet.
4. With an oversized suction line an eccentric reducer must be used, keeping the pipe flat on top.
5. Suction line should be airtight, with no high spots where air or gases may separate out of the fluid.
6. A check valve and a gate valve should be installed at the pump discharges of a multi-pump system. These should be installed in the order named to enable the check valve to be serviced without draining the discharge line.
7. Both the suction and discharge pipe connections must be supported separately and in such a way as to impose no strain on the pump.
8. The suction line for the pump operating with a negative static head (suction lift) should have no valves other than a foot valve. The suction line should be large and as direct as possible.

INSULATION

It is advisable not to insulate the pumps intended for chilled water (brine) service or hot water service. The refrigerant condensing water pumps need not be insulated. If a pump is insulated, the insulation should be applied in a form which permits disassembling of the pump for servicing without wrecking the insulation.

ISOLATION

Cork is not an effective isolation material for rotative speeds below 200 rpm. Rubber-in-shear or corrugated rubber is useful on the ground floor installations. In more critical installations, on floors above occupied areas (especially those of executive offices, board rooms, libraries, hospital areas) steel spring isolation is recommended for isolation effectiveness approaching 100%. The concrete foundation of one to two times the machinery weight serves as a dampening mass and must be of reinforced construction. For piping isolation refer to *Part 3*.

FOUNDATION

Where requirements for isolation of a centrifugal pump are at a minimum (basements, outdoors, any remote location), a foundation is desirable to keep the pump off the floor or ground level.

STARTING

Unless the pump is self-priming, it must be primed before starting.

When starting the pump, the discharge valve is usually closed, then gradually opened so as not to run the risk of overloading the drive motor.

For more information there is vast experience of pump manufacturers recorded in their catalog and handbook data and in innumerable authoritative articles written by engineers from these manufacturing concerns. A classical book on pump design and application is *Centrifugal and Axial Flow Pumps*, 2nd edition, by A.J. Stepanoff, 1957.

CHAPTER 2. MOTORS AND MOTOR CONTROL

This chapter presents the characteristics of various motors that drive the equipment normally applied in air conditioning and refrigeration systems, the functions of motor controllers, and a brief discussion of the behavior of electric energy to produce mechanical power.

EQUIPMENT SERVED

The air conditioning and refrigeration systems include fans, pumps, and reciprocating, rotary and centrifugal compressors. To effect the transfer or compression of various liquids and gases such as air, water, brine or refrigerants, it is necessary to put this equipment into motion by prime movers, in this instance, electric motors. Apart from the factors (source of electric energy, speed, power) which are used in the selection of particular motor-starter combinations, a knowledge of the load torque characteristic for a particular driven equipment is the most fundamental requirement. The operational torque characteristics include those required for starting from rest, acceleration, and for full load running. The starting or locked rotor torque is the initial turning effort for bringing the driven equipment from standstill into motion; the acceleration torque is the developing of this motion into operating speed in as allotted time. The full load torque is the sustained effort by the motor to maintain the driven equipment in motion under the work load. The driven equipment torque requirements must be matched with a drive complex (motor and its control) of the proper torque and current characteristics.

NORMAL OR HIGH TORQUE MOTORS

With the exception of the reciprocating and rotary compressors, the equipment considered is of the centrifugal type (fans, refrigeration compressors, pumps) operating at starting within a system of high and low sides that are equalized. Ordinarily no specific requirement of starting torque other than normal is needed. At times with large centrifugal compressors or fans there exists a pull-up torque problem because of the large rotational inertia (Wk^2)* of the massive impellers or wheels. The pull-up minimum torque must exceed Wk^2 . A possible problem may exist when small equipment is driven by an oversized motor with

overpowering torque; this equipment may be damaged because of excessive acceleration or torque applied.

The duration of acceleration to full speed at full voltage is usually 1 to 3 seconds. With open centrifugal compressors using a standard integral oil pump, it should be at least 8 seconds, permitting oil to reach all the lubricated surfaces before high speed is developed. When an auxiliary oil pump is used, it should be at least 5 seconds to prevent excessive stress concentration on the keyway of the compressor shaft.

The present methods of starting the larger reciprocating compressors with cylinders either fully or partially unloaded permit the use of normal starting torque motors. The smaller, hermetically driven compressors are started fully loaded with a requirement of high starting torque.

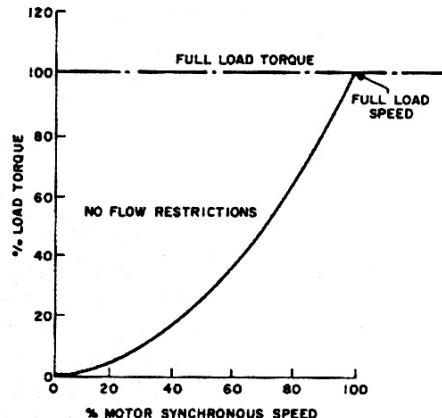
The application of rotary compressors as low pressure differential boosters in a refrigeration system does not present any unusual requirement of starting torque; therefore, a normal starting torque motor is applicable.

Centrifugal, propeller or axial fans may be either belt or direct connected to electric motor drives. In all cases the torque requirements are normal. The fans should start smoothly and without undue noise.

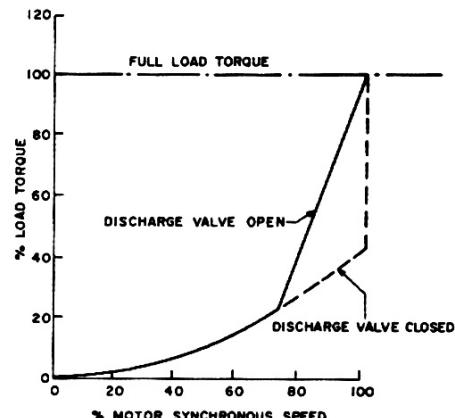
The fan cfm is directly proportional to speed; the system resistance varies as the square of speed; and the horsepower required varies as the cube of speed.

Because the gas density at the suction of a centrifugal compressor usually increases during shutdown, the torque requirements of centrifugal compressors do not necessarily follow the fan laws. Normal torque motors are usually used for driving centrifugal compressors; however, they must be started either with an almost completely closed suction damper or pre-rotation guide vanes to prevent the increased gas density from imposing an excessive overload at full speed.

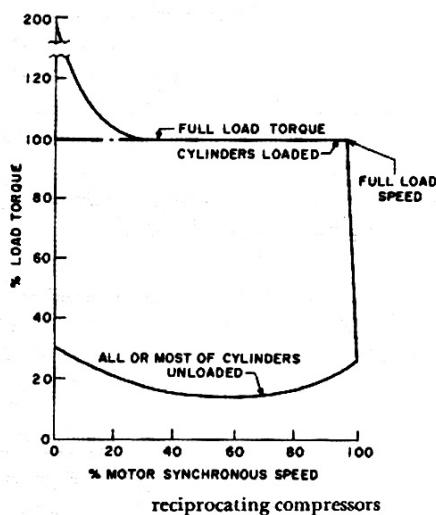
*In this expression W = weight of the body; k = radius of gyration



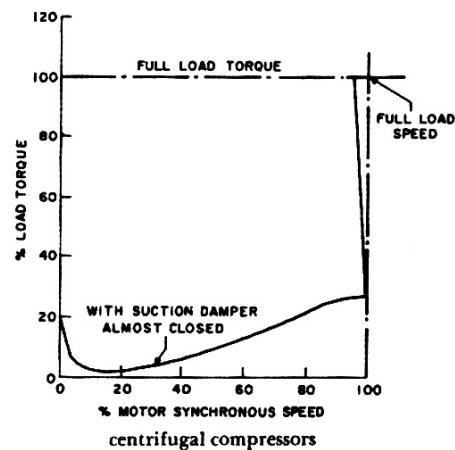
fans



centrifugal pumps



reciprocating compressors



centrifugal compressors

FIG. 23-TORQUE CHARACTERISTICS

Figure 23 illustrates typical torque requirements of fans, pumps, and reciprocating and centrifugal compressors. Pumps usually have a check valve in the discharge; therefore, the break exists in the torque requirement curve. There is a decided difference in torque requirements of reciprocating compressors, whether they are started with cylinders loaded or unloaded. The breakaway and acceleration torques shown for centrifugal compressors are determined by the friction and the Wk^2 .

MOTORS OF MATCHING CHARACTERISTICS

The energy necessary to operate motors is available in two services: (1) direct current (d-c), unidirectional and at constant pressure, and (2) alternating current (a-c), alternating in pressure and direction. Since direct current is used infrequently except in certain industrial processes, special purposes, or in some remote communities, this text concentrates only on a-c electrical equipment.

TABLE 1-SINGLE AND POLYPHASE A.C. MOTOR CHARACTERISTICS

Motor Type	HP Rating	Speed Characteristics	Full Voltage		Remarks
			Starting Torque	Starting Current	
POLYPHASE					
Squirrel-cage induction	Small to large	Constant and multi-speed	High to normal	Low to normal	Most widely used for constant speed service
Wound-rotor	All	Constant or variable	High	Low	For application requiring high starting torque and low starting current, or limited variation in speed control
Synchronous	Medium to large	Strictly constant	Normal to low	Low to normal	For constant speed service and where power factor correction is required
SINGLE-PHASE					
Capacitor-start, induction-run	Small*	Constant	High	Normal	General purpose
Capacitor-start, capacitor-run	Small*	Constant	High	Low	High efficiency
Split-phase	Fractional	Constant	Normal	Normal	Least expensive of higher starting torque types, general purpose
Permanent split-capacitor	Fractional and small integral	Constant or adjustable varying	Low	Normal	Quiet, efficient; low running current; poor starting torque
Shaded-pole	Fractional	Constant or adjustable varying	Low	-	Inexpensive; poor starting torque; least efficient; high running current

*Up to 7.5 hp

This chapter describes a-c motor drives and motor controllers which match the torque characteristics of the driven equipment. The motor sizes discussed are fractional (up to 1), integral (above 1) and medium to large horsepower. The types of motors include single phase capacitor, polyphase squirrel cage induction, and synchronous motors. However most applications use the simple polyphase squirrel cage induction motor. Major characteristics of a-c motors are shown in Table 1.

Each type in Table 1 offers specific motor characteristics of starting torque, starting current and operating speed to meet the requirements of various industrial applications. The motors used in air conditioning systems fall into two groups: (1) singlephase motors for small systems, and (2) polyphase squirrel-cage induction motors for large systems. Occasionally wound-rotor and synchronous motors may be used for refrigeration centrifugal compressors.

In the medium sizes of squirrel-cage induction motors Type B (Table 3) is preferred, having normal starting torque and low starting current; these characteristics conform to normal equipment torque requirements and to the regulations of power distribution by the utilities. These regulations are directed toward leveling the demand for current by the consumers so that at any one moment of power flow there is no extreme dip that might cause flickering of the lights and other anomalies along the electric system.

EQUIPMENT AND MOTORS

The purpose of a motor is to supply mechanical power to drive equipment. The preceding discussion states that the motor must inherently possess necessary torque, and must not affect the power line adversely by its current requirements. Table 2 lists the major varieties of equipment and motors that are applied in each case.

TABLE 2 – EQUIPMENT AND MOTORS

EQUIPMENT	MOTORS	
	Single Phase	Approximate Horsepower Range
Room fan-coil units	Shaded-pole (air-over)	Fractional up to 1/3 hp
Small fans with any equipment and Hermetic compressors	Permanent, split-capacitor (air-over, self-ventilated or refrigerant-cooled) Capacitor-start, capacitor-run (air-over, self-ventilated or refrigerant-cooled)	Fractional and integral up to 5 hp
	Polyphase	Approximate Horsepower Range
Fans, pumps and centrifugal compressors	Squirrel-cage induction (constant speed)*	Integral above 1 hp
Open reciprocating compressors	Squirrel-cage induction (constant speed)**	Integral above 1 hp
Centrifugal compressors	Wound rotor (varying speed)	Large
Centrifugal compressors, Pumps	Synchronous (constant speed)	Large, medium
Hermetic reciprocating compressors	Hermetic (refrigerant-cooled)	Small to medium
Hermetic centrifugal compressors	Hermetic (refrigerant-cooled)†	Medium to large
Absorption machine solution pumps	Hermetic (solution-cooled)††	Small

* NEMA Design B, Insulation Class A (Tables 3 and 4).

** NEMA Design C, Insulation Class A (Tables 3 and 4).

† At times wound for star-delta starting.

†† Insulation Class F (Table 4).

Fans may be either included with a built-up system or coupled directly in any type of equipment complex containing coils, filters and spray chambers. The composite equipment may include fan-coil units, self-contained packages, condensing units, heat pumps, unit heaters and cooling towers.

The motors may be encased in any enclosure (open type to explosion-or weatherproof type), depending on the design of equipment, application and customer desire.

of the National Electric Manufacturers Association (NEMA). Motor installation should conform to the utility regulations and local codes and ordinances. NEMA standards for motors cover frame sizes and dimensions, horsepower ratings, service factors, temperature rises, and performance characteristics.

Reference is also made to the National Electric Code (NEC) sponsored by the National Fire Protection Association, Underwriters' Laboratories, Inc., AIEE Standards, and federal and military standards when applicable.

The standard ambient conditions for normal motor operation are assumed to be a location with an unobstructed circulation of clean, dry air at a temperature

STANDARDS AND CODES

Motor manufacturers are guided by the Standards

TABLE 3-CHARACTERISTICS OF SQUIRREL-CAGE INDUCTION MOTORS, NEMA DESIGN A, B AND C

NEMA DESIGN	TORQUE (Percent of Full Load)		STARTING CURRENT	SLIP	APPLICATION
	Starting	Breakdown			
A (Rarely used)	Normal 100 to 275	Higher than Design B	Normal	Normal	On moderately easy-to-start loads requiring slightly more than full load starting torque, low slip and moderately high breakdown torque to sustain occasional overloads (Design A higher than Design B).
B	Normal 100 to 275	200 to 300	Normal	Low	For fans and blowers, centrifugal pumps and compressors, reciprocating compressors (started unloaded).
C	High 200 to 250	190 to 225	Normal	Low	On hard-start loads requiring high starting torque but not high overload demands. Used with open reciprocating compressors (started loaded), rotary pumps.

of 40 C (104 F) and at an altitude not exceeding 3300 feet (1000 meters). At higher altitudes the rarefied air produces insufficient cooling.

Special insulation must be provided for motors applied in the tropics because they may be exposed to excessive ambient temperatures, humidity and fungus.

The motors and motor controls utilized to drive the equipment used in air conditioning and refrigeration systems are described in the following sections

POLYPHASE A-C MOTORS

The operating characteristics inherent in various polyphase alternating current motors (squirrel-cage, wound-rotor and synchronous) are shown in *Table 1*. The text that follows describes the mechanical construction, electrical behavior and application.

Fundamental relations and terminology used in the field of electricity are to be found in *Fundamental Relations*.

SQUIRREL-CAGE INDUCTION MOTOR

The most widely used motor is the squirrel-cage induction type. It is simple in construction, easy to start, and in combination with the starting equipment it is the least expensive in dollars per horsepower; it is efficient and has a reasonably good power factor. *Figure 24* illustrates a representative performance of a standard squirrel-cage induction motor.

The two basic components of a squirrel-cage induction motors (*Fig. 25*) are the stator (stationary part) and the rotor (rotating part) reminiscent of a squirrel cage.

A stator consists of a laminated iron core within and around the inner rim of which are distributed insulated windings. These primary windings are three in number for three-phase current and two for two-phase current. The arrangement of primary windings is controlled by the line voltage, number of phases, and number of poles. The power source is connected to the primary windings.

The rotor consists of a laminated iron core with bar windings in various shaped slots around the periphery of the core. The bar windings at a design resistance specific to various NEMA design (*Table 3*) are interconnected (short-circuited) with rings. The rotor mounted on a shaft is in turn mounted in bearings. There are no direct power connections to the secondary windings. The current in the rotor is induced, therefore the name induction motor.

Thru a specific design arrangement of windings within the stator and with the positive and negative

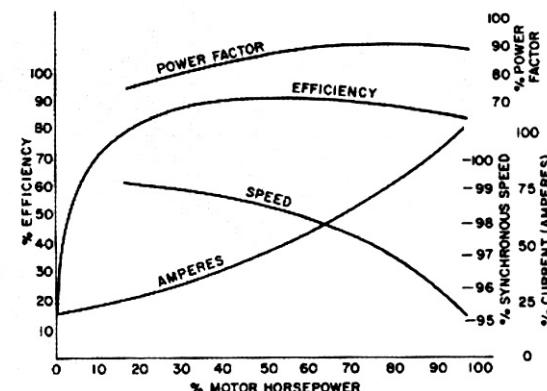


FIG. 24 – TYPICAL PERFORMANCE, STANDARD SQUIRREL-CAGE INDUCTION MOTOR (MEDIUM SIZE)

alternations of the current imposed, a magnetic field known as flux is established. This magnetic field has a definite polarity changing with each alternation in current. With an arrangement of windings to form two poles within the stator, the resultant flux leaves the stator at one point (north) and re-enters at an opposite point (south) (*Fig. 26*). During the next alternation the polarity changes; thus the flux is rotated. In a four-pole windings arrangement the flux leaves the stator at two opposite points (both north) and re-enters at two opposite points (both south). This flux pulsates with the rise and fall of current; these pulsations and alternating polarity in the stator poles produce the rotating magnetic field. As the stator-created flux revolves, it cuts the bars or coils of the rotor; in so doing, it induces a voltage within the rotor circuits (transformer-like action).

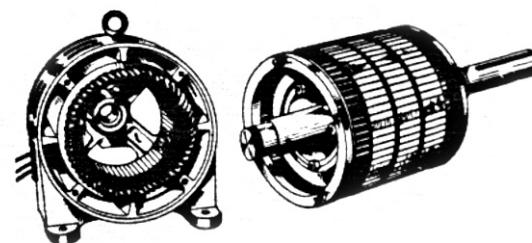


FIG. 25 – STATOR AND ROTOR, SQUIRREL-CAGE INDUCTION MOTOR

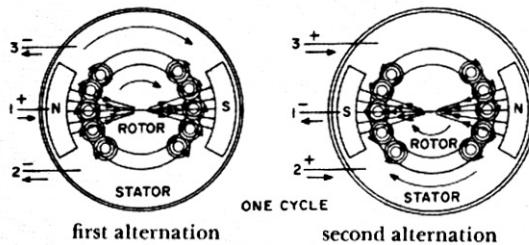


FIG. 26 – INITIAL FLUX IN STATOR, INDUCED FLUX IN ROTOR, SQUIRREL-CAGE INDUCTION MOTOR (2-POLE, 3-PHASE)

Current generated in the rotor bars sets up a magnetic field of its own *Fig. 26*). The interaction of forces created produces the turning torque that accelerates the rotor and in turn puts in motion the external load to which the motor is connected.

The speed of the stator-created rotating flux is the synchronous speed (rpm) of the motor. If a current is impressed on the stator and if the rotor is held at a standstill, a magnetic field revolves past the rotor conductors at a synchronous speed, generating a maximum current in rotor conductors. If the rotor is driven at the same synchronous speed, then its conductors do not cut the stator flux, and no current is generated within the rotor. Since there is no current in the rotor conductors, there is no torque, no turning effort developed by the rotor. However the windage, friction and applied load create a slowing down of the rotor below the synchronous speed of the flux, allowing the motor to develop torque. The difference (by design) in rotor speed is the slip of the motor. The current generated within the decelerated rotor is sufficient to produce the torque necessary to rotate the driven equipment.

NEMA Designs

To obtain uniformity in applications NEMA has defined specific designs of integral horsepower squirrel-cage induction motors up to 200 hp in size. Each design conforms to specific starting and breakdown torque, starting current and slip.

Table 3 gives the ranges of starting and breakdown torques, current and slip characteristics of

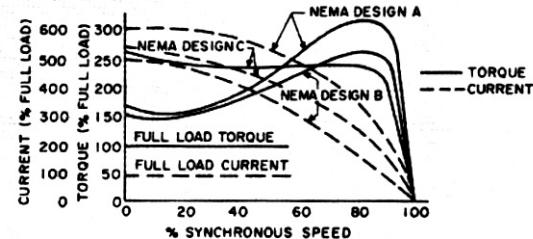


FIG. 27 – TYPICAL CURRENT AND TORQUE CURVES FOR NEMA DESIGNS, SQUIRREL-CAGE INDUCTION MOTOR

NEMA Design A, B and C squirrel-cage induction motors. (Designs D and F are not included since they are not used in air conditioning applications.) The table also cites the equipment to which the motor designs A, B and C are applicable.

NEMA Design C motors usually have double windings in the rotor. The outer slots are utilized to provide high resistance at starting, creating the high locked rotor torque and moderate starting current. The low resistance inner slots carry most of the induced current during full load, thus offering low slip and high efficiency.

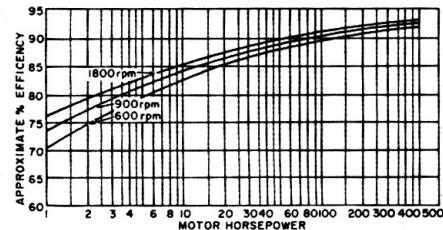
Figure 27 demonstrates the shape of torques developed and current used by NEMA Design A, B and C squirrel-cage induction motors. The significance of the magnitude of starting torques is their ability to overcome driven equipment inertia; the significance of starting currents is their capacity to affect adversely the power supply. *Chart 1* illustrates approximate efficiencies of these motors.

Manufacturers must be consulted for motor data for a given application.

Special Winding Arrangements

To accommodate a power company requirement of reduced current draw on the power line at start-up, there are two varieties of squirrel-cage induction motors. These have a special arrangement of primary stator windings, namely part-winding (*Fig. 44*) and star-delta motors (*Fig. 45*).

**CHART 1 – APPROXIMATE FULL LOAD
EFFICIENCIES, SQUIRREL-CAGE INDUCTION
MOTORS**

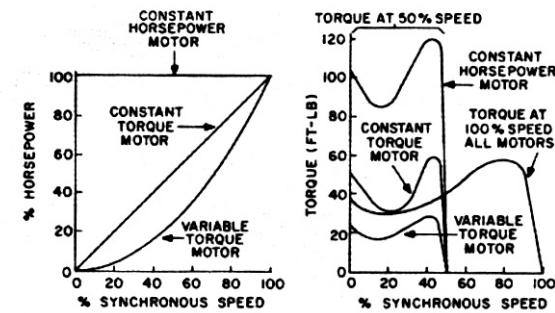


The part-winding type is a polyphase motor with two or more circuit winding. It may be a dual voltage (110/220 or 220/440) motor; the suitability should be checked with the manufacturer (see also *Motor Controls*). The starter is arranged to start the motor on one set of windings and after a time delay to apply all windings across the line. Such a combination provides motor starting on about 65% of full voltage locked-rotor amperes while the locked-rotor torque available is about 48% of full voltage starting torque. This arrangement may be less expensive than the use of a standard motor and a reduced voltage starter. A reciprocating compressor, either open or hermetic, may be equipped with part-winding motors.

The star-delta type is a motor with stator windings in delta arrangement with additional leads to circuit the windings in star arrangement; the leads brought out from each end of each winding may be connected either in star or delta by the starter. The motor is started on star arrangement of windings and is fully operated on delta arrangement of winding. The starting locked-rotor current is about 33% of the maximum, and the torque is about 33% of full voltage starting torque; these conditions are suitable for low starting torque applications such as centrifugals with inlet closed. However the star-delta (wye-delta) arrangement has been adopted for hermetic centrifugal compressors.

Multi-Speed Motors

At times there is a need for two or more fixed steps in speed change for the operation of driven equipment (fans). The polyphase squirrel-cage induction motors may be obtained in two-, three- (rarely used) or four-speed arrangements. The multi-speed motor operation is obtained by either multiplying or rearranging the stator windings. Depending on the complexity of these design requirements, the multi-speed motor may be contained either in the same frame size as the single-



**FIG. 28 – TYPICAL HORSEPOWER AND TORQUE
CURVES, MULTI-SPEED SQUIRREL-CAGE
INDUCTION MOTOR**

speed motor of the same horsepower rating or in a frame larger by at least one size (contributing to an increase in cost).

The two-speed motors have either single consequent windings (separate leads) or two independent windings (double superimposed) in the stator to obtain respectively 2:1 or 3:2 ratios in speed change, and variable or constant torque characteristics.

The four-speed motors are usually in 1800/1200/900/600 rpm combinations for 1800 rpm synchronous speed, and 1200/900/600/450 rpm combinations for 1200 rpm synchronous speed. Three and four-speed motors usually have consequent pole separate windings.

The multi-speed polyphase squirrel-cage induction motors are constructed according to these standards:

1. Motors producing variable torque, that is decreasing torque with decreasing speed. Horsepower delivered varies as the square of the speed. These motors may be used to drive centrifugal pumps or fans.
2. Motors producing constant torques throughout the range of speeds. Horsepower varies directly as speed. These motors are suitable for reciprocating compressors.
3. Motors producing constant horsepower at all speeds. Torque increases with a decrease in speeds. These motors have no particular application with equipment in air conditioning systems.

Figure 28 illustrates the horsepower and torque delivery of three types of multi-speed induction motors.

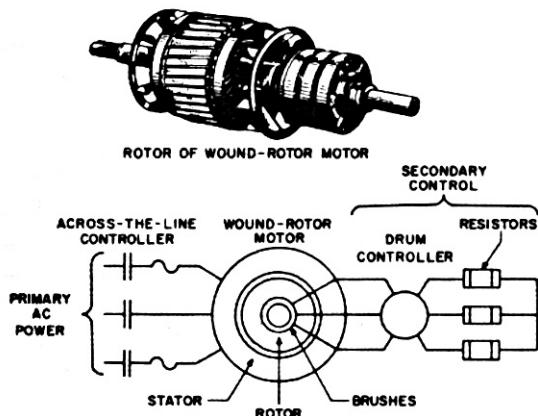


FIG. 29 – WOUND-ROTOR MOTOR ROTOR AND CONTROL ASSEMBLY

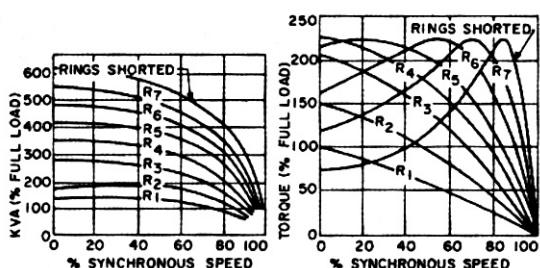


FIG. 30 – TYPICAL CURVES OF KVA AND TORQUE, WOUND-ROTOR MOTOR

WOUND-ROTOR MOTOR

Another variety of squirrel-cage induction motor that provides higher torque at start-up and a range of adjustable reduced speed operation is the wound rotor or slip-ring motor. The reduced speed operation is of particular interest since it permits part load operation of refrigeration centrifugal compressors. Next to the turbine drive with its infinite speed variations, the wound-rotor motor speed changing is an efficient capacity control (Part 7, chapter 2, Fig 4).

The wound-rotor motor is constructed with three-phase windings in the rotor. One end of each rotor phase is brought out to a slip ring on the rotor shaft. Stationary brushes in contact with the slip ring are connected to an external secondary circuit into which any desired amount of resistance may be introduced to obtain the needed speed (Fig. 29). With the slip rings shorted (external resistance totally excluded) the

wound-rotor motor has speed and torque characteristics of the standard NEMA Design B squirrel-cage induction motor.

The kva (Fundamental Relations) and torque characteristics of a wound-rotor motor are illustrated in Fig. 30, with succeeding external resistances removed from the circuit. The R_1 curve represents all resistances in; R_2 curve shows part of the resistance removed, and so on to R_7 when all resistances are removed. The power factor during acceleration is constant.

An example of wound-rotor motor application to a centrifugal refrigeration machine is demonstrated in Fig. 31. The motor control has five balanced motor load torque points dictated by the speed of the compressor to obtain the partial load operation.

SYNCHRONOUS MOTOR

Synchronous motors are inherently and strictly constant speed motors. Their application is characterized by the high efficiency of conversion of electric energy into mechanical energy and by operating at either unity power factor or leading power factors, for example 0.9, 0.8. Their speed is unaffected by changes in voltage or load. Large horsepower synchronous motors at low speeds are simple and compact, less costly than the squirrel-cage induction motors of equivalent rating.

In construction the synchronous motor consists of a stator to which a-c power is applied, producing the primary revolving magnetic field and the rotor spider that contains field poles and amortisseur (damper) windings; these windings are similar to those used in induction motors. The amortisseur windings develop most of the starting and accelerating torque. At start-up the synchronous motor simulates the squirrel-cage induction motor operation; it depends on the arrangement of slots and windings.

There are several varieties of synchronous motors. This text discusses only the direct connected exciter motors (Fig. 32). On the rotor shaft in addition to the two windings, there are collector rings and a d-c exciter. Another method of excitation is by a current furnished by a separate motor-generator set external to the motor. As soon as the rotor comes up to speed and runs with a slip of about 2-3%, a d-c field current from the exciter is applied to the field windings on the salient (projecting) rotor poles. The torque developed to pull the motor in step is called pull-in torque.

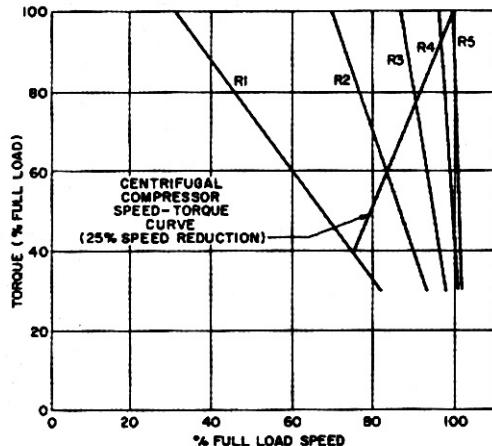


FIG. 31 – SPEED-TORQUE CURVE WITH FIVE BALANCED POINTS, WOUND-ROTOR MOTOR

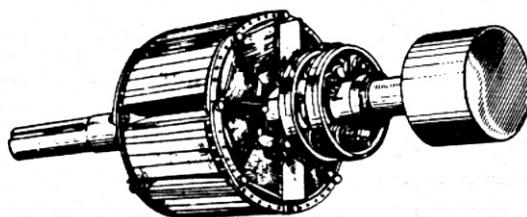


FIG. 32 – SYNCHRONOUS MOTOR ROTOR

The magnetized rotor poles lock in step with the stator revolving magnetic field and the rotor revolves at synchronous speed. However if d-c field current is applied before the rotor reaches 97-98% of synchronous speed, the rotor may not synchronize, resulting in severe vibration and high pulsating input current.

When a mechanical load (resisting torque) is applied to the shaft of a synchronous motor operating at synchronous speed, a balancing counter-torque is developed and the rotor field poles tend to lag the stator magnetic field. Any increase in load is

accompanied by an increase in lag angle, resulting in the motor developing its maximum pull-out torque. Any further increase in the mechanical load stops the motor. The normal pull-out torque is usually 150% of full-load torque with unity power factor motors and 200-250% with 0.8 leading power factor motors.

While driving its load a synchronous motor can have the a-c current input into its stator varied by changing the strength of the field excitation. This varies the power factor; it adjusts the armature current to be in phase with or leading the voltage at any given load. With a weaker field strength the power factor is less and the armature current lags the voltage. This is an abnormal operation of the synchronous motor. When the field is overexcited, the synchronous motor provides magnetization (kvar) in excess of its own requirements. This extra margin is fed into the power supply system.

This latter feature (Fig. 33) is especially desirable in systems where a considerable number of squirrel-cage induction motors are operating. The excess kvar produced by a synchronous motor is consumed by the induction equipment in the plant, thus correcting the electric system power factor.

Synchronous motors may be useful because of their inherent tendency to regulate the voltage of the power system. With a fall in line voltage the leading kvar of a synchronous motor is increased, raising the supply line voltage by the improved power factor of the line. Rising voltage in a line reverses the processes. This voltage regulation may be useful on the ends of long transmission lines, especially if a large inductive load is present.

HERMETIC MOTOR

Both centrifugal and reciprocating compressors are available in hermetically closed arrangements including motors. The refrigeration machine hermetic motors are in a separate class since they are cooled by either liquid or vapor refrigerant at temperatures much lower than the air used for cooling open motors. Such motors may operate with a higher temperature rise without exceeding the maximum temperature on which the rating of general purpose squirrel-cage induction motors is based.

Since their application is quite different, hermetic motors are usually not rated on a horsepower basis. They are identified by the full-load and locked-rotor currents; the significance of this identification becomes apparent when selecting controls.

Hermetic motor manufacturers furnish only the matched polyphase squirrel-cage induction motor less shaft, end shields and bearings (no enclosure). The compressor manufacturer assembles these stator-rotor matches with compressors within the same en-closures using proper bearings. The windings are properly insulated and well bonded, specially for larger size motors. The small integral motors are occasionally single-phase and, since sparking contacts cannot be used, they are the capacitor or resistance split-phase types with capacitors and switches mounted outside the compressor assembly.

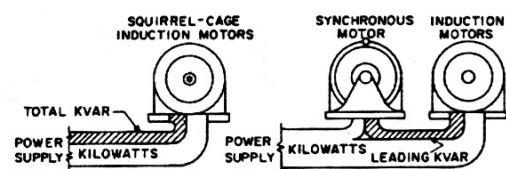


FIG. 33 – POWER FACTOR IMPROVEMENT WITH SYNCHRONOUS MOTOR

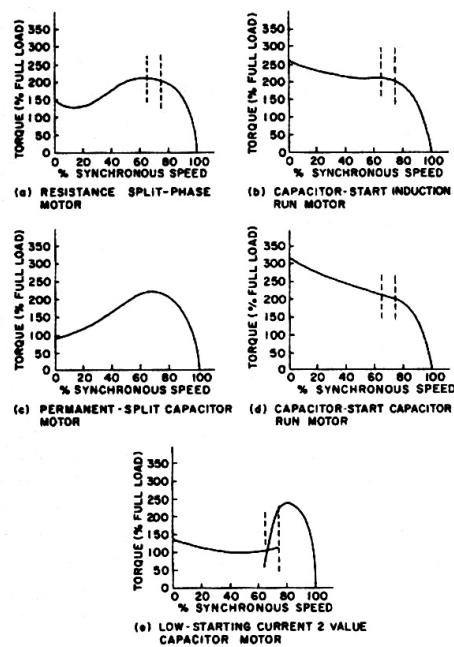


FIG. 34 – TYPICAL SPEED-TORQUE CURVES, SINGLE-PHASE MOTOR

SINGLE-PHASE MOTORS

FRACTIONAL AND SMALL INTEGRAL HORSEPOWER MOTORS

Small integral motors are generally the polyphase type; however in many areas of extensive use power is available only in single phase. Polyphase motors have two or three separate and uniformly distributed windings in the stator, one for each phase. The current in these windings alternates continually and progressively to produce a revolving magnetic field, resulting in torque that turns the rotor.

In single-phase induction motors there is only one winding in the stator. The alternating current produces a magnetic field with alternating polarity, but it does not revolve; it is on "dead center." Therefore an auxiliary means must be provided to produce torque to start and accelerate the motors to full load speed. At full speed the single-phase motor operates like a polyphase motor in respect to slip, efficiency and power factor (Table 1 and Fig. 34). The single-phase motors are limited in overload capacity, and are confined to fractional and small integral sizes (1/100 to 6 horsepower).

The most popular single-phase motors are generally available in the following types, voltages and horsepower ratings:

MOTOR TYPE	VOLTAGE	HORSEPOWER
Shaded pole	115 and 230	1/100 to 1/4
Resistance split-phase	115 and 230	1/20 to 1/3
Capacitor-start, induction-run	115 and 115/230	1/20 to 1.2
Permanent split-capacitor	115 and 230	1/20 to 5
Capacitor-start, capacitor-run	115 and 230	1/20 to 6

Resistance Split-Phase Motor (Fig. 35)

The resistance split-phase motor is the oldest arrangement of single-phase motors. The rotor has a squirrel-cage winding similar to a conventional polyphase motor. There are two stator windings, main and auxiliary. The main stator winding is made of heavy wire to provide low resistance and high reactance; the auxiliary torque-producing winding is made of fine wire to provide high resistance and hence a higher power factor. The latter winding is magnetically displaced from the main or running winding. This arrangement causes a displacement between the current in the main and phase windings to simulate a revolving magnetic field.

With the current on, the rotor is caused to rotate. When a speed approximately 70% of full load speed is reached, a centrifugal switch mounted on the rotor and in series with the auxiliary winding removes this winding from the circuit. With this impetus the rotor comes up to speed and the motor operates as a regular squirrel-cage induction motor. The resistance split-phase motor has a low starting torque and takes a relatively large starting current, causing a flicker in the lights. The switch is sensitive to heat and must be protected whenever exposed to hot air or radiant heat. These motors are classed as general purpose motors and are applied to small propeller fans.

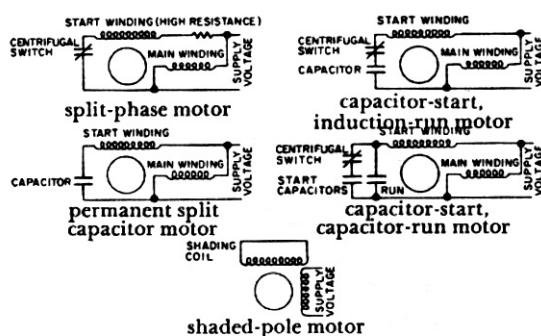


FIG. 35 – CONNECTION DIAGRAM,
SINGLE-PHASE MOTORS

Capacitor-Start, Induction-Run Motor (Fig. 35)

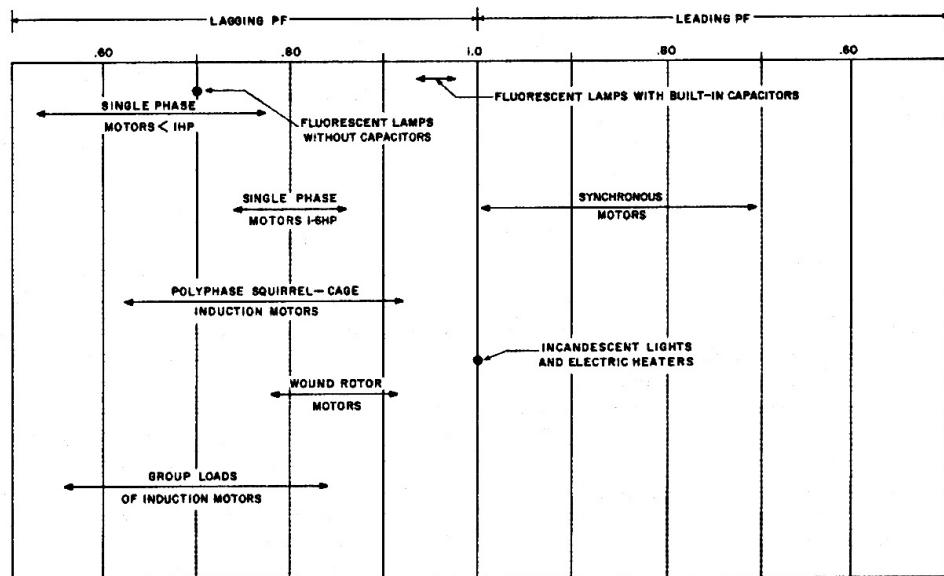
To improve on the characteristics of the split-phase motor, there is a variety of capacitor motors that have higher starting torques. The capacitor-start, induction-run motor usually has an electrolytic capacitor added in

the auxiliary winding circuit; the centrifugal switch is eliminated. As with split-phase motors, when the motor has come up to approximately 70-75% of full load speed, the capacitor and the phase winding are removed from the circuit by a voltage relay and the motor runs as a regular squirrel-cage induction motor, hence the name capacitor-start, induction-run. The displacement between the current in the main and phase windings is increased. As compared to resistance split-phase motors this feature produces increased starting and accelerating torques; the latter enables these motors to come up to speed faster. The increase in starting torque is due to the use of a low impedance capacitor. These motors may be used to operate small fans and blowers of heavier load requirements.

Permanent Split-Capacitor Motor (Fig. 35)

The permanent split-capacitor motor is similar to the capacitor-start, induction-run motor except that the capacitor and the auxiliary winding remain permanently in the circuit with the main winding after the motor is started. The capacitor may be oil-filled for continuous operation. This motor has no switch and therefore is simpler to operate. Its starting torque is low (about 45%) since the value of the capacitance is constant. The capacitance is higher than the normal compromise value; it is selected for running operation rather than for starting needs. The breakdown torque is high. Because of starting torque limitations these motors are not used in belt-driven applications. However they are efficient, quiet, and low in current requirements.

CHART 2 – POWER FACTORS OF ELECTRICAL EQUIPMENT AT FULL LOAD



Capacitor-Start, Capacitor-Run Motor (Fig. 35)

The capacitor-start, capacitor-run motor has two capacitors in series with the auxiliary winding and a transfer switch which cuts out the low impedance starting capacitor after the rotor reaches two-thirds to three-quarters full load speed. The running capacitor of high impedance and low capacitance stays in the circuit with the auxiliary winding. This motor has the highest starting torque. *Figure 34* demonstrates the torque characteristics of various single-phase motors (split-phase and capacitor types).

The capacitor motors are suited to applications with normal starting torque such as fans, blowers and centrifugal pumps. Motors of higher starting torque may be applied to reciprocating compressors; these motors have a rather high lagging power factor while running (*Chart 2*).

The capacitors are either electrolytic or oil-filled types; performance of both may be affected by low ambient temperatures. The electrolytic capacitors fall in performance (about 15%) at a temperature of 0-15 F. Similarly the oil-filled capacitors fall in performance at a temperature approaching -10 F. The motor torque

performance must be reduced accordingly at a slightly higher rate.

Shaded-Pole Motor (Fig. 35)

The shaded-pole motor (often of subfractional size) is very similar to the permanent split-capacitor motor in torque characteristics, that is, low at starting. In place of auxiliary winding the shaded-pole motor has a depression at each salient pole filled with a continuous copper loop, thus shading a small portion of each pole. Current applied to the main winding of the stator produces an effect in this shorted loop (shading coil) that helps to establish the initial low starting torque which turns the rotor and the load. The running torque is also low. Thus motors of this type may be applied only to direct-driven fans such as with room fan-coil units. The motor is air-over cooled. The efficiency and power factor of shaded pole motors are very low. They are the smallest single-phase motor available, usually in sizes smaller than 1/5 horsepower. *Figure 35* Shows connection diagrams for single-phase motors.

With the use of tapped main windings shaded-pole motors may satisfy multi-speed applications. Fractional horsepower, single-phase motors can be adapted to

multi-speed operation by using an external resistor, reactor or auto transformer to vary the terminal voltage in fixed, predetermined steps.

Other single-phase motors available (generally not in use with air conditioning equipment) are the repulsion-induction and repulsion-start, induction-run motors. These are the commutator type. This construction utilizes an arrangement in which the main field winding is connected in series with the compensating winding and the brushes are short-circuited. These motors have been developed to produce a particularly high starting torque. A repulsion motor has the variable speed characteristics while the repulsion-start, induction-run motor has constant speed characteristics of the regular squirrel-cage induction motor.

Fractional horsepower series motors that are adapted for use on either d-c or a-c circuits of a given voltage are called universal motors.

MOTOR MECHANICS AND ENVIRONMENT

This section is devoted to the physical-mechanical aspects of motors in relation to power impressed, full load operation and the environmental conditions to which motors are subjected.

INTERNAL OVERHEATING OF MOTOR

The motor rating is an arbitrarily specified safe operating limit for the machine determined in accordance with certain accepted standards. It is intended to represent the operating limit which the machine cannot ordinarily exceed for a considerable length of time without damage to itself. The motor may exceed its rated load by 10%, 25%, 50%, but at a risk of a rise in temperature that may permanently injure the winding and its insulation; in fact the motor will stall on reaching its maximum in torque rating regardless of temperature. Motors designed for continuous service can carry specified loads for reasonably long periods of time without exceeding the heating limits.

Windings and Insulation

From previous discussions it is quite evident that the motor windings are the heart of the motor. The power impressed on them must be contained; therefore the winding must be electrically insulated from adjacent parts. An electric motor in operation is higher in temperature than the ambient; the various motor parts are actually at different temperatures as are also the sections of the winding. The section of the winding at

the highest temperature is termed "hot spot" and is usually on the axial center line of the core in one of the slots.

Under normal operating conditions the temperature rise of the motor is due to the natural process occurring during the conversion of electric energy into mechanical energy and the rotation of parts.

There are three sources of energy losses appearing as heat that raise the motor temperature:

1. Winding – heat produced by a flow of current against resistance and equal to the product of current squared and resistance (I^2R). (With a motor design resulting in lower current and/or lower resistance less heat is produced and the motor is more efficient.)
2. Iron core – heat produced by hysteresis* and eddy current losses set up by the magnetic field in the stator and rotor.
3. Mechanical parts – bearings, fans, brushes (when used). Proper control of the driven load or number of motor starts required can also influence the winding losses.

The losses occurring during full load operation of the motor can be divided into two groups: (1) fixed losses, running light losses (I^2R no-load current losses), iron losses, bearing friction and internal fan (when used), and (2) applied losses of the driven load.

The major heat losses are in the windings. There is a definite maximum temperature which the windings can withstand under a given load and with a given insulation without undue deterioration either within themselves or in the insulation. In order that the maximum output of the motors may be secured without overheating, it is necessary to keep the heat losses to a minimum. Thus the insulation of the motor windings performs a dual function, that of an electric insulator and also a controlled heat dissipator.

NEMA has established six classes of insulation designed for various loads and for keeping the hot-spot temperatures within safe limits. *Table 4* lists class designations, description of insulation materials, and the limiting safe hot-spot temperatures (C).

The limiting hot-spot temperatures shown are determined by adding together:

1. Ambient environment temperature, normally 40 C (104 F).

*Hysteresis is the conversion of electrical energy into heat energy due to molecular friction opposing magnetic polarity changes, friction that opposes the turning about of atoms.

2. Ambient environment temperature, normally 40 C (104 F).
3. Hot-spot temperature allowance, ranging from 5-15 C (usually 10 C).
4. Service factor, normally 15 C.
5. Allowable design motor temperature rise.

TABLE 4 – CLASSIFICATION OF MOTOR-INSULATING MATERIALS

Insulation Class	Description	Open or Driproof Guarded Motor Temp Rise (C)	Limiting Safe Hot Spot Temp (C)
O	Cotton, silk, paper and similar organic materials neither impregnated with insulating compounds* nor immersed in a liquid dielectric.	40†	90(194 F)
A	Same materials as in Class O but impregnated or immersed in liquid dielectric*; also enamel coated on conductors.	40	105(221 F)
B	Mica, glass fiber asbestos and other inorganic or organic materials in built-up form using suitable binders.	70	130(266 F)
C	Entirely of mica, porcelain, glass, quartz or similar inorganic materials.		
F	Same as Class B, using modified organic binders.	90†	155(311 F)
H	Same as Class B, using silicone resin binders.	110	180(356 F)

*An insulation is considered to be impregnated when a suitable substance replaces the air between its fibers.

†Approximate temperature rise.

Motors used in air conditioning and refrigeration systems normally use Class A insulation that permits a 40 C temperature rise for the windings. With present standards the life of the motor winding is approximately 35,000 hours when operated at rated temperature and subjected to normal dielectric and mechanical stresses and humidity.

For open motors applied in the tropics or similar environments, special insulation must be provided because the motors may be exposed to excessive ambient temperatures and humidity.

TABLE 5 – SERVICE FACTOR, A.C. INDUCTION MOTORS

Motor Horsepower	Service Factor
1/8 and below	1.40
1/6, 1/4, 1/3	1.35
1/2, 3/4, 1	1.25
1 1/2, 2	1.20
3 and larger	1.15

Service Factor

Standard open type motors of NEMA Design A, B and C (also Design F) carry a service factor, an allowable continuous overload above the rated nameplate horsepower, without causing a dangerous temperature rise because of overload. *Table 5* lists the service factors for fractional and integral horsepower induction motors.

Service factors apply only when the voltage and frequency are held at the rated value. When a motor is operated continuously overloaded, the motor naturally has a higher temperature rise and, therefore may have an efficiency, power factor and speed different than the rated load. The locked-rotor torque, current and breakdown torque remain the same. It must be remembered that the temperature rise caused by operating a motor at a continuous service factor overload shortens the life of insulation and therefore the life of the motor. As a rule each temperature rise of 10 C halves the life of the insulation.

EXTERNAL OVERHEATING OF MOTOR

The temperature rise previously discussed is the result of current flow occasioned by the load applied at the rated voltage and frequency. However there are other considerations under which motor overheating may result:

1. Obstruction to heat dissipation due to improper ventilation.
2. Obstruction to heat dissipation due to physical debris inside or outside the motor.
3. Rise in ambient temperature above 40 C (104 F).
4. Unbalance in voltage.
5. Voltage and/or frequency variation from rated.

6. Other unpredictable misbehaviour of power transmission component parts affecting the winding performance.
7. Failure to start, stalling.

Thermal Protection-Overcurrent

The fundamental requirements for thermal protection of electric motors are contained in the National Electric Code (NEC), Article 430 of Motors and Motor Controllers. There are two methods of motor protection, one external to and separate from the motor, one internal within the motor. The former is an over-current protection in either or all of the following: the power feeder line, motor branch power line, and motor starter, but positively in the motor starter. The internal motor protection is a device responsive to the motor current and temperature.

Overcurrent protection devices guard the motor against excessive current up to and including the locked-rotor current. The branch power line protection guards against a possible short circuit or ground currents in the conductors. (See *Motor Controls*.)

The well-designed internal motor protection allows the motor to carry any load including an overload just long enough so that the motor does not overheat. Only small motors, particularly fractional horsepower, are equipped with inherent over-heating protective devices which are imbedded in the motor windings and which respond directly to the heat generated within the motor.

Motor Enclosures

Environmental conditions generally refer to the ambient temperature, humidity, altitude and access to ample dry and clean ventilation air. The enclosure of the stator and rotor as a support and container is also a protector against the following environmental conditions:

1. Moisture – dripping, splashing, corrosive, exceedingly damp or even steaming.
2. Gases (fumes) – corrosive or explosive.
3. Dust – gritty, combustible (explosive) or conductive.
4. Outdoor installation - rain, wind, sun, etc. with above items; also insects, birds and small animals.
5. Temperature below 10 C (50 F).

All items except the last are quite obvious in their physical aspect. Operation below 10 C (50 F) reduces conductor resistance reflected in a small increase in starting current and a decrease in starting torque. Another danger of operation in low ambient is the

probable moisture condensation on motor winding insulation. A thermal stress deterioration of the insulator may occur due to changes in temperature from cold standstill to warm running operation.

Motors used in air conditioning and refrigeration systems are normally the standard open type, simplest in construction and lowest in cost. An open machine has ventilating openings which permit the passage of external cooling air over and around the windings of the machine.

NEMA has defined many different types of open enclosures in its publication MG1-1.20, Open Machine. The most common are (1) drip-proof enclosures protecting a motor from solid or liquid drops falling on the motor at any angle not greater than 15 degrees from vertical and (2) splash-proof enclosures protecting from solid or liquid particles falling on the machine or coming towards it in a straight line at any angle not greater than 100 degrees from the vertical. Additional protection is also defined for open machines as semi-guarded, guarded, and rip-proof fully guarded.

There are also the totally-enclosed motors described in NEMA MG1-1.21 Totally-Enclosed Machine. These motors are machines so enclosed as to prevent the free exchange of air between the inside and the outside of the enclosure, but not sufficiently enclosed to be termed air-tight. The totally-enclosed motor range covers nonventilated, fan-cooled, explosion-proof, dust-ignition-proof, waterproof, externally and pipe-ventilated, water-cooled, water-air-cooled, air-to-air-cooled, and fan-cooled guarded and weather-protected machines.

In addition to the NEMA standardized enclosures listed, other motors exist such as lint free (textile systems), sanitary (dairy and food industries), encapsulated (sealed enclosure), and canned pump motors used particularly in nuclear applications. NEMA standards and motor manufacturers should be consulted for specific data on any special motor enclosure for a given application.

Bearings

Next to the stator, rotor and the enclosure, the most important part of the motor is the rotor shaft support, the bearings. There are two major types: (1)anti-friction ball or roller bearings and (2) sleeve bearings. The latter are either waste-packed (used mostly in fractional horsepower motors), oil ring lubricated, or pressure oiled on large motors. Ball bearings are either grease- or oil-lubricated. Most ball bearings are grease-packed,

either the pre-lubricated (sealed) or relubrication type. Oil-lubricated ball bearings are applied usually on large size motors; these bearings require more complex housing and careful control of oil level, and must be mounted in a prescribed position. The bearing should be equipped with a sight gage for observing a proper oil level.

The grease-packed ball bearings must have grease that is quiet, have low friction and oxidation rates, and must be clean. For applications where motors are exposed to winter ambient or various low temperature conditions special low temperature greases must be utilized. Excess grease may lead to overheating of the bearing.

NOISE

The noise level is increasingly important in many motor applications. Motors produce airborne sound and physical vibration as unavoidable byproducts of the conversion of electrical to mechanical energy. The undesirable manifestation of sound and vibration is termed noise.

Airborne Noise

Airborne noise is produced by all the vibrating parts of the motor. The initial sources are magnetic, mechanical and windage.

Magnetic noise is produced by magnetic forces (flux) in the air gap and other parts of a magnetic circuit. The frequency (cycles per second), usually twice the line frequency and its harmonic is a function of either the number of slots and rps (varying) or the line frequency (constant). The air gap forces are to be considered only in relation to the stator. The rotor (usually quite rigid) may be a source of noise in the case of hermetic motors and close-coupled motor pumps. In the latter case the shaft vibration noise may be transduced to the water.

Mechanical noise may result from disrepair, unbalance or bearing disorders. The first two are abnormalities that should not exist in a well-constructed, balanced motor. Bearing noise may be differentiated between that of a sleeve type or ball type of bearing. The former is inherently quiet with a few distinguishable sound frequencies. Ball bearings with numerous component parts moving relative to each other produce many sound frequencies. Rigidity of bearing support is very important. The noise level of both types increases with lubrication impurity and surface roughness appearing in the course of wear and

tear. Therefore care must be exercised in the choice of motor enclosure in relation to ambient environment.

Although rarely encountered in the air conditioning field, another mechanical noise is brush noise, resulting from the sliding contact of brushes against a slip ring or commutator. In the case of a slip ring the noise is less than that produced by brushes sliding over a segmented commutator. In either case the brush noise is characterized by high frequencies. Since brush noise is a function of surface finish, it also varies during motor operation because of wear.

The passing of ventilation air thru the motor together with the propulsive elements creates only airborne windage noise. Its pulsations contribute to stator vibrations. The windage noise is of broad band characteristics. Motors having open enclosures are principal generators of windage noise. The totally-enclosed fan-cooled motor equipped with an external fan may at times have higher level windage noise. Totally-enclosed nonventilated motors with internal fan air circulation have subdued noise levels. Windage noise from high speed motors dominate over noises from other sources.

Of all the motors compared on the basis of equal horsepower and speed, synchronous motors are the most quiet.

The single-phase fractional motors have a terminal 120 cps vibration (60 cycle current) caused by the pulsating, 120 alternation power supply and transmitted to driven apparatus and motor supports. Since their bearings are the sleeve type, the bearings seldom contribute to noise.

Mountings and Isolation

The second aspect of undesirable noise is the vibration coupling between the motor and its support, transmitting unwanted vibration noise to building structure. Careful attention must be given to the motor mounting and support isolation. A standard rigid base is the simplest and least expensive normal motor mounting. To reduce vibration and noise either from the motor or motor-driven machine assembly, various resilient mountings are available. Resilient elements are used either under motor feet (where applicable) or under the base of the total assembly. Fractional horsepower motors used on fan-coil units are often isolated by rubber rings around the bearing supports. There exist also flange or face mountings used on such apparatus as close-coupled motor-pumps. These

assemblies may be isolated from the floor by resilient mounts.

Motors can be installed in any position, horizontal, vertical, upside-down or sideways, provided they are equipped with proper bearings and lubrication.

The motor mechanical power may be transmitted to driven equipment thru (1) a direct shaft such as with hermetic assemblies or small fans, (2) couplings with pumps and reciprocating compressors, (3) matched V-belts with fans, (4) step-up gears and couplings with centrifugal compressors, or (5) hydraulic and magnetic couplings with fans or centrifugal compressors.

MOTOR CONTROLS

Motor characteristics and the requirements imposed by the equipment used in air conditioning and refrigeration systems are set down in the preceding section on motors. These requirements and characteristics and the rules imposed by the power companies constitute the guides for selecting motor controls.

In order to obtain adequate motor performance electric energy must be regulated. The controller may be a simple on-off toggle switch or a combination of complex automatic equipment.

PURPOSE

The purpose of the motor controller is to:

1. Admit electric energy to the motor at a proper rate.
2. Protect against any fault that may occur in the electric system which may cause a sudden inrush of current.
3. Prevent overheating of the motor while operating.
4. Regulate the motor speed.
5. Withdraw electric energy when the need ceases.

This discussion gives an insight into the functions of motor starting and protective equipment. The detailed selection of equipment to satisfy given

requirements is the responsibility of the electrical engineer.

STANDARDS AND CODES

The National Electric Code, Article 430, Motors, Motor Circuits and Controllers covers basic minimum provisions and rules for the use of the subject equipment. The provisions are a guide to the safeguarding of persons and of buildings and their contents from hazards arising from the use of electricity. This code is not a design manual. The Underwriters Laboratories, Inc. provide standards for Industrial Control Equipment (#508) and for Temperature Indicating and Regulating Equipment (#873).

The local, city and state codes must also be followed as well as the regulations of the local power company.

CONTROL ELEMENTS

Figure 36 is a schematic diagram of the various possible elements of a power supply circuit to the motors.

Protective equipment that prevents major malfunctioning of the power supply system such as a short circuit, reverse-phase and open-phase operation, voltage variation or stoppage, and interlocking of controls is discussed later. Most starters for motors of larger than one horsepower provide motor overload protection either firmly fixed in the starter or in an assembly of contactor and overload protection. Fractional and small integral horsepower motors often have overload protection as part of the motor. Without this basic protection the starters are switches or contactors.

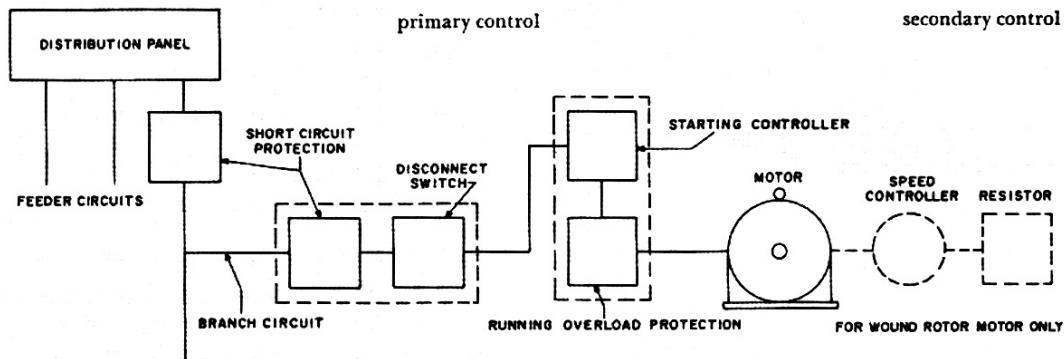


FIG. 36-MOTOR CONTROL CIRCUIT

Various possible components of motor control are:

1. Switching mechanisms such as manual switches or magnetic contactors which open or close the power circuits.
2. Power-absorbing or transforming devices such as resistors or reactors which absorb part of the power applied to the motor; and auto-transformers which reduce the line voltage before application to the motor.
3. Protective devices which are motivated by temperature or voltage.
4. Pilot or initiating devices such as push buttons, float switches and thermostatic switches.

The push buttons are either a part of the starters or are installed remotely on a separate panel for the convenience of the operator in charge of the air conditioning and refrigeration system. Other initiating devices are discussed with their applied equipment.

The motor controller furnishes a means for a motor to:

1. Start and accelerate.
2. Operate the load.
3. Regulate its speed.
4. Protect itself, including controller and wires.
5. Stop.

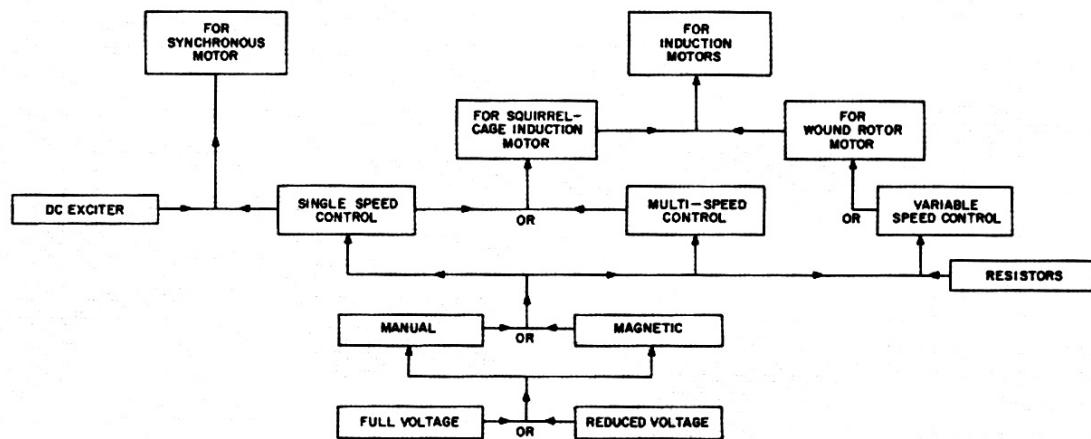


FIG. 37-STARTER SELECTION GUIDS

STARTERS

Starter selection is integral with motor selection and should be so considered in relation to the following factors: horse power rating, permissible current, desirable torque, necessary protection and combined economics.

An outline of the basic process of selection of available starters is given in *Fig. 37*. There are many variations and combinations with protective and pilot devices.

Manual or Magnetic Starter

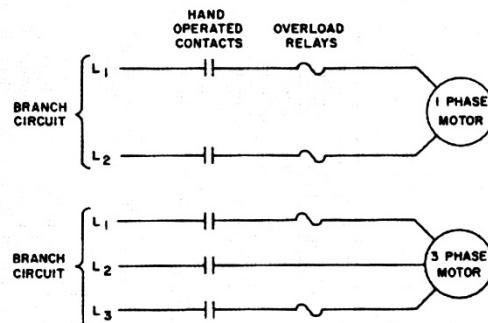
The first decision is whether the particular application calls for a manual or magnetic starter. The former performs all of the required functions and is operated by hand. The latter is automatic thru the use of electromagnets, and is initiated either by hand, push button, or by some starting device involved in the process control; from this point on, the starter is sequenced thru the steps designed into the control circuit.

The choice of manual or magnetic starter is influenced by the size of the motor and frequency of operation. Infrequently operated motors may often have manual starters. Most motors should be started magnetically, either because of the size of the motor or because of the convenience of remote starter operation. Magnetic starters are more expensive but their higher cost is offset by lower maintenance costs and greater safety. Another advantage of a magnetic starter is the fact that it is automatic; once committed to certain duty the possibility of introducing human error is eliminated. Because of the possibility of including a variety of pilot relays, automation has the flexibility to achieve any desired end to operate and protect the motor. Magnetic starters include under-voltage protection.

Full or Reduced Voltage Starter

There are two fundamental classes of starting equipment serving squirrel-cage induction motors: (1) full voltage, across-the-line and (2) reduced voltage, reduced current inrush starters. Wound-rotor motor and synchronous motor controls are discussed separately.

Four factors influence a choice between a full or reduced voltage starter: (1) cost, (2) size of the motor, (3) current inrush and starting torque behavior of the motor with reduced voltage, and (4) power company restrictions on the use of electric energy (in relation to the requirements of the driven machine). These factors are discussed under a specific class of starter.



NOTE: Three-phase circuit normally includes two overload relays; in remote and inaccessible locations all three phases are protected by overload relays. Often the three-phase overload protection is provided within the motor by a thermal disc.

FIG. 38 – ACROSS-THE-LINE MANUAL STARTERS

Full Voltage, Across-the-line Starter

The least expensive are the manual full voltage starters (*Fig. 38*).* These are applicable especially to small size motors, single phase up to 5 hp and three-phase up to $7\frac{1}{2}$ hp; they consist of switching contacts and overload relay trips. They do not provide automatic undervoltage protection. Motors restart on reinstatement of voltage on the power line.

When using small switches for fractional horsepower motors, protection is provided by inserting fuses in circuits.

The magnetic full voltage starters provide convenience, flexibility and safety that is greater than with manual starters; they include undervoltage protection.

A push-button relay that continues to maintain contact on voltage failure (*Fig. 39a*)† illustrates one variant for safeguarding against low voltage. However with voltage reduction the magnetic strength of the starter coil weakens, permitting the contacts to open. When voltage is reinstated, the coil is re-energized and contacts are closed. This is a low voltage release that allows the equipment to operate on voltage recovery.

In cases where such automatic procedure is undesirable, a momentary contact push button is used in combination with a set of normally open auxiliary contacts in the starter (*Fig. 39b*). When voltage returns, the motor cannot restart and requires a manual resetting.

* Figures 38, 39, 41-45, 47 and 49 are diagrammatic only. No attempt is made to illustrate the actual starters.

† Control circuits shown here are basic. Further starter diagrams do not show control circuits.

Reduced Voltage Starters

Reduced voltage on the motor reduces locked-rotor current inrush and torque as well as accelerating torque (Fig. 40). The reduced torque produced is generally greater than that required by the equipment used for air conditioning systems (Fig. 23). Thus a reduction in current inrush in accordance with local power company current limitations is the primary reason for the use of reduced voltage starters.

The common practices by power companies are to:

1. Limit starting current to a fixed percentage of locked-rotor current inrush.
2. Limit starting current to certain increments at fixed intervals of time using closed transition between successive steps, thus helping the network to adjust itself to a gradually imposed load.

All deviations from across-the-line starting methods are grouped together under reduced voltage types. However some types actually reduce voltage; others reduce current inrush directly. Both methods result in the reduction of current and torque. Reduction of current is of concern here.

The general class of reduced voltage starters divides into two groups:

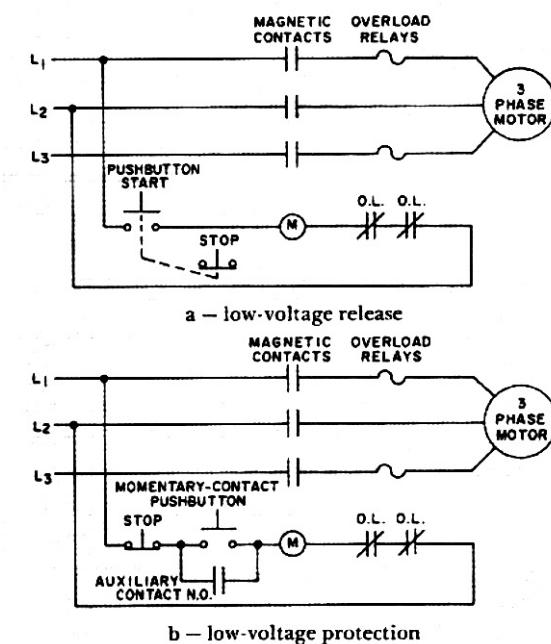


FIG. 39 – ACROSS-THE-LINE MAGNETIC STARTERS WITH LOW VOLTAGE SAFEGUARD

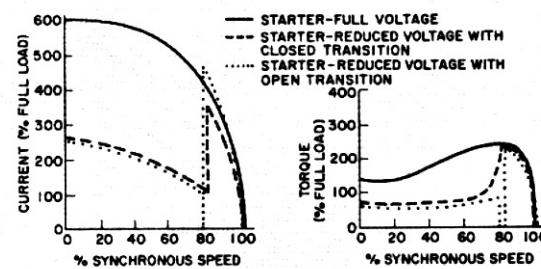


FIG. 40 – CURRENT AND TORQUE CHARACTERISTICS SQUIRREL-CAGE INDUCTION MOTOR WITH AUTO-TRANSFORMER REDUCED VOLTAGE STARTER

1. Reduced voltage starters applied to any motor.
 - a. Auto-transformer
 - b. Primary-resistor
 - c. Primary-reactor
2. Reduced current inrush starters applied to specially wound motors.
 - a. Part-winding
 - b. Star-delta (wye-delta)

Table 6 lists locked-rotor current and torque characteristics of various starters.

TABLE 6 – COMPARISON OF STARTING METHODS

Method of Starting	Inrush Current (percent full voltage locked-rotor current)	Starting Torque (percent full voltage locked-rotor torque)
Across-the-line	100	100
Auto-Transformer		
80% tap	71	64
65% tap	48	42
50% tap	28	25
Primary Resistor or Reactor		
80% applied voltage	80	64
65% applied voltage	65	42
58% applied voltage	58	33
50% applied voltage	50	25
Star-Delta	33	33
Part-Winding	60	48
Part-Winding with Resistors	60-30	48-12
Wound Rotor (approximate)	25	150

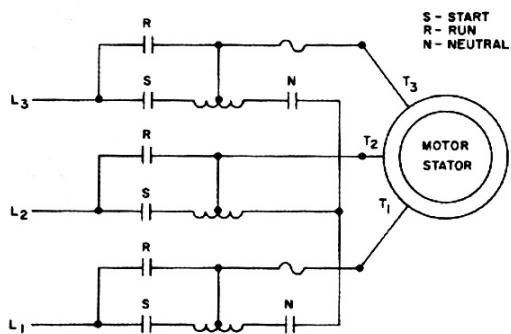


FIG. 41 – AUTO- TRANSFORMER REDUCED VOLTAGE STARTER, CLOSED TRANSITION

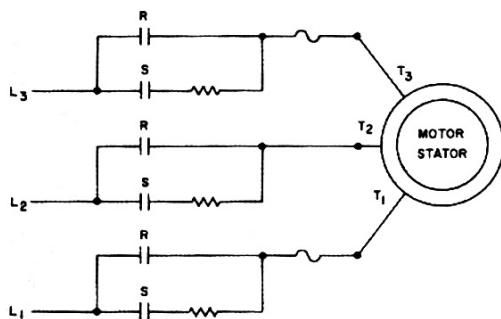


FIG. 42 – REDUCED VOLTAGE STARTER, PRIMARY-RESISTER

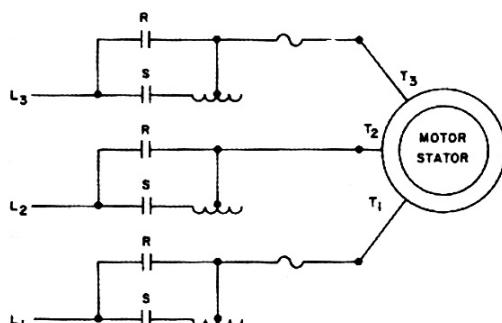


FIG. 43 – REDUCED VOLTAGE STARTER, PRIMARY-REACTOR

Some of these starters are manual. However since the majority of applications are of the magnetic type, only this variety is discussed. The schematic illustrations are intended to show starting sequence only and do not represent the actual wiring of any starter. Refer to starter manufacturers' catalogs and data for wiring diagrams and complete details.

The auto-transformer starter usually has three voltage taps (50%, 65% and 80%). On closing the circuit for a starting contactor the motor is connected to the power line thru the design voltage tap. Simultaneously a timing unit is energized. After a brief lapse of time the auto-transformers are removed and the motor is connected to full voltage. In effect there is a brief lull, then a "bump"** on the power line. This is an open-circuit transition version of starting. Figure 41 shows one method used by manufacturers to achieve closed circuit transition starting. Before the run contacts R are closed, the neutral contacts N are open and the auto-transformers operate briefly as reactors in series with starter windings. Then the run contacts are closed. The flow of current is not interrupted.

The primary-resistor starter (Fig. 42) with closed circuit transition limits voltage and locked-rotor current by inserting an external resistance in series with the stator windings. This starter is frequently used as an increment starter. Any number of steps can be provided to reduce the incremental current inrush. Pressing the start button energizes the start contacts having the resistance. This places the motor on reduced voltage. After a brief lapse of time the run contacts are closed, bypassing the start contacts and resistors. Then the motor is on full voltage.

The primary-reactor starter (Fig. 43) has a three-phase reactor in place of the resistors. This starter is primarily used for high voltages (2300-4800 volts) because the reactors are self-contained and do not present insulation problems encountered when in- stalling resistors.

With multi-circuit winding motors the part-winding starter (Fig. 44) provides reduced locked-rotor current inrush and torque by successively connecting the available winding circuits; the motor stator part windings are energized in steps. The use of one circuit of the usual two-circuit winding ordinarily gives 60-75% of the full-voltage full-winding starting current and torque. The number of circuits in the stator winding may be greater than two to provide a greater number of increments in starting. The part-winding starter is not a reduced-voltage

*There is also a "bump" in motor torque; this imposes stresses on motor windings, shaft and coupling.

starter, but a reduced-current starter.

Part-winding reduced-current starting has certain advantages. It is simple and less expensive than most reduced-voltage methods because it requires no voltage-reducing elements such as transformers, resistors or reactors; it uses smaller contactors. It is inherently a closed circuit transition starter.

The part-winding starter also has an advantage in that it is not adversely affected by high voltages. Continuous high voltages (not high voltage surges) such as 250 or 260 on a nominal 220-volt system can result in motor burnout when using an auto-transformer starter. The auto-transformer is normally rated for short-time duty and is therefore rather small. If an over-voltage of about 15% is applied, the transformer will saturate and allow very high currents to pass thru the starting contactor which, in turn, welds shut and puts the motor on single phase the next time it is started. The part-winding starter does not impose a limit on the starting duty cycle as does the auto-transformer since there is no insulated voltage reducing equipment which may over-heat.

The part-winding motor starter is almost always an increment-start device. Not all motors can be part-winding started; it is quite important that the motor manufacturer be consulted before this type of starting is applied. Some motors are wound sectionally with part-winding starting in mind; indiscriminate application to any dual voltage motor (for example, a 220/440 volt motor which is to run at 220 volts) can lead to excessive noise and vibration during starting, to overheating, and to extremely high transient currents upon switching.

For the delta wound motor provided with six leads (3-phase motor only) there is the star-delta or wye delta starter that provides reduced locked-rotor current inrush and torque. This behavior is achieved by connecting first the motor windings in star arrangement, and then on the second step by rearranging the windings in delta arrangement. The essential difference is that, for the same motor winding, the star connection draws only one third (33%) as much current as the normal delta connection, and gives one third as much torque.

Figure 45 shows a closed transition arrangement in which additional protection in the form of a resistor is provided against high inrush current during the switch-over period from star to delta winding. Initial inrush is the same as in the open transition arrangement; however, depending on the time lapse the incremental inrush is reduced with closed transition because the current does

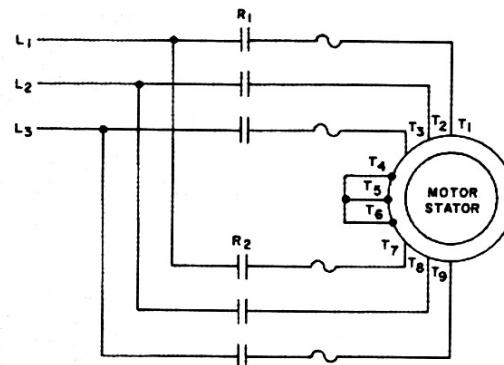


FIG. 44 – PART-WINDING STARTER

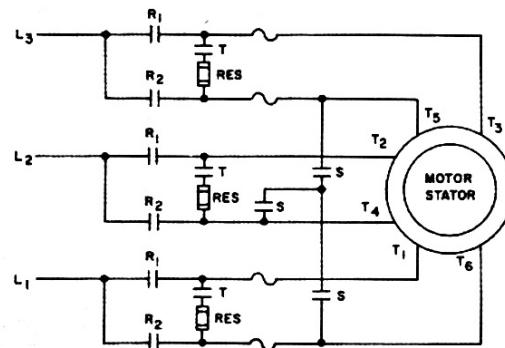
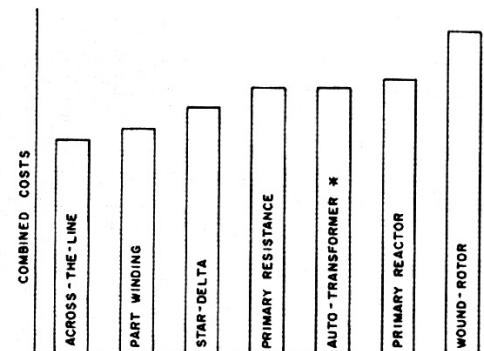


FIG. 45 – STAR-DELTA STARTER, CLOSED



*Under some circumstances this combination may be less expensive than star-delta.

TRANSITION

FIG. 46 – COMPARATIVE COMBINED COSTS OF MOTOR AND STARTER FOR VARIOUS STARTING METHOD

TABLE 7-COMPARISON OF STARTERS

TYPE OF STARTER	PER-CENT TAP	STARTING CHARACTERISTICS (percent of rated value)					ADVANTAGES	LIMITATIONS
		Voltage at motor	Motor current	Line current	Torque	Torque efficiency		
FULL-VOLTAGE								
Magnetic	---	100	100	100	100	100	1. Lowest cost 2. Least complex 3. Least maintenance 4. Suitable for low or high voltage	1. Draws highest current from line during starting 2. Starting torque may be too high for some applications
REDUCED-VOLTAGE								
Auto-transformer (Closed-transition standard)	80 65 50	80 65 50	80 65 50	64* 42* 25*	64 42 25	100 100 100	1. Starting characteristics easily adjusted 2. Provides maximum torque per line ampere for reduced voltage starters (high torque efficiency) 3. Closed-transition starting	1. Additional external voltage-reducing component may impose additional limits to duty cycle
Primary resistor (2-step)	---	80†	80	80	64	80	1. Increment starting can be constructed in any desired number of steps to meet any inrush limitation 2. Improved power factor 3. Inherently closed transition	1. Unavoidable power loss in resistor 2. Low torque efficiency 3. Introduces external voltage-reducing component 4. Not readily adapted to high voltage 5. Duty cycle limited by thermal capacity of resistor
Primary reactor	80 65 50	80 65 50	80 65 50	80 65 50	64 42 25	80 65 50	1. Least complex method to obtain reduced-voltage start for high voltage motors 2. Starting characteristics easily adjusted 3. Inherently closed transition	1. Lower torque per unit of line amperes than auto-transformer-type 2. Additional external voltage-reducing device (reactor) may impose additional limits to duty cycle 3. Low-starting power factor

* Does not include autotransformer magnetizing current which is usually less than 25 percent of motor full-load current.

† If application dictates, other voltage increments can be furnished.

not first drop to zero before stepping up to the higher value provided by delta connections. In the open transition arrangement there is a brief period when the stator windings are not energized. This may result in a momentarily high current inrush at the instant of making the delta connection. In some power systems this

"bump" inrush is objectionable and therefore a closed transition arrangement is preferred.

The star-delta motors and starters are widely employed with hermetic centrifugal machines. The primary appeal of this starting arrangement is the absence of voltage-reducing equipment. Voltage

reduction is inherent in the star connection of the delta-wound motor.

Of all the starters discussed here the reduced-voltage stepless resistance starter gives a smoother start for the squirrel-cage induction motor. However in the case of severe limitations of starting current, a resistance starter may not be applicable because of a possible severe torque reduction below a point of positive starting; other starters may have to be used.

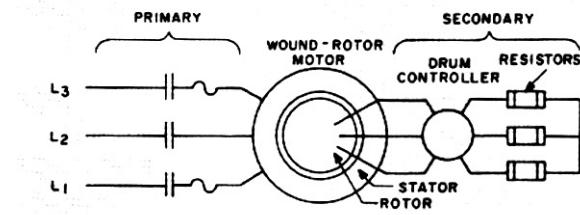


FIG. 47- WOUND-ROTOR MOTOR CONTROL

TABLE 7-COMPARISON OF STARTERS (Contd)

TYPE OF STARTER	PER-CENT TAP	STARTING CHARACTERISTICS (percent of rated value)					ADVANTAGES	LIMITATIONS
		Voltage at motor	Motor current	Line current	Torque	Torque efficiency		
REDUCED CURRENT INRUSH								
Part Winding 1/2-1/2 Winding	---	100	65	65	50	71	1. Reduced starting torque always provided 2. Closed-circuit transition-type provided	1. Possibility of motor not accelerating due to severe torque dip at half speed 2. Limitation in motor selection
2/3-1/3 Winding	----	100	65	65	40	----	1. Reduced starting torque always provided 2. Closed-circuit transition-type provided 3. Motor will usually accelerate to full speed in one step	1. Limitation in motor selection
Star-delta (Open or closed transition)	----	100	33	33	33	100	1. Starting duty cycle usually limited by motor heating only 2. High torque efficiency for all speeds 3. No torque dips or unusual stresses because full-winding transition from start to run 4. Closed-circuit transition-type eliminates line surges during transition from start to run	1. Starting characteristics not adjustable 2. Requires motor with a normally delta-connected winding with all leads brought out for connection to control

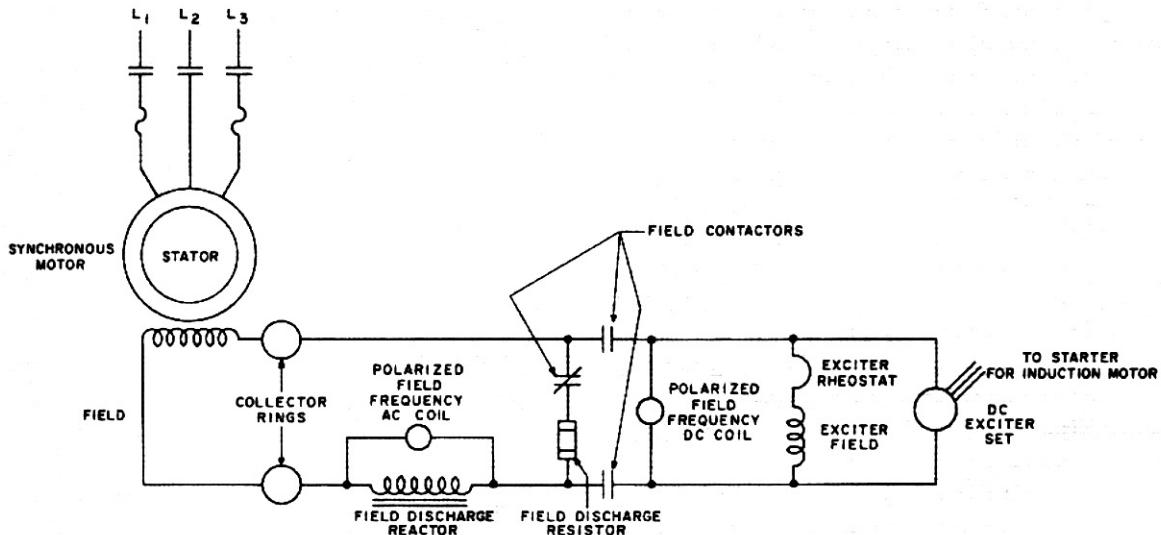


FIG. 48-TYPICAL SYNCHRONOUS MOTOR CONTROLLER

Across-the-line starters are always lowest in cost. *Figure 46* shows comparative costs of motor-starter combinations. *Table 7* gives comparative data on various starters.

Wound-Rotor Motor Starter

The wound-rotor motor variable secondary resistance starting equipment (*Fig. 47*) is the most expensive motor-starter combination and consists of:

1. Primary across-the-line starter with major protective elements, overload and undervoltage.
2. Secondary resistors and drum controller which acts to insert into the motor rotor windings the resistance required to provide the design speed control. The drum controller may be manually or automatically controlled.

The change in rotor resistance provided by the controller results in a change of the motor speed-torque curve; thus this method can be used as a means of speed control. It also results in a change of the motor speed-current curve so that this method is used to limit the starting current drawn from the power line.

A safety relay does not permit motor starting unless all the resistance is in the circuit.

Synchronous Motor Starter

The synchronous motor starting equipment (*Fig. 48*) is essentially the same as for a squirrel-cage induction motor because the synchronous motor starts operating as a squirrel-cage induction motor. Thus the main control may be either across-the-line or any of the reduced-voltage types, depending on the power company regulations.

To start up and operate, the synchronous motor requires a-c power; therefore the main contactor must be closed. During the starting period the d-c field winding is shorted thru the starting and discharge resistor. The latter serves two purposes; (1) it limits the high induced voltages that would otherwise appear at the field terminals and (2) it increases motor pull-in torque at start-up by serving as an added resistance in the field circuit. As a discharge resistor it limits the field voltage when the field supply is disconnected.

When approximately 97% of the synchronizing speed is reached, the starting resistor is automatically

disconnected from the slip rings, and the d-c power is applied to stabilize the motor synchronous speed. One other important condition must exist at the moment of application of d-c excitation; a correct relationship between the rotor field and the stator revolving magnetic field which also contributes to developing maximum pull-in torque.

If a sudden overload or voltage dip occurs, the required load torque can exceed the maximum pull-out torque of the motor. Thus the required torque pulls the motor out of its synchronous speed; the motor is pulled out of step. The d-c field is disconnected immediately; otherwise severe vibration due to torque pulsations may develop, and stator pulsating current inrush may rise to dangerous levels.

The polarized field relay operates at the instant of proper motor slip, bringing in d-c excitation, and thus automatically resynchronizing the motor if there is sufficient torque left in the motor, after removing the disturbance which caused the pull-out. Otherwise the motor is automatically taken off the line. A series of protective devices are included to provide a proper sequence of operation.

Multi-Speed Motor Controllers

The control of multi-speed motors is achieved thru separate starters (in one enclosure) acting either individually on each winding with separate-winding motors (fig. 49b) or in interlocked manner with the consequent-pole motors (Fig. 49a). No attempt is made to analyze the multiplicity of speed-winding combinations or control circuits that may apply under various circumstances. Most large fan applications use only two speeds, either with single (2:1 ratio) or two (3:2 ratio) windings.

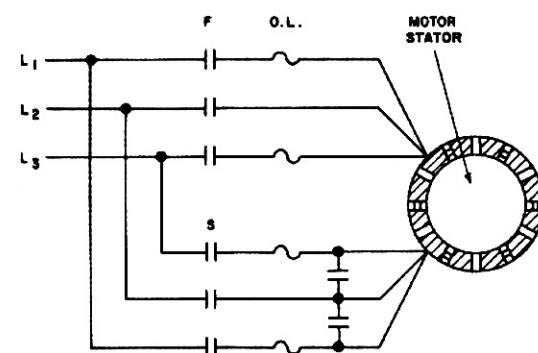
PROTECTION

The power supply lines nearest the motor are the feeder and branch circuits. The feeder circuit is the conductor that extends from the service entrance equipment to the branch circuit protective device. A branch circuit is that portion of the wiring system which extends beyond the final overcurrent device providing protection.

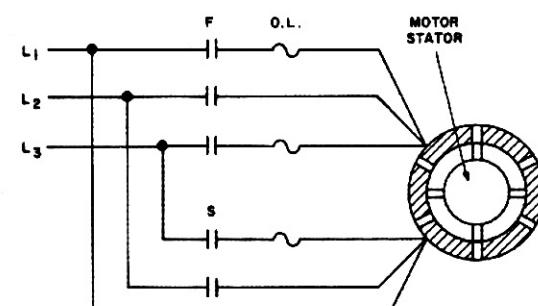
Switches

A majority of air conditioning and refrigeration installations are low voltage applications which at times may use manually-operated circuit switches as permitted by local codes. There are several varieties:

1. Disconnect switches for isolating purposes. They have no interrupt rating and should not be operated with a load on the line.
2. Interrupt switches in sizes up to 600 ampere continuous current rating. They can be opened with a load on the line, and are used mostly as service entrance equipment.
3. Enclosed safety switches, fused or unfused, available for light duty a-c service up to 600 ampere and 240 volt rating; for normal duty service (general purpose) up to 1200 ampere and 600 volt rating; and for heavy duty industrial service up to 1200 ampere and 600 volt rating.



a – two-speed, single winding,
three- and five-pole starter



b – two-speed, two winding,
two three-pole starters

FIG. 49 – MULTI-SPEED CONTROL

Fuses and Circuit Breakers

The design performance of a motor is delivered under a normal supply of electric energy. Any disturbance to normal flow leads either to overheating and eventual destruction of the motor, or to nondelivery of the required mechanical power.

The greatest hazard to any electric service is a short circuit, a flow of an enormously excessive current (running into thousands of amperes) caused by some fault either in the power line or at the motor. Sufficient protection must be designed into the system to safeguard the feeder and branch circuits as well as to isolate the feeder system from a fault in the individual branch circuit.

In an air conditioning and refrigeration system it is important to maintain full system capacity. Thus protection of the branch circuits that lead to the motors driving various fans and refrigeration machines is very important. Isolation of a defective branch circuit affords immediate attention for diagnosis and repair of the fault while the rest of the system is still able to deliver its partial air conditioning capacity. This does not obviate centralization of the system because present day electrical equipment is well designed and dependable; nevertheless, careful attention must be paid to the selection of electrical equipment appropriate to needs.

The electric system protection is twofold, (1) from a fault in the power supply and (2) from a fault occurring at the motor. A fuse or circuit breaker current interruption in the branch circuit must be instantaneous before the effect is cumulated back to the feeder circuit breaker.

An a-c squirrel-cage induction motor has three levels of electric current usage:

1. Fundamental or operating full-load (100% load) level.
2. Code permissible over-load level (service factor generally 115%, *Table 5*).
3. Almost instantaneous level* of starting current inrush (600%).

Neither the motor nor the starter is able to continuously withstand a short-circuit without damage. The starter (controller) is equipped with normal overload relays; therefore, the time-current characteristics of the short-circuit protection must be carefully coordinated with that of the normal overload protection so that the short-circuit overcurrent protection does not operate under any of the three levels of usage but operates instantaneously under short-circuit conditions. Fuses and circuit breakers are used for short-circuit interruption. When fuses or simple circuit breaker are installed in the same enclosure

with the motor starter, the assembly is called a combination starter.

A fuse is a low cost short-circuit protection device. It may be a plug or cartridge type. The plug type is available in ratings up to 30 amperes and is used on lines not exceeding 125 volts. There are two basic types of fuses, one with a single fusible zinc element and one with a dual-element time delay fuse. The latter has the ability to open the circuit on either the overload or short circuit.

Commercial or industrial cartridge type fuses are available in either single or dual-element varieties. There are also renewable or nonrenewable designs. Fuses of renewable design are more expensive, but the cost of replacing fuse links is less than that of fuses of a nonrenewable design.

A circuit breaker functions both as a circuit protector and as a branch circuit disconnect switch. Its advantage is that upon being opened by a short circuit it may be reset without the necessity of replacement, as in the case of a fused disconnect switch. With fused polyphase circuits there exists another danger, namely single-phasing in case only one fuse blows. A circuit breaker disconnects all three phases.

Overload Relays

The line overcurrent protection of the motor and starter is provided by varieties of switches, fuses and circuit breakers, or combinations of these. The motor overheating protection is accomplished by overload relays in the starter itself.

Overload relays are either a melting alloy or bimetallic type. The latter may be the compensating type, that is, compensating for ambient temperature difference between motor and starter locations. The compensated overload relay thus safeguards the motor from unnecessary outage and acts to trip only on motor overcurrent conditions.

A third type of overload relay is the magnetic induction type, the Heineman relay; it is non-sensitive to ambient temperature and is instantaneously resetting.

Undervoltage

There are many types of relays that may protect against any failure or malfunction. Only the most applicable are described.

Power systems are subject to occasional voltage fluctuations of varying magnitude and duration. Lightning

*The almost instantaneous nature of starting current inrush does not provide sufficient temperature rise in a protective element for it to act.

accidental short circuits or line overloads may create undervoltage dips and failures; motors may slow down and even stop. Minor voltage dips below 10% or frequency variations below 5% may be tolerated. More extensive variations may overheat the motor causing it to stop. There are three methods of protection that deal with line undervoltage:

1. Instantaneous and complete stoppage – the protective device trips the starter and the motor stops. The motor can be reinstated in operation only manually.
2. Time-delay – the motor is not shut down, but remains connected to the line for a brief duration, i.e. 2 seconds. Beyond this time interval the motor is disconnected either to be restarted manually or automatically with the voltage on again.
3. Time-delay and automatic reconnection – the starter is instantaneously disconnected from the power line and restarts the motor with voltage restoration. This protection is permissible if automatic reinstatement of equipment operation is required and is safe for personnel, and if in the case of a multitude of motors a combined instantaneous inrush of current can be tolerated by the power supply line.

Another protective means, undervoltage release, may be applied which stops the motor instantaneously but restarts it after any indefinite period of voltage shutdown. This method may be applied after a careful analysis of motor restarting relative to driven equipment and plant operating personnel.

With synchronous motors provisions must be made for automatic resynchronization after a voltage dip where continuity of operation of the driven equipment is required. Time delay undervoltage protection or some means of motor unloading must be provided during resynchronization unless the motor has a sufficient pull-in torque to resynchronize when the voltage is reinstated.

Phase Failure

Phase failure in a polyphase system must be prevented. It may occur under a varied set of circumstances, either in a power supply line or a branch circuit – a fuse failure, malfunction of one of the starter contacts, or a line break. When one of the phases opens while the motor is running under full load, the current in other phases increases in value and may trip the overload relays in the starter. Occasionally at certain partial loads the overload relays may not be tripped, yet current in the

circuit of low impedance may cause overheating. Damage to fractional horsepower motors is rare; since this protection is an extra expense, it is usually considered only with larger, more costly motors.

Reversing of Phases

Reversing of phases results in reverse rotation of the motor. Such a situation completely upsets the flow of fluid handled. Usually such a fault is rare since great care is exercised in wiring a motor. For instance, the fans rotating in reverse are unable to deliver the design air quantity. In both instances, either open or reverse phase, there are available relays that stop the motor or prevent backward operation respectively.

Interlocking

One form of protection is interlocking of the equipment or functions within the equipment. Examples of equipment interlock are relays that prevent starting of the refrigeration compressor until (1) the condenser or chilled water pump or both are started, (2) oil pressure is up or oil pump is started (centrifugal compressor), or (3) prerotational vanes are closed (hermetic centrifugal). An example of interlocking functions within a given equipment is an interlock that prevents wound-rotor motor starting until the drum controller is in the starting position, that is, with all the resistors in the circuit.

ENCLOSURES FOR STARTERS

Starters, either singly or in combination or in multiples thereof, are usually encased in general-purpose sheet metal enclosures furnished with a dowelled or hinged access panel and doors. The small enclosures are not ventilated but are inherently protected from dust and light indirect splashing; they also protect the operator from accidental contact with the live parts.

Multiples of individual starters or in combination with protective devices may be assembled in vertical multiple cubicle control centers and may be pre-wired. Two NEMA types are:

Type A – contains no terminal boards (blocks) for either load or control connections.

Type B – contains terminal boards for load and control connection at each starter (most popular).

There are also dusttight and watertight enclosures that do not admit dust or water; the watertight enclosures may be used for outdoor installations.

For hazardous areas there are Class 1 and 2 enclosures. The Class 1 enclosures for flammable and

corrosive vapor areas are made for both air-break and oil-immersed control. The air-break controls are heavy enough to withstand an internal explosion and to prevent hot gases from escaping to the outside. Oil-immersed controls are also used where corrosive atmospheres are present; oil protects the metal parts. Class 2 enclosures are made dusttight for locations where air-dust explosive mixtures may form.

NEMA classification of the motor control enclosures for mechanical and electrical protection of the operator and equipment are listed as follows:

General Purpose NEMA 1 – indoor, atmospheric conditions normal, sheet metal, does not prevent entry of liquid or airborne foreign particles, conduit entrances standard.

General Purpose NEMA 1 Gasketed – indoor, designed to exclude dust and other foreign airborne particles, does not meet dusttight requirements, sheet metal, conduit entrances standard.

Driptight NEMA 2 – indoor, general purpose enclosure with shields for protection from dripping liquids, conduit gasketed entrances may require special glands or hubs.

Weather Resistant (Raintight) (Weatherproof) NEMA 3 – outdoor, controls operate satisfactorily exposed to rain or sleet, sheet metal, special conduit hub or entrance to maintain weather resistant characteristics.

Watertight NEMA 4 – outdoor, water or moisture excluded from splashing or direct stream, meets specific hose test requirements, sheet metal or cast construction, special hubs or glands required for conduit entrance, no conduit entrance knockouts, external mounting feet.

Dusttight NEMA 5 – indoor, prevents entry of dusts, nonhazardous locations, sheet metal or cast construction, gasketed or equivalent, no conduit knockouts, conduit entrances predrilled, sealtight bushings required, external mounting feet.

Hazardous Locations (Gas) NEMA 7D – meets requirements of NEC for Class 1 Group D hazardous locations, cast enclosure bolted or threaded, conduit entrances threaded, special hubs or glands required, external mounting feet.

Hazardous Locations (Dust) NEMA 9E-FG – meets requirements of NEC for Class II hazardous locations, cast construction, bolted or threaded, conduit entrances threaded, special hubs or glands required, external mounting feet.

Industrial NEMA 12 – indoor, meets JIC electrical standards for industrial equipment, excludes dust, lint, fibers, flyings and oil or coolant seepage, sheet metal gasketed, no conduit entrances, seal-tight bushings required, external mounting feet.

Oiltight – no specific NEMA number designation, indoor, designed to exclude entrance of oils or coolant, used in applications similar to NEMA 12.

HAZARDOUS LOCATIONS

The NEMA classifications and definitions of hazardous locations are:

Class I, Group A – atmospheres containing acetylene.

Class I, Group B – atmospheres containing hydrogen or gases or vapors of equivalent hazard such as manufactured gas.

TABLE 8 – STANDARD NEMA SIZES AND MAXIMUM HORSEPOWERS

Size	Maximum Horsepower				
	2-or- 3-phase		Single-phase		
	Volts				
	110	208/220	380,440,550	115	230
0	1 1/2	3	5	1	2
1	3	7 1/2	10	2	3
1 1/2				3	5
2	7 1/2	15	25		
3	15	30	50		
4	25	50	100		
5		100	200		
6		200	400		
7		300	600		
8		450	900		

Class I, Group C – atmospheres containing ethyl ether vapor.

Class I, Group D – atmospheres containing gasoline, petroleum, naphtha, alcohols, acetone, lacquer solvent vapors and natural gas.

Class II, Group E – atmospheres containing metal dust.

Class II, Group F – atmospheres containing carbon black, coal or coke dust.

Class II, Group G – atmospheres containing grain dust.

NEMA SIZES FOR STARTERS

Standard NEMA sizes and corresponding maximum horsepower are listed in *Table 8*.

FUNDAMENTAL RELATIONS

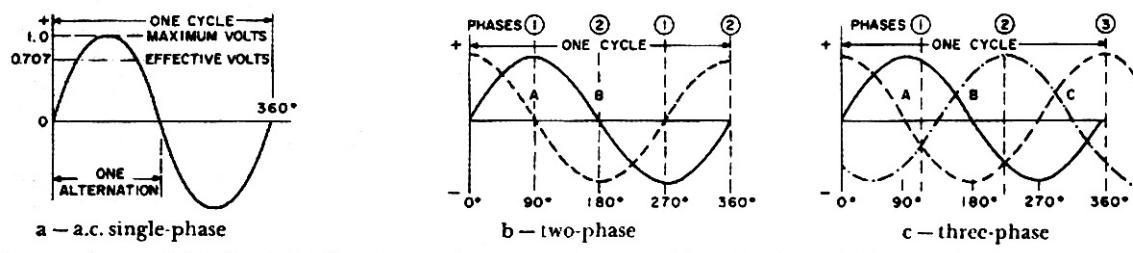
Electric motors consume electric energy. Energy is utilized in various ways by the specific designs of motors. It is the purpose of this section to review briefly the fundamental elements of electric energy and their interplay affecting the performance of a motor drive to provide mechanical power for the operation of various equipment.

The text is elementary; however the correct application of motors and motor control depends on a thorough understanding of the rudiments of electric current phenomena.

The standard alternating current service is generated usually at medium voltage, distributed at very high voltage using smaller size conductor, and transformed at points of use to single, two-or three-phase, 60-cycle current of 120, 240, 480 or 600 voltages. The a-c current is also available in 50 cycles (used primarily in foreign

countries) and 25 cycles. The 60 cycle frequency is most utilitarian for power and lighting applications. Medium high voltages (230 to 4160 and 4800 volts) are used for large motors (200-250 horsepower and up) to achieve whenever possible a lower over-all installation cost of motor and auxiliaries.

Alternating current voltage alternates regularly in value and direction. *Figure 50a* illustrates a single-phase wave. Frequency or cycle is the number of complete 360 degree cycles per second (two alternations per second). If the electric power is supplied over two circuits in one of which the voltage reaches zero and other corresponding values 90 degrees later than in the other circuit, the service is two-phase (*Fig. 50b*). If the power is supplied over three circuits with corresponding current values reached at 120 degree intervals, the service is three-phase (*Fig. 50c*).



NOTE: With 60-cycle current one complete cycle takes place in 1/60 of a second.

FIG. 50-ELECTRIC SERVICE

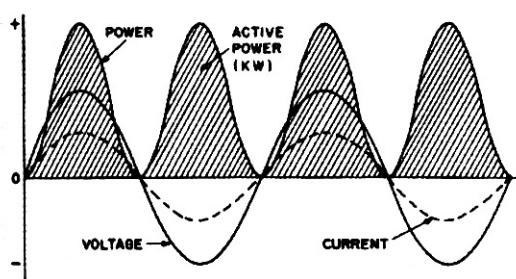


FIG. 51 – CURRENT AND VOLTAGE IN PHASE, POSITIVE ACTIVE POWER ONLY

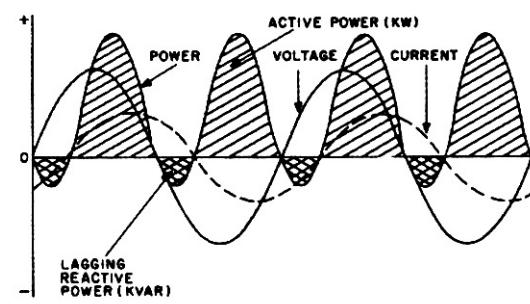


FIG. 52 – CURRENT LAGS VOLTAGE, POSITIVE AND NEGATIVE POWER

PRESSURE, INTENSITY, RESISTANCE AND ACTIVE POWER

Flow of electricity is caused by electromotive force (emf); the unit volt (E) is the common measure of electric pressure (Fig. 50a). The top of the sine curve is the maximum line pressure. The actual effective average voltage (root-mean-square, rms, voltage) is 0.707 of the maximum, and is measured by the a-c voltmeter.

The unit ampere (I), the intensity of current, is the measure of rate of flow of electric current. The effective rms value is the value indicated on a common a-c ammeter.

A conductor of electricity inherently has resistance to flow. For a given resistance expressed in ohm units (a flow of one ampere under pressure of one volt) the emf has to be varied to change the rate of flow. With reduced resistance a given pressure (emf) increases the rate of flow.

Electric power (W) is measured in watts.

$$kw = \frac{W}{1000}$$

A watt (EI) is the product of one amper effective current flowing at a pressure of one effective volt, in a circuit that does not contain either inductance or capacitance, for instance, as an incandescent light bulb or a heating device.

In these noninductive a-c circuits the voltage and current are in phase, reaching the maximums and minimums at the same time (fig. 51). When voltage and current are in phase, the power is the total active power consumed:

$$1. \text{ On single-phase service, } kw = \frac{EI}{1000}$$

$$2. \text{ On two-phase service, } kw = \frac{2EI}{1000}$$

$$3. \text{ On three-phase service, } kw = \frac{1.73EI}{1000}$$

CURRENT-VOLTAGE INTERACTIONS

The relationship between current and voltage is an important aspect of motor design for two reasons: (1) power factor and (2) electromagnetism, the life blood of transformers, motors and other electric apparatus (solenoid valve) with magnetic effects created within iron cores. The magnetic lines crossed by a conductor induce

a current within tie conductor. This is the foundation of the motor concept.

The magnetic effects produced by electric current in an electric circuit containing coils or windings react in turn upon the current. The magnetic effects retard (check back) the current, causing it to lag behind the voltage; the current still flows in the circuit even if the voltage is zero (Fig. 52); the magnetic reaction is called inductance. A condenser in an electric circuit causes current to lead ahead of the voltage. This reaction is called capacitance and tends to counteract the inductance.

APPARENT POWER

In electric circuits containing inductance (induction motors) with a continuous flow of current the product of effective current and effective voltage is greater than the actual power used to drive the motor. The cumulative apparent power is measured in volt-amperes, or usually in kilovolt-amperes (kva).

$$1. \text{ On single-phase service, } kva = \frac{EI}{1000}$$

$$2. \text{ On two-phase service, } kva = \frac{2EI}{1000}$$

$$3. \text{ On three-phase service, } kva = \frac{1.73EI}{1000}$$

Figure 52 is the power plot, usually positive; when the current or voltage is negative, the product EI is negative power. A motor draws positive power from the line to do the actual work; the negative power (kvar) goes back to the line. The actual power is the net flow of power measured on the wattmeter.

The kvar may be evaluated as follows:

$$1. \text{ On single-phase service, } kvar = \frac{EI \sqrt{1-PF^2}}{1000}$$

$$2. \text{ On two-phase service, } kvar = \frac{2EI \sqrt{1-PF^2}}{1000}$$

$$3. \text{ On three-phase service, } kvar = \frac{1.73EI \sqrt{1-PF^2}}{1000}$$

(PF = power factor.)

POWER FACTOR

The negative aspect of the power is the result of magnetism, the reactive current that does no actual work; however it provides the necessary magnetic field. The

ratio of real active power to apparent power (watts/volt-ampere, kw/kva) is the power factor. A power factor of 1.0 (unity) all positive (Fig. 51) is ideal; this exists in circuits having resistance only such as incandescent lights and electric heaters. A lagging power factor less than unity is undesirable in circuits having squirrel-cage induction motors. A decrease in power factor means an increase in kvar for a given kw load. Chart 2 shows the range of power factor effects of various electrical equipment on the power circuit.

There are various methods of controlling a power factor as close to unity as possible. The kvar inherent in induction motors is to be contained within the plant which uses the actual power (Fig. 33). Without control of the power factor the effects of its lagging are deleterious; they are of vital interest to the power supplier as well as the power consumer. The reasons are three-fold:

1. Low power factor means more current per kilowatt used: hence it costs more to transmit the useful power being dragged by apparent power. The consumer may have to pay more for the real power he uses.
2. Low power factor reduces the capacity of the power system to carry the real power of the total system from generator to switches at the motors; the whole system must be larger to transmit a given kilowatt load. The power producer's investment per kilowatt of load is higher.

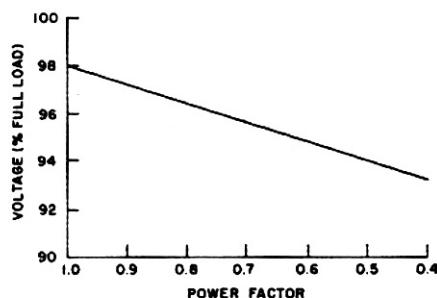


FIG. 53 – APPROXIMATE DROP IN VOLTAGE WITH LAGGING POWER FACTOR

3. Low power factor may depress the voltage, resulting in detrimental reduction of the output of electric apparatus. This lowers the performance of the consumer's plant. Figure 53 shows the effect of a low power factor on voltage.

VOLTAGE VARIATION

A variation of the line voltage affects the induction motor power factor and motor efficiency as shown in Fig. 54. The motor torques are raised or lowered from their design value proportionally to the square of voltage; for 90% of line voltage (10% drop), there is available only 81% (.9 x .9) of design torque. Table 9 lists the effects of voltage variation on the elements of motor behavior. Figure 55 presents graphically the effect of voltage and frequency variation on the two basic characteristics of a motor, the starting torque and starting current.

A decrease in voltage increases the full load current and thus increases the full load temperature rise. An increase in voltage may have the physical effects of shearing off couplings and even producing some damage to the driven equipment itself because of a sharp rise in starting and running torque.

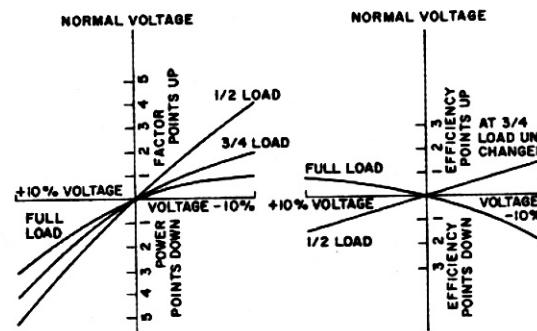


FIG. 54 – EFFECT OF LINE VOLTAGE VARIATION ON MOTOR POWER FACTOR AND EFFICIENCY

TABLE 9-VARIATION IN MOTOR CHARACTERISTICS WITH CHANGE IN VOLTAGE

Motor Characteristic		Percent Variation with Change in Voltage of		
	Function of Voltage	+20%	+10%	-10%
Starting and Maximum Running Torque	$(\text{Voltage})^2$	Increase 44%	Increase 21%	Decrease 19%
Synchronous Speed	Constant	No Change	No Change	No Change
Percent Slip	$1/(\text{voltage})^2$	Decrease 30%	Decrease 17%	Increase 23%
Full-Load Speed	(Syn. Speed Slip)	Increase 1.5%	Increase 1%	Decrease 1 1/2 %
Efficiency	----	Small Increase	Increase 1/2 to 1 point	Decrease 2 points
Full-Load	----	Decrease 1/2 to 2 points	Practically no change	Practically no change
3/4 Load	----	Decrease 7 to 20 points	Decrease 1 to 2 points	Increase 1 to 2 points
1/2 Load	----			
Power Factor				
Full-Load	----	Decrease 5 to 15 points	Decrease 3 points	Increase 1 point
3/4 Load	----	Decrease 10 to 30 points	Decrease 4 points	Increase 2 to 3 points
1/2 Load	----	Decrease 15 to 40 points	Decrease 5 to 6 points	Increase 4 to 5 points
Full-Load Current	----	Decrease 11%	Decrease 7%	Increase 11%
Starting Current	Voltage	Increase 25%	Increase 10 to 12%	Decrease 10 to 12%
Temperature Rise, Full Load	----			
Maximum Overload Capacity	$(\text{Voltage})^2$	Decrease 5 to 6 C	Decrease 3 to 4 C	Increase 6 to 7 C
Magnetic Noise-No Particular Load	----	Increase 44%	Increase 21%	Decrease 19%
		Noticeable Increase	Increase Slightly	Decrease Slightly

NOTE: Applicable to NEMA Design A, B and C motors.

MOTOR TORQUE

The load torque of a driven machine must be matched by the torque characteristics of the motor. The relationship between torque, power and speed is given by:

$$T = \frac{P \times 5252}{S}$$

Where T = torque, pound-feet P = power, horsepower S = speed, rpm

$$5252 = \frac{33000}{2\pi}$$

For example, a 500 hp, 1750 rpm (full load rpm) motor has a full load torque of

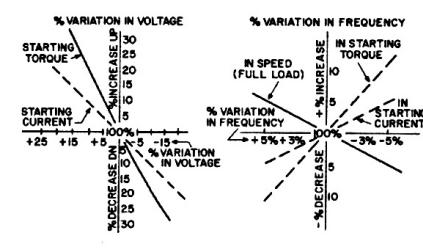
$$\frac{500 \times 5252}{1750} = 1500 \text{ pound-feet}$$

Motor torque is created by the interaction of a rotating magnetic field (Fig. 26) and the induced voltage in the rotor coils.

Figure 56 illustrates a torque curve characteristic of a squirrel-cage induction motor. It also points out the approximate locked rotor, pull-up breakdown and full load torque values against the percent motor synchronous speed.

Definitions of various torques follow:

1. Locked-Rotor* (starting, static, breakaway) Torque is developed at the instant of starting for any angular



with variation in voltage with variation in frequency

FIG. 55 – MOTOR PERFORMANCE

* Locked-rotor nomenclature is derived from the fact that in measuring starting torque the rotor is locked in position and is motionless when the current is applied to the rotor.

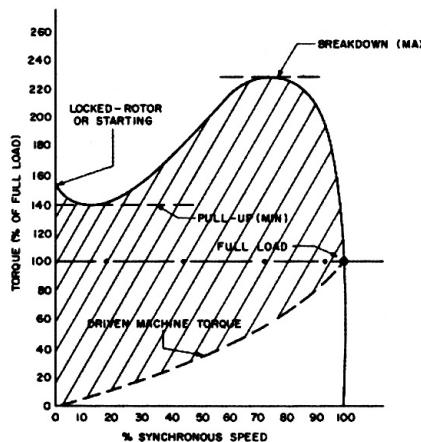


FIG. 56 – SPEED- TORQUE RELATIONSHIP, INDUCTION MOTOR

position of the motor rotor when the rated voltage is applied at rated frequency. It is the turning effort applied to the load at rest.

2. Pull-Up Torque is the minimum torque developed by a motor at rated voltage during the acceleration from rest to the speed at which the breakdown torque occurs, or in general the minimum torque developed up to rated speed. A drop in minimum torque below the load torque prevents acceleration or stalls the motor.
3. Acceleration (net) torque is the margin by which the motor torque exceeds the load torque from standstill to full speed (Fig. 56)
4. Breakdown (pull-out) Torque is the maximum torque developed with rated voltage applied at rated frequency without an abrupt drop in speed. It accommodates brief overloads.
5. Full-Load Torque is that necessary to produce rated horsepower needed to operate the driven machine, performing in turn its task as full load speed.
6. Pull-in Torque, applicable only to synchronous motors, is the torque that the motor develops when pulling its connected inertia load into synchronism upon application of d-c excitation.

SYNCHRONOUS SPEED

The theoretical speed of a rotating magnetic field (flux) produced by electric current in the primary windings of the starter of an a-c induction motor is the synchronous speed of the motor. The synchronous motor is the only one that operates at 100% synchronous speed

at full load. Other types of motors have a speed that lags the synchronous speed by a difference called slip.

$$\text{Synchronous speed } S = \text{theoretical motor rpm} = \frac{120f}{p}$$

Where:

f = frequency, cycles per second

p = number of starter poles

120 = number of alternations per second for 60-cycle current

Thus theoretically a two-pole motor rotates at 3600 rpm with 60 cycle current (3000 rpm with 50 cycle, 1500 rpm with 25 cycle current). A sixteen (16) pole motor operates at 450 rpm with 60 cycle current.

SLIP

The difference between the synchronous and the operating speed of a motor is called slip (Fig. 57). It is expressed in percent of synchronous speed. The greater the load, the greater the slip; that is, the slower the motor runs. But even at full load the slip generally is below 5%; the motor is still considered a constant-speed motor.

$$\text{Percent slip} = \frac{\text{synchronous speed} - \text{full load speed}}{\text{synchronous speed}} \times 100$$

A motor rated at 1800 rpm and running at 1750 rpm when fully loaded has

$$\frac{1800 - 1750}{1800} \times 100 = 2.77\% \text{ slip}$$

The significance of low slip is in the utilization of the motor synchronous speed and its maximum efficiency.

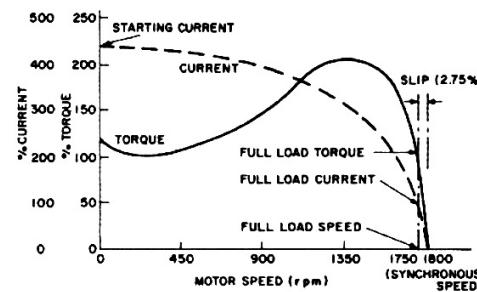


FIG. 57 – TYPICAL CURVES, MOTOR TORQUE AND CURRENT

TABLE 10-STANDARD EQUATIONS

DESIRED DATA	ALTERNATING CURRENT		
	Single-phase	2-Phase	3-Phase
Horsepower (output)	$\frac{\text{Volts} \times \text{amps} \times \text{eff} \times \text{PF}}{746 \times 100}$	$\frac{2 \times \text{volts} \times \text{amps} \times \text{eff} \times \text{PF}}{746 \times 100}$	$\frac{1.73 \times \text{volts} \times \text{amps} \times \text{eff} \times \text{PF}}{746 \times 100}$
Amperes (when horsepower is known)	$\frac{\text{hp} \times 746 \times 100}{\text{volts} \times \text{eff} \times \text{PF}}$	$\frac{\text{hp} \times 746 \times 100}{2 \times \text{volts} \times \text{eff} \times \text{PF}}$	$\frac{\text{hp} \times 746 \times 100}{1.73 \times \text{volts} \times \text{eff} \times \text{PF}}$
Amperes (when kilowatts are known)	$\frac{\text{kilowatts} \times 1000}{\text{volts} \times \text{PF}}$	$\frac{\text{kilowatts} \times 1000}{2 \times \text{volts} \times \text{PF}}$	$\frac{\text{kilowatts} \times 1000}{1.73 \times \text{volts} \times \text{PF}}$
Amperes (when kva is known)	$\frac{\text{kva} \times 1000}{\text{volts}}$	$\frac{\text{kva} \times 1000}{2 \times \text{volts}}$	$\frac{\text{kva} \times 1000}{1.73 \times \text{volts}}$

NOTE: equations for 2-phase are set up for 4-wire circuits. In 3-wire circuits the current in the common conductor is 1.41 times that in either of the other two conductors. Efficiency is expressed in an integral number (90%). Power factor is expressed as a decimal (0.85). Refer to Charts 1 and 2

MOTOR CURRENT

Because of usually low resistance in the motor circuit when the motor is at rest, the locked-rotor momentary inrush of current (starting current) is four to six (up to 10) times greater than the full load (Fig. 27). The low figure is the standard for the majority of motors specifically designed to satisfy the power companies' concern with taxing the transmission lines with disturbances that affect the power transmission performance; these disturbances are due to possible large low power factor starting currents. The customer charges normally are affected only slightly since the inrush is momentary in nature; this inrush may have only slight effect on the demand charge which is based on continuous use of current for at least fifteen minutes. However in the case of frequent starting or long acceleration periods, the demand is integrated over a period of time (usually fifteen minutes) and may up the demand charge. The same amount of current is drawn at starting in case a motor is stalled because of mechanical overload.

EFFICIENCY

Motor efficiency is a measure of the motor capacity to convert electric energy input to mechanical horsepower output and is expressed in percent of kw input:

$$\text{Percent efficiency} = \frac{\text{hp output} \times .746}{\text{kw input}} \times 100$$

Approximate comparative efficiencies of standard squirrel-cage induction motors at three different synchronous speeds are shown in Chart 1.

HORSEPOWER AND CURRENT

To facilitate the evaluation of horsepower output and current consumption in amperes, standard equations are presented in Table 10.

The objective of this chapter has been to provide an outline or an introduction to the great wealth of material available on motors and motor controls. The manufacturers' data and catalogs provide the necessary details. The proper selection of motors and motor controls is an inseparable part of the design of air conditioning and refrigeration systems that are part of the total over-all mechanical equipment. The performance and acceptance of a system may well rest on the electrical equipment selected to operate it.

CHAPTER 3. BOILERS

This chapter presents information to guide the engineer in the practical application and layout of boilers when used in conjunction with air conditioning and refrigeration systems.

The scope of this chapter is limited to packaged boilers which have capacities to cover the applications with which the engineer is concerned. Steam generation as well as water heating may be effected by the utilization of such boilers up to comparatively high steam pressures and water temperatures respectively.

TYPES OF BOILERS

Boilers may be classified in two general groups:

1. Sectional cast iron boilers.
2. Steel firebox boilers, fire-tube or water-tube.

Cast iron boilers may be rectangular (or square) with vertical sections or round with horizontal sections. These boilers are usually shipped in sections and assembled at the place of installation.

Some smaller boilers are factory-assembled. Some have water-filled spaces completely surrounding the combustion chamber. Cast iron boilers are normally limited to 15 psig steam pressure and 30 psig water pressure (274 F) with IBR* net load ratings ranging up to approximately 2,500,000 Btu/hr output.

Fire-tube steel boilers have their combustion gases passing thru tubes surrounded by circulating water. A packaged steam or hot water fir-tube boiler is a modified Scotch type boiler† having all component in an assembled unit. Components include burner, boiler, controls and auxiliary equipment. Most modern fire-tube units operate at or below 250 psig and below about 20,000 lb steam/ hr. Fuels for packaged fire-tube units may be oil, gas or a combination of these.

* Institute of Boiler and Radiator Manufacturers.

† Type of boiler evolved to meet space and weight requirements of the merchant marine. It is self-contained, requires no brick setting, and can be operated at high ratings without damage.

Water-tube steel boilers have their combustion gases circulating around the tubes and water passing thru the tubes. Most modern water-tube packaged units have capacities ranging up to 60,000 lb steam/ hr and pressures up to 900 psig. Capacity is limited by shipping clearances. Water-tube units are designed principally for oil, gas or a combination of these fuels. These boilers can be adapted to solid fuels more readily than can fire-tube steel boilers.

APPLICATION

Cast iron boilers are suitable for steam generation or hot water heating where low pressures are used. They may be applied in commercial and industrial buildings within the capacity range available.

The capacities of cast iron and steel boilers overlap. Where this occurs, any comparison should include the following:

1. Steel boilers in the larger sizes are more efficient.
2. With proper maintenance and use, a cast iron boiler outlasts any steel boiler made. However, where the character of maintenance is apt to result in neglect, the serviceability of the steel boiler is of marked advantage.
3. A skilled steam fitter is required to assemble the heating sections of cast iron boilers (when field-erected). The steel boiler has only to be placed into position. However, since the sections of a cast iron boiler are so designed as to be readily carried thru doors or windows, ease of installation generally favors the cast iron boiler.
4. The relative cost of steel boilers in the smaller sizes is greater than that of cast iron boilers of the same capacity.
5. When more boiler capacity is required in the extension of a system, additional sections may be added to a cast iron boiler, whereas a separate or replacement steel boiler of a larger size must be considered.

Fire-tube steel boilers are used principally in small heating and industrial plants. Its popularity is growing in the industrial, commercial and institutional fields. Shell diameters are limited to about 96 inches. Cost of installation including setting is considerably less than that of a corresponding water-tube boiler. With a water-filled cylindrical shell housing an internally fired furnace, a relatively long gas-travel path yields high efficiency in a compact unit.

Water-tube steel boilers pick up in capacity near the upper end of the fire-tube range to extend the availability of the packaged concept. Pressure and size limitations of fire-tube boilers do not exist in water-tube units; these boilers require no prepared setting other than a floor of sufficient strength and no skilled labor for assembly prior to operation.

Fire-tube and water-tube steel boilers may be used for hot water heating.

STANDARDS AND CODES

Boiler installation should conform to applicable national, state, local, ASME, utility and insurance code requirements. The ASME boiler and pressure vessel code (Sections I and IV) prescribe methods of boiler design, construction and installation. The Mechanical Contractors Association of America prescribe boiler testing and rating procedures.

STEAM BOILERS

Where applicable, low pressure steam generators are recommended because boilers operated at more than 15 psig pressure must, generally, be tended by a licensed operator.

LOW PRESSURE BOILERS

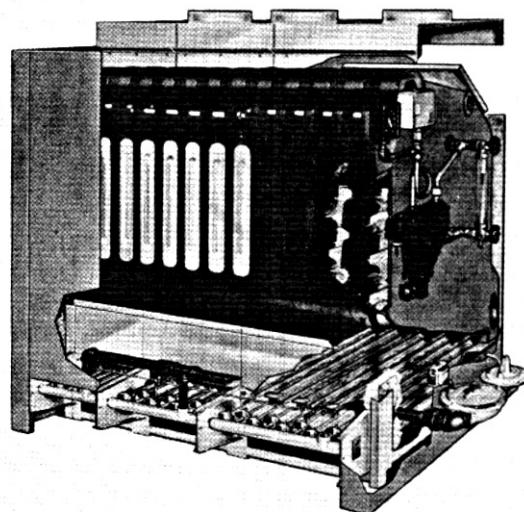
Cast iron or fire-tube steel boilers may be applied to low pressure steam generation.

Hartford Return Loops illustrated in *Part 3* are recommended to prevent the loss of boiler water by backward flow into the return mains.

Cast Iron Boilers

Cast iron boilers are designed for oil, gas or coal fuel.

Figure 58 shows a typical gas-fired, cast iron steam generator. Good boiler design incorporates methods of breaking up the hot gases leaving the firebox and, by means of passes or baffles, promotes contact with the heating surface at a high gas velocity but with a reasonable resistance.



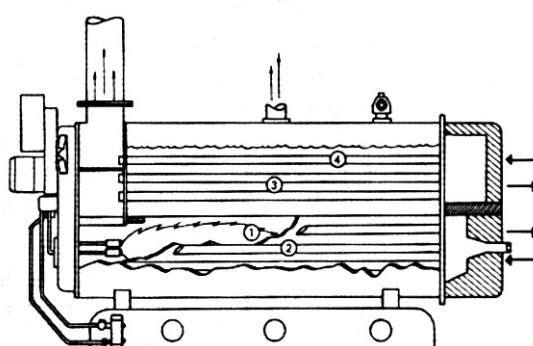
Courtesy of Bryant Manufacturing Co.

FIG. 58 – TYPICAL GAS-FIRED CAST IRON GENERATOR

Fire-Tube Steel Boilers

Practically all packaged fire-tube units are available for low pressure heating service (15 psig and below). They are relatively inexpensive compared to the corresponding water tube boilers. *Figure 59* shows a typical fire-tube steam generator.

The design and construction of a fire-tube boiler presents definite limits to the sizes which can be built. Practical limits of size and pressure result from the fact that the entire steam-making process takes place inside a shell. Since shell strength to resist rupture is proportional to pressure times diameter, high pressures and large diameters lead to prohibitively thick shells.



Courtesy of Cleaver Brooks Co.

FIG. 59 – TYPICAL FIRE-TUBE STEAM GENERATOR

The fire-tube boiler has a large water-storage capacity; thus the wide and sudden fluctuations in steam demand are met by only a slight change in pressure. Because of the large water content, a longer time is required to bring the boiler up to operating pressure. Overload capacity is limited and exit gas temperatures rise rapidly with increased output. Oil- or gas-fired, the modern packaged fire-tube boiler operates with efficiencies of about 80% over a wide load range. Coal, stoker-fired boilers operate from 60-75% efficiency.

The fire-tube design is not readily adaptable to the installation of soot blowing equipment. However, with relatively large tube diameters compared with water-tube boilers and with the products of combustion confined within the tubes, the turbulent high speed gas tends to produce a scrubbing action and maintain tube surfaces relatively free of combustion deposits. The fire-side surfaces of the tubes may require brushing at periodic intervals, the length of the intervals depending on the cleanliness of the combustion process and the type of fuel used.

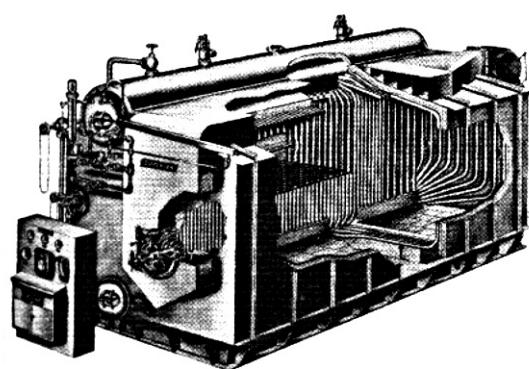
HIGH PRESSURE BOILERS

Both fire-tube and water-tube steel boilers may be applied to high pressure steam generation.

Water-Tube Boilers

Water-tube boilers (Fig. 60) have compact and efficient heating surface layouts by combining water-wall and convection surfaces; they are well suited for low head, limited space applications.

Waterwalls handle the bulk of the heat absorption in most packaged water-tube units. Exposed to radiant heat the waterwall heat transfer rate is high. In nearly all designs the drum is arranged with its long axis parallel to the furnace length.



Courtesy of Superior Combustion Industries Inc.

FIG. 60 – TYPICAL WATER-TUBE STEAM GENERATOR

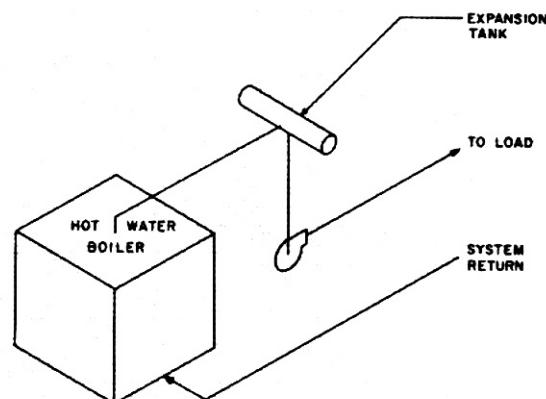


FIG. 61 – DIRECT SYSTEM,
HIGH TEMPERATURE WATER

Practically all water-tube boilers are equipped with soot blowers when delivered, or have provision for easy installation of soot blowing elements. These are usually of the steam type.

HOT WATER SYSTEMS

In hot water applications the range of temperatures involved is from 180 F (conventional gravity hot water heating system) to 400 F (accepted practical upper limit for industrial applications). Two basic types of hot water systems are the indirect cascade and the direct systems.

A direct system (Fig. 61) generally had a separate tank which provides expansion as the water temperature changes. If forced circulation is used, a centrifugal pump draws water from the tank, circulates it thru the system, sends it to the boiler for reheating, then returns it to the tank to complete the cycle.

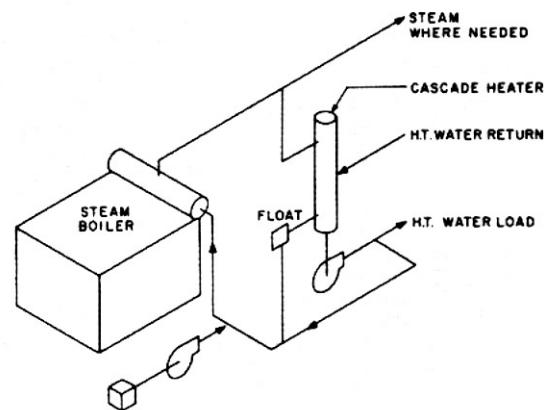


FIG. 62 – INDIRECT SYSTEM,
HIGH TEMPERATURE WATER

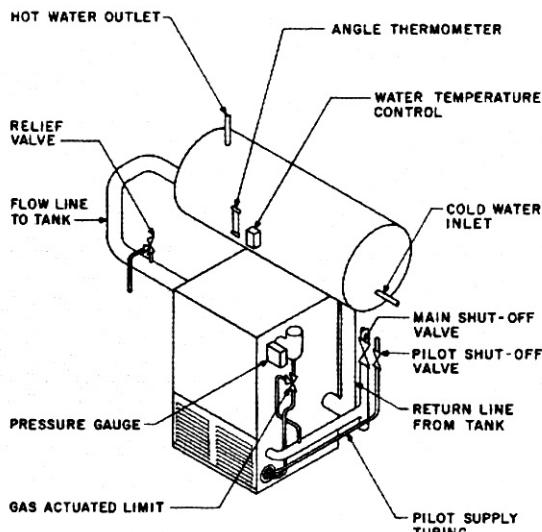


FIG. 63 – DIRECT SYSTEM,
LOW TEMPERATURE HOT WATER

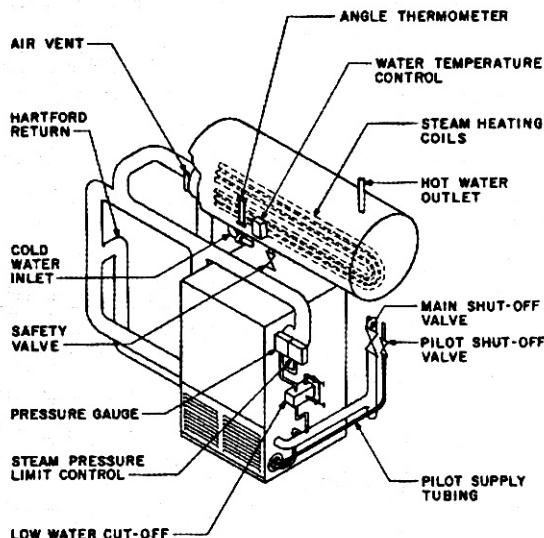


FIG. 64 – INDIRECT SYSTEM,
LOW TEMPERATURE HOT WATER

An indirect system (Fig. 62) takes steam from a boiler and carries it to a direct contact heater that raises the water temperature to within about two degrees of the entering steam temperature. From the heater, pumps circulate the high temperature water to heat exchangers at points of use. Condensate is generally returned to a hot well. Feed water may be supplied from both the hot well and water portion of the direct contact heater.

The direct type of system is generally employed except on installations where existing steam generators are used, when a source of exhaust steam is used with a cascade heater to produce high temperature water, or where specific limitations on the use of a cast iron boiler prevent it from being used on a direct system. Specific limitations on a cast iron boiler are these:

1. Not recommended where the hardness of the water produces lime deposits in the boiler sections.
2. Not recommended where the city water mains are used as an expansion tank and the city water supply pressure is greater than the boiler maximum working pressure.

High temperature water applications may be divided into three categories:

1. Low temperature (LTHW) range is from 180-250 F with corresponding saturation pressures from 0-15 psig.
2. Medium temperature (MTW, sometimes called intermediate) range is from 250-300 F with saturation pressure ranging from 15-52 psig.
3. High temperature (HTW) range is from 300-400 F with saturation pressure readings of 52-233 psig.

LOW TEMPERATURE HOT WATER SYSTEMS

Cast iron and fire-tube boilers may be applied to low temperature hot water heating with direct and indirect systems. A typical direct system using a cast iron boiler is shown in Fig. 63.

With suitable provision for introducing the return low temperature water without thermal shock to the unit, the conventional fire-tube packaged steam boiler may be adapted to the direct system.

A typical indirect system using a cast iron boiler is shown in Fig. 64. Any steam generating unit can be used in a cascade system. With low temperature hot water applications temperature rises up to 50 degrees may be used.

MEDIUM AND HIGH TEMPERATURE WATER SYSTEMS

Water temperatures greater than 274 F can be secured with some cast iron boilers utilizing a direct system. Boilers may also be water-tube or fire-tube, and may be equipped with any conventional fuel firing apparatus.

Since there is a partial correlation between pressure and capacity, maximum pressure and temperature seldom prove economical except in the higher capacity range. Water-tube boilers are seldom designed for pressures below 150 pounds; they are preferred for the higher pressure and capacity ranges.

With medium and high temperature hot water applications, advantage may be taken of high temperature rises up to 100 F and 200 F respectively.

Figure 65 shows a typical fire-tube hot water boiler. Figure 66 shows the flow pattern in a hot water boiler.

BOILER PERFORMANCE

The term performance refers to the rate of output, efficiency of heat transfer, and draft and pressure requirements of the unit or any of its component parts.

CAPACITY

The capacity or output of a boiler is expressed in many ways. The most accurate method of rating is in terms of total heat transferred per hour to the water or steam as it passes thru the unit. Capacity may also be expressed in equivalent direct radiation, boiler horsepower or actual evaporation.

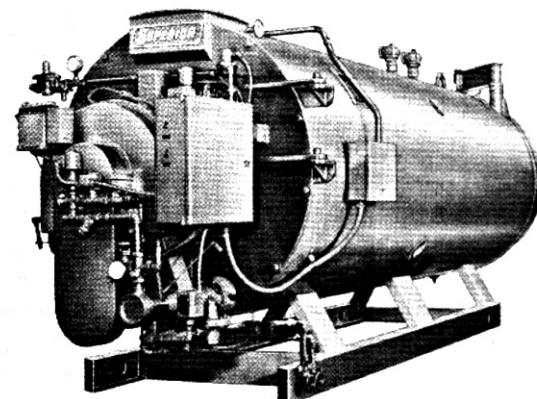
However such a rating reflects only the boiler output under laboratory test conditions and does not provide for piping loss and starting load allowances; when selecting a boiler, its net load rating (IBR, SBI*, ABMA†) should be equal to or exceed the calculated heat requirements of the building. The net load rating varies from 75% for oil, gas and automatic coal-fired boilers to approximately 40% of the gross output for small hand, coal-fired boilers. When required by job conditions, the calculated heat requirements of the building should take into consideration the startup steam demand of the miscellaneous equipment supplied by the boiler.

Equivalent Direct Radiation

An equivalent square foot of steam radiation surface (EDR) is defined as the amount of surface which emits 240 Btu/hr, with a steam temperature of 215 F and a room air temperature of 70 F. With hot

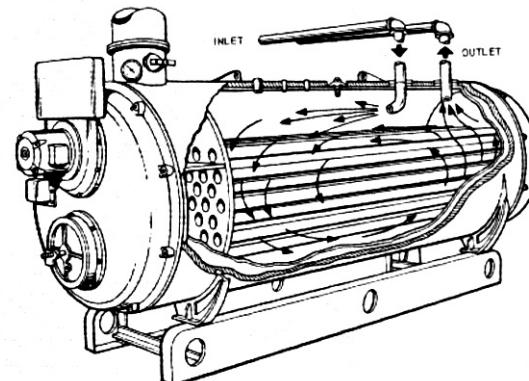
* Steel Boiler Institute.

† American Boiler Manufacturers Association.



Courtesy of Superior Combustion Industries Inc.

FIG. 65 – TYPICAL FIRE-TUBE HOT WATER BOILER



Courtesy of Cleaver Brooks Co.

FIG. 66 – INTERNAL FLOW PATTERN, HOT WATER BOILER

water the value of 150 Btu/hr may be used for a 20 F drop. However, the EDR unit is being replaced by the more universal Btu/hr rating.

Boiler Horsepower

A boiler horsepower (BHP) is defined as the evaporation of 34.5 lb of water per hour from a temperature of 212 F into dry saturated steam at the same temperature. This is equivalent to 33,475 Btu/hr or 139.5 sq ft of equivalent direct steam radiation or 223.1 sq ft of hot water radiation.

Actual Evaporation

The term most commonly used is actual evaporation, i.e. pounds of steam generated per hour (lb steam/hr) at the given steam temperature and pressure. This does not offer an accurate comparison between one unit and another since the heat transferred per pound of steam generated may vary widely, depending on steam pressure, temperature and feed-water temperature.

Percent of Rating

It has been customary to rate boilers on the basis of 10 square feet of heating surface per boiler horsepower. However, as boiler designs and firing methods have improved, boilers can now develop several times the capacity based on former methods of rating. The ratio of actual to nominal capacity has been stated as percent of rating. Although the term has become obsolete, it is still used occasionally with reference to standardized boilers of low capacity.

Corrections to Ratings

For elevations above 2000 feet, boiler ratings should be reduced at the rate of 4 percent for each 1000 feet above sea level unless the boiler mechanical draft fan capacity is adjusted accordingly.

Minimum required gas pressures for gas-fired boilers should be adjusted upward for altitudes above 700 feet. Correction factors should be obtained from the boiler manufacturer.

EFFICIENCY OF HEAT TRANSFER

The efficiency of a boiler is the ratio of the heat absorbed by water and steam to the heat (calorific value) in the fuel. In commercial practice, the combined efficiency of the boiler and furnace (including grate) is used. It is extremely difficult to determine the actual efficiency of a boiler alone, as distinguished from the efficiency of the combined apparatus.

Stack losses (sensible heat lost in flue gas) are almost always the most serious source of furnace inefficiency. A maximum stack temperature of 500-600 F is considered good practice by many engineers. Exit gas temperatures of 100-150 degrees above saturated steam temperatures are typical. *Figure 67* shows the typical performance of an oil-fired fire-tube boiler at a constant pressure.

DRAFT AND PRESSURE

The various items included in the pressure differential across the convection surface of a boiler are:

1. Friction due to flow across tubes.

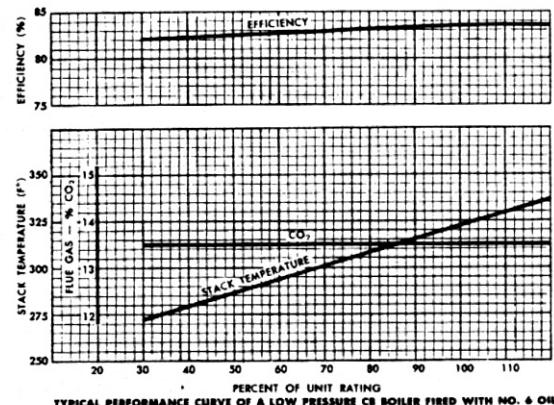


FIG. 67 – TYPICAL PERFORMANCE CURVES, OIL- FIRED FIRE- TUBE BOILER

2. Loss in head due to turns.
3. Friction due to flow thru or parallel to tubes.
4. Stack effect.

Turns in boiler passages are usually of the severest type in that they are generally 180 degrees and are very sharp.

Because of the great difference in the coefficient of heat transfer between cross and parallel flow, lower velocities are usually used for cross flow in order to obtain reasonable draft losses.

The flow of air thru the fuel bed and the products of combustion thru the boiler breeching and stack result in a pressure drop. In order to keep the gases moving at the rate required to maintain combustion, either mechanical or natural draft is required to overcome this pressure difference.

Mechanical draft implies the use of forced or induced draft fans whose characteristics and selection are similar to those in ventilating work, except for a heavier construction.

Natural draft is produced by chimneys or stacks which serve to discharge the gaseous combustion products at an elevation sufficiently high to avoid pollution of the immediate surroundings. Their selection involves the determination of (1) the amount of draft required, (2) the stack height needed to produce this draft, (3) the weight rate of flow of flue gases and (4) the stack section area necessary to accommodate this flow.

Chimneys produce a draft as a result of the difference in density between the column of hot gases inside and the air outside. The net useful draft is the difference between this theoretical static head and the resistance of the chimney itself due to gas flow.

Mechanical draft fans for packaged boilers are designed in accordance with the combustion requirements of the burner. Natural stack draft is not required with the packaged automatic boiler. Stack construction and maintenance costs are eliminated. Only a small vent is needed to carry flue gases outdoors.

FUELS

The principal fuels used for combustion in a boiler are coal, oil and gas; the choice of fuel is usually based on availability, dependability, cleanliness, economy, operating requirements and control.

AVAILABILITY

The unavailability of a particular type of fuel may preclude its use. Reasonably certain long term availability of a fuel and less likely interruption of supply in the event of any emergency should be considered.

Local codes may prohibit the use of certain types of a fuel.

DEPENDABILITY

Dependability may be measured in terms of quantity and quality.

An interruptable service rate to consumers of gas fuel is lower than the normal service rate but at the same time permits the gas company to interrupt the service during times of greatest demand, such as may occur under extreme weather conditions. To accept such an arrangement for gas service when available means that the fuel is not dependable as to quantity. However, if the firing equipment of the boiler is a combination gas-oil burner, oil can be used during short periods of interrupted service to provide an optimum arrangement.

It is desirable that the fuel used be of a consistent quality. A varying fuel quality can prevent optimum economy due to decreased efficiency and increased maintenance.

CLEANLINESS

General cleanliness is inherent in oil- and gas-fired boilers. However, there is an increasing demand by both government agencies and private industry for coal-fired packaged boilers. As a result over the past few years there has been a concentrated effort on the part of the coal-fired boiler and firing equipment designers to approach the cleanliness of the oil- and gas-fired equipment.

ECONOMY

Relative economy of various fuels does not depend on the heating value of the fuel itself as much as on the conditions attending its use. The final cost of steam or hot water which determines the most economical fuel depends on (1) charges for operation and maintenance, (2) cost of fuel, (3) charges for handling fuel, (4) cost of operation and maintenance of auxiliary equipment and (5) fixed charges for stand-by capacity. Item 1 is common to all fuels; items 2 to 5 vary with each fuel.

The average cost of burning coal in this country exclusive of fixed charges is about 5% of its cost; for fuel oil approximately 1.5% of the equivalent coal cost, and for natural gas 0.5%.

Storage and handling problems assume greater proportions with the solid fuels. They are essentially nonexistent with gas and are easily handled with oil. While a somewhat higher initial investment may be required for a coal-fired unit than for a gas- or oil-fired unit, other factors tend to have a balancing influence on a long term basis. In many areas coal offers a lower cost per Btu than other fuels delivered to the plant.

The advantages of fuel oil over coal are these:

1. Weight 30% less and space occupied 50% less than coal of equivalent heat content.
2. Freedom from spontaneous combustion.
3. Storage may be distant from furnace.
4. Fuel immediately available, stored or removed with practically no labor.
5. High combustion rates per cubic foot of combustion space.
6. Great flexibility in furnace to carry peak and valley loads readily and economically.
7. Low labor cost to handle oil at the furnace and to clean boiler tubes.
8. No labor for cleaning fires or removing ashes.
9. High efficiency and relatively no smoke.
10. Absence of wear on machinery due to ash and dust.
11. Low pressure drop thru the furnace.
12. Minimum of excess air required for complete combustion.

The advantages of gas over coal are these:

1. Burned in furnaces where the supply can be varied almost instantaneously between wide limits by manual or automatic control.
2. Complete combustion obtained with low excess air; flue losses low and operation smokeless.
3. Furnace can be maintained with an oxidizing or reducing atmosphere with ease and little reduction in efficiency.

- No storage facilities needed on the premises of the customer.

OPERATING REQUIREMENTS

With most coal and some gas boilers, when a fuel is burned continuously at a rate to match the load, the maximum load rarely occurs. For this reason poor efficiency can be tolerated at full load if the bulk of operation occurs at good efficiency. Conversely, boilers with intermittent oil or gas burners operating at maximum load at all times during the on cycle, should be selected for good efficiency at this load.

CONTROLS

Controls are a consideration in the choice of a fuel. For equivalent control, coal-fired boiler control is more complicated and expensive than that for oil or gas. Similarly, control for oil is more complex and costly than that for gas.

BOILER SELECTION

Factors which exert the greatest influence on the selection of boilers are fuel characteristics, capacity and steam conditions, space conditions, cost and individual preference.

FUEL CHARACTERISTICS

Prior to a preliminary selection of equipment, complete information should be available concerning fuels on which boiler types and predicted performance are based. Numbers 5 and 6 fuel oil require preheating equipment before the boiler. It is also desirable to determine a secondary fuel supply for emergency use when the primary fuel supply is interrupted or when changes in price make the secondary fuel more economical.

Where possible, equipment selection should be such that secondary fuel performance is equivalent to that of the primary fuel. However, if any interruption in primary fuel supply is only temporary and if the price differential between primary and secondary fuels is fairly stable, it may be more economical to design for maximum efficiency with the primary fuel and to accept some compromise in performance and maintenance costs with the secondary fuel. Packaged boilers are currently offered for gas firing with oil standby. They operate with equal efficiency on oil or gas.

CAPACITY AND STEAM CONDITIONS

Capacity is one of the most important factors in determining the type of unit to be selected. There is a partial correlation between steam conditions and capacity. Maximum pressures and temperatures

seldom prove economical except in the higher capacity ranges. Limitations imposed by steam pressure and temperature are predominantly structural. They affect the weight of steel required, hence the cost; temperature affects the space required by the superheater and adaptability of the boiler to provide that space.

SPACE CONDITIONS

In an existing building both shape and volume of the space available have a marked effect on the capacity of the unit to be installed, type of firing, and possibly the range of fuels which can be fired at a given capacity.

COST

Caution should be exercised in the degree to which first cost is allowed to influence the equipment selected. A complete economic study should be made by considering the load factor of the installation, the cost of fuel, and the efficiency of the installation as a whole rather than the boiler equipment alone.

A small plant with an ample supply of low priced fuel and a seasonal load of a few months each year can justify standard boiler and natural draft. However, a plant with a load factor approaching 100% using a high priced fuel can readily justify an efficient fuel burning system, high steam pressure and temperature, and induced draft fans. The cost of the fuel burned during the life of such a unit may be many times the initial investment. Even a small advantage in reliability, efficiency or flexibility gives economic justification for the relatively small additional first cost necessary to provide the better unit.

INDIVIDUAL PREFERENCE

Individual preference should be considered if the plant personnel is familiar with the operation of a given type of equipment, or if the plant is designed for specific equipment and is unsuitable for other equipment without expensive changes. However the improvements in design and the higher efficiency or capacity that may be obtained within the same space at reduced cost for labor and maintenance should be overlooked.

LAYOUT

Considerations in the layout of a boiler installation are location, vent or chimney, air supply and water treatment.

Most boiler manufacturers publish information relating to the specific details of their boilers and the

requirements of auxiliary equipment used in connection with boiler plant design.

LOCATION

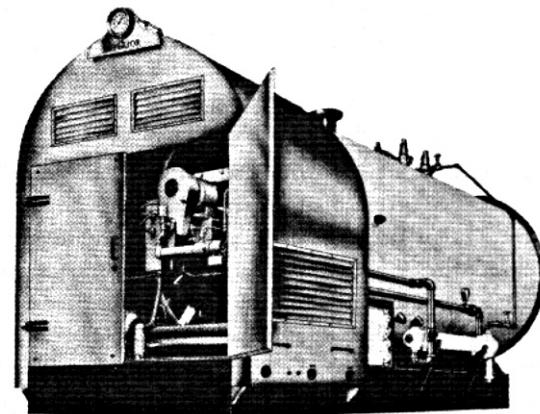
Boilers should be located at a central point with respect to the heat transfer equipment it serves and in a space provided with maximum natural light. For example, a gas fired boiler with mechanical draft located in a roof penthouse with the central station air conditioning equipment may prove economically attractive. The greater part of the piping normally required is that needed to supply gas to the boiler and interconnect the boiler and air conditioning equipment. Minimum gas pressure requirements at the boiler should be checked and compared with the available pressure. Oversized gas trains at the boiler may be used to reduce gas pressure requirements. Only a small vent is needed to carry flue gas from the boiler to the outdoors.

An adequately strong and level floor is required for the location of a packaged boiler. If the floor is not level, a concrete pad should be constructed. This also provides inspection accessibility to the piping beneath the boiler, and added height for washing down the area beneath the boiler. A boiler should not be installed on combustible floors unless so approved. Isolation of the boiler may be necessary in low sound ambient areas.

There should be adequate clearances around the boiler for access and service. Manufacturers should be consulted for recommended clearances. The space in front of the boiler should be sufficient for firing, stoking, ash removal, and cleaning or renewal of flue tubes. Space should be allowed on at least one side of every boiler for convenience of erection and for accessibility to the various dampers, cleanouts and accessories. Space at the rear of the boiler should be ample for vent or chimney connection and cleanouts. A service trench in the boiler room floor for fuel and miscellaneous piping is recommended for optimum room appearance. Boiler room height should be sufficient for the location of boiler accessories and for proper installation of piping. Room height varies directly with:

1. Height and size of boiler.
2. Steam header size and location.
3. Breeching size and location.
4. Local and insurance code requirements.

While more boilers are installed in boiler rooms completely protected from the elements, such housing is not entirely essential to their operation when built especially for permanent outdoor installation. To cover the vital working parts, a special housing called a "dog house" is available or is included in the design. While



Courtesy of Superior Combustion Industries Inc.

FIG. 68 – BOILER FOR OUTDOOR INSTALLATION

providing the required protection, this housing provides access to working parts. Figure 68 shows a packaged boiler for outdoor service.

VENT OR CHIMNEY

Natural stack draft is not required with mechanical draft packaged boilers. Only a small vent the size of the boiler vent outlet is needed to carry flue gases outdoors. On multiple boiler installations when building conditions permit, the simplest and most efficient method of venting the flue gas is the use of individual stacks. To minimize steel breeching and stack condensation, insulation is used to lower heat losses.

Stack heights in excess of 150 feet or extremely large breeching and stack combinations may cause excessive draft. A barometric damper located close to the stack in the breeching should be considered only after serious burner adjustment problems.

Considerations relating to a chimney for a natural draft boiler are these:

1. Recirculation effect decreases with chimney height and an increase in flue gas velocity.
2. Two or more chimneys (large or small) should be used separately, never connected.
3. Excessive height in a chimney does no harm but means are necessary for controlling the induced draft.

AIR SUPPLY

All rooms or spaces containing boilers should be provided with a constant supply of combustion (and ventilation) air at adequate static pressure to insure proper combustion in the fuel burners. The importance of providing proper combustion air should not be underestimated and a failure to do so may result in

erratic or even dangerous operating conditions for the equipment. Rules for providing air supply openings are found in technical standards, in state and municipal building codes, and in service and installation bulletins published by manufacturers of fuel burning equipment.

Approximately 1 cfm of combustion air per 4200 Btu/hr boiler gross output and 1 cfm of ventilation air per 17,000 Btu/hr boiler gross output should be provided for the boiler room for oil- or gas-fired boilers for altitudes up to 1000 feet. At higher elevations three percent more air per each 1000 feet should be provided if the boiler rating is not reduced.

WATER TREATMENT

If the boiler water is scale- or sediment-forming or corrosive, measures should be taken to correct this condition. Consult a water treatment specialist and make necessary piping arrangements to provide such treatment. Refer to *Part 5*.

Bottom blowdown helps remove impurities. A continuous blowoff system should be considered whenever the percentage of raw make-up water is 50% or more or when the raw water contains a high amount of impurities.

CHAPTER 4. MISCELLANEOUS DRIVES

This chapter presents practical information to guide the engineer in the application and layout of steam and gas turbines and gas and diesel engines used with air conditioning system.

These drives may replace electric motor drives when there is a lack of electric power or when there is an economic advantage. Gas may be used where utility companies offer favorable rates for off-season users. Steam may be available as waste from a high-pressure source.

Steam turbines are used for driving refrigeration machines (centrifugal or reciprocating), fans and pumps. Gas turbines, gas engines and diesel engines are usually used only for driving refrigeration machines.

STEAM TURBINE DRIVE

A steam turbine drive is usually chosen to improve a heat balance where exhaust or high pressure steam is available. When a centrifugal refrigeration machine, fan or pump is fitted into a heat balance, operating economies can be obtained.

TYPES OF STEAM TURBINES

Steam turbine drives are available as single stage and multi-stage.

Single Stage Turbine

In a single stage turbine steam expands from the initial to the final exhaust pressure in one nozzle or set of nozzles (all working at the same pressure), and the energy is absorbed in one or more rows of revolving blades.

Multi-Stage Turbine

In a multi-stage turbine the expansion of steam from the initial to the exhaust pressure is divided into two or more drops thru a series of sets of nozzles. Each set is followed by one or two rows of revolving blades which absorb the energy of each pressure drop.

A typical steam turbine is shown in *Fig. 69*.

APPLICATION

A steam turbine may be operated as a condensing or noncondensing (back pressure) turbine. When steam is not otherwise required for process heating or other

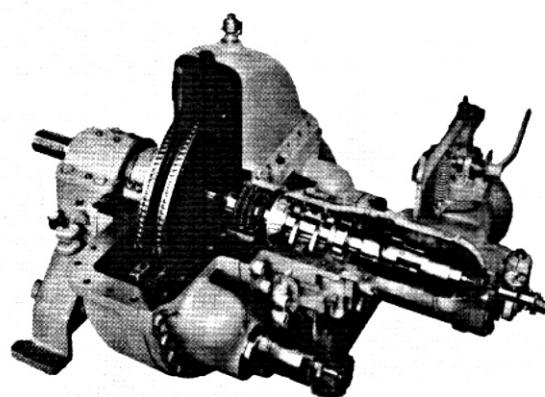
application, a condensing turbine drive produces power for the least amount of steam. All the steam used is chargeable to power costs. When steam is required for other applications, a noncondensing turbine provides power at the lowest cost because the exhaust steam from the turbine can be used for other applications.

Condensing Turbine

Condensing turbine drives may be used with either high or low pressure steam. This turbine is higher in first cost than a noncondensing unit because of the additional condensing equipment required.

High pressure condensing turbines are used to produce power with a minimum amount of steam when the exhaust steam cannot be utilized or to secure a maximum amount of power with limited boiler capacity.

Low pressure condensing turbines utilize exhaust steam from existing equipment, producing power from steam that would otherwise be wasted. They are often utilized in summer when available exhaust steam cannot be used for heating.



Courtesy of Elliott Co.

FIG. 69 – TYPICAL STEAM TURBINE

Noncondensing Turbine

Noncondensing turbine drives are particularly economical when the demand for process or heating steam is sufficient to utilize all of the turbine exhaust steam. Under such circumstances the turbine acts as a reducing valve and produces power at a very low cost. It is also used when very low cost steam is available and the exhaust from the turbine is wasted or when no condensing water is available.

STANDARDS AND CODES

Steam turbine application and installation should conform to all codes, laws and regulations applying at the job site.

TURBINE SELECTION

The system requirements influencing the selection of a steam turbine drive are type of driven equipment, governor, maximum horsepower and rpm, available turbine inlet steam pressure, superheat and design turbine exhaust pressure. When these requirements are known, the selection of a steam turbine drive usually involves the choice of the most inexpensive combination of frame size and stages with an acceptable steam rate.

The selection of a turbine having a horsepower rating 5% greater than the design horsepower required for the refrigeration machine is recommended for comfort cooling applications. A minimum 10% safety factor is recommended for industrial refrigeration applications at air conditioning temperature levels. These recommendations are based on a minimum scale factor of .0005 for both the cooler and condenser.

Multi-stage turbines are more efficient than single stage turbines and more expensive. However, for the same operating conditions the exhaust steam is of lower quality. For certain applications a lower quality exhaust steam may be undesirable.

STEAM RATE

An approximate turbine steam rate may be determined from this formula:

Approximate steam consumption (lb/hp/hr)

$$= \frac{\text{Theoretical steam rate (lb/hp/hr)}}{\text{approx. over-all efficiency}}$$

Theoretical steam rates and approximate over-all efficiencies may be obtained from *Table 11* and *Chart 3* respectively. Actual turbine efficiencies and steam rates should be obtained from the turbine manufacturer.

CONDENSER

A condenser is required to condense the exhaust steam from a condensing turbine. A shell-and-tube type is used with the steam condensed in the shell and condenser water from the refrigeration machine pumped thru the tubes.

Water required for condensing should be piped first thru the refrigeration condenser and then in series thru the steam condenser. This arrangement results in minimum piping, power requirements and steam consumption. A higher fouling factor than that used in the selection of the refrigeration machine condenser is recommended when selecting the steam condenser because the higher condensing temperature causes greater fouling.

CHART 3-APPROXIMATE OVER-ALL EFFICIENCIES OF STEAM TURBINES

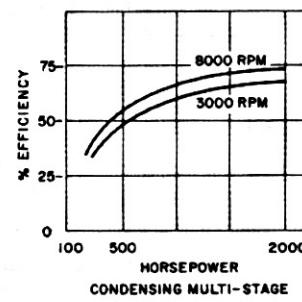
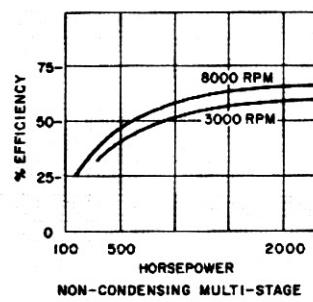
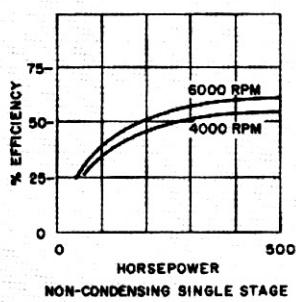


TABLE 11-TURBINE THEORETICAL STEAM RATE (lb/hp/hr)

EXHAUST PRESSURE		INITIAL PRESSURE (PSIG)														
		60			100			125			150			175		
		INITIAL SUPERHEAT (F)														
0	42.7	92.7	0	62.1	112.1	0	97.2	122.2	0	84.2	134.2	0	76.2	122.6		
Condensing	3.5 in. Hg abs.	10.4	10.1	9.8	9.3	9.0	8.7	8.9	8.4	8.2	8.6	8.1	7.9	8.3	7.9	7.7
	4.0 in. Hg abs.	10.7	10.4	10.1	9.5	9.2	8.9	9.1	8.6	8.4	8.8	8.3	8.0	8.5	8.1	7.8
	4.5 in. Hg abs.	11.0	10.7	10.4	9.8	9.4	9.1	9.3	8.7	8.6	9.0	8.5	8.2	8.7	8.3	8.0
Noncondensing	5 lb/sq in. gage	25.6	24.9	23.9	19.4	18.6	17.8	17.5	16.2	15.9	16.2	15.2	14.5	15.2	14.4	13.8
	10 lb/sq in. gage	30.5	29.6	28.2	22.0	21.0	20.1	19.5	18.1	17.7	17.9	16.7	16.0	16.7	15.7	15.1
	15 lb/sq in. gage	36.2	35.0	33.2	24.8	23.6	22.4	21.6	20.0	19.5	19.6	18.3	17.5	18.1	17.1	16.4

EXHAUST PRESSURE		INITIAL PRESSURE (PSIG)														
		200			250			300			400			600		
		INITIAL SUPERHEAT (F)														
0	62.2	137.2	0	94	169	0	78.3	153.3	0	101.9	201.9	86.2	186.2	261.2		
Condensing	3.5 in. Hg abs.	8.1	7.8	7.4	7.8	7.3	7.0	7.6	7.1	6.8	7.2	6.7	6.2	6.3	5.9	5.6
	4.0 in. Hg abs.	8.3	8.0	7.6	7.9	7.5	7.1	7.7	7.3	6.9	7.3	6.8	6.4	6.4	6.0	5.7
	4.5 in. Hg abs.	8.5	8.1	7.7	8.1	7.6	7.2	7.8	7.4	7.0	7.5	6.9	6.5	6.5	6.1	5.8
Noncondensing	5 lb/sq in. gage	14.4	13.7	12.9	13.3	12.3	11.6	12.5	11.7	11.0	11.5	10.5	9.7	9.5	8.8	8.2
	10 lb/sq in. gage	15.7	15.0	14.1	14.4	13.3	12.5	13.5	12.6	11.9	12.2	11.2	10.3	10.0	9.2	8.7
	15 lb/sq in. gage	17.0	16.2	15.2	15.4	14.3	13.4	14.4	13.5	12.6	13.0	11.9	10.9	10.6	9.7	9.1

$$\text{Theoretical steam rate (lb/hp/hr)} = \frac{2544.1}{h_1 - h_2}$$

where:

h_1 = enthalpy of initial steam (Btu/lb)

h_2 = enthalpy of exhaust steam at the entropy of the initial steam (Btu/lb)

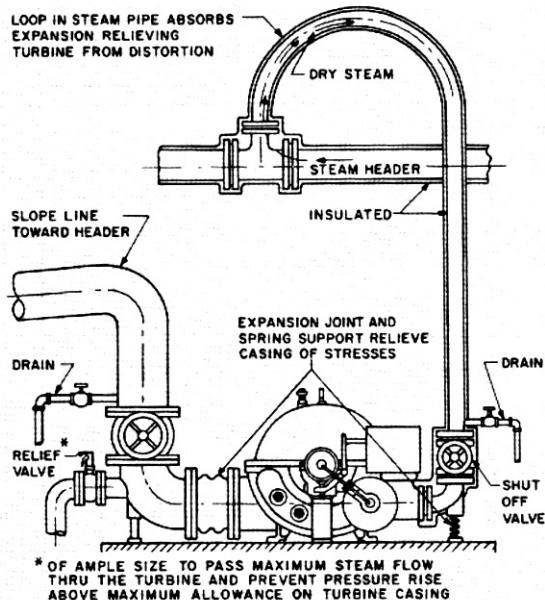


FIG. 70 – RECOMMENDED STEAM AND EXHAUST PIPING ARRANGEMENT

The condenser water rise in the steam condenser may be determined from this formula:

$$\text{Rise} = \frac{\text{Btu/hr}}{500 \times \text{gpm}}$$

where:

Btu/hr = turbine steam rate (lb/bhp/hr)
 X centrifugal bhp X 950
 gpm = condenser water flow

PIPING DESIGN

No part of the turbine installation is more important for successful operation than well-designed, installed piping.

Steam Piping

There are two objectives for good piping:

1. Prevent the heated piping from imposing strains on the turbine casing, thus affecting alignment.
2. Connect and drain the turbine inlet and exhaust lines so that dry steam is furnished to the turbine and water accumulation in these lines is prevented.

A shutoff valve is recommended in the steam line (preferably at a convenient accessible location in the turbine room) between the steam header and the

turbine inlet to allow service on the turbine without shutting down the boiler.

The turbine casing must be protected from piping weight or expansion strains. Piping weight should be carried separately by suitable supports. Expansion joints or bends should be provided adjacent to the turbine connections. Connections between piping and turbine should be made without forcing the pipe line in any direction in order to make a satisfactory joint. Figure 70 illustrates the recommended steam and exhaust piping arrangement.

A receiver type separator with ample drains should be provided ahead of the shutoff valve in the steam supply to prevent slugs of water from damaging the turbine. When a separator is not provided, a blow-off valve or continuous drain should be connected to the lowest point of the steam inlet piping. It is imperative that feed water treatment and boiler operation be carefully controlled to insure a supply of clean steam at all times.

Piping must be designed in accordance with the turbine-exhaust hand selected. Figure 71 shows the available hand for single and multi-stage turbines.

Miscellaneous Piping

Properly planned miscellaneous piping gives a workmanlike appearance to an installation. Drain lines should be grouped and brought to a common drain arrangement. All open drain connections should be brought into a common closed collector box with a glass window for visual checking by the operator. Water cooling connections should be connected to a water supply at a maximum of 85 F. Figure 72 shows the miscellaneous piping connections to a typical single stage turbine.

INSULATION

All heated surfaces of steam turbines such as casings and chests, connections, flanges and valves should be insulated to prevent heat loss and condensation in the turbine. Wet steam results in power losses, unnecessary wear, and possible damage to the turbine. To protect the insulation, metal lagging is fitted closely over the surfaces of the insulation. Insulation and jacketing can normally be provided by the turbine manufacturer.

CONTROLS

The function of the controls is to adjust the horsepower output of the drive to the horsepower requirement of the load. The speed of the turbine must also be controlled either at a constant speed or variable speed depending on the load requirements.

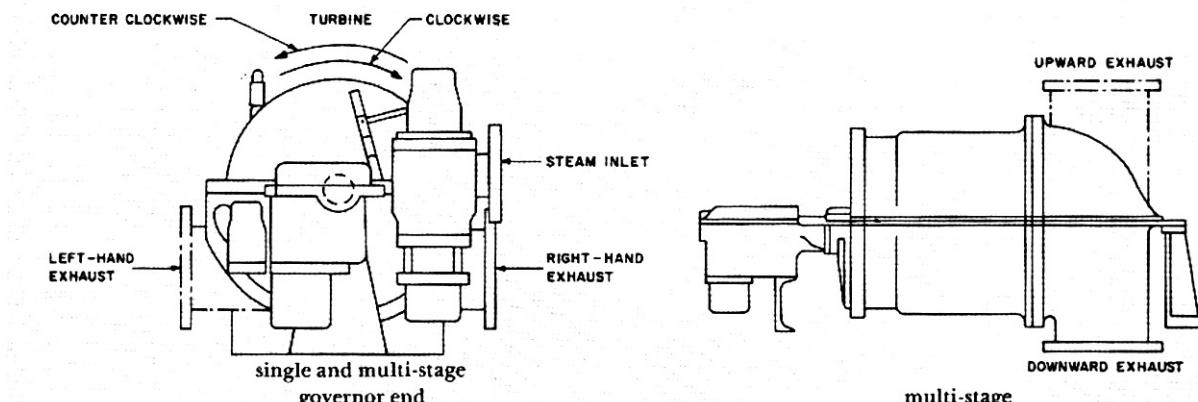


FIG. 71 – TURBINE EXHAUST HAND AND ROTATION

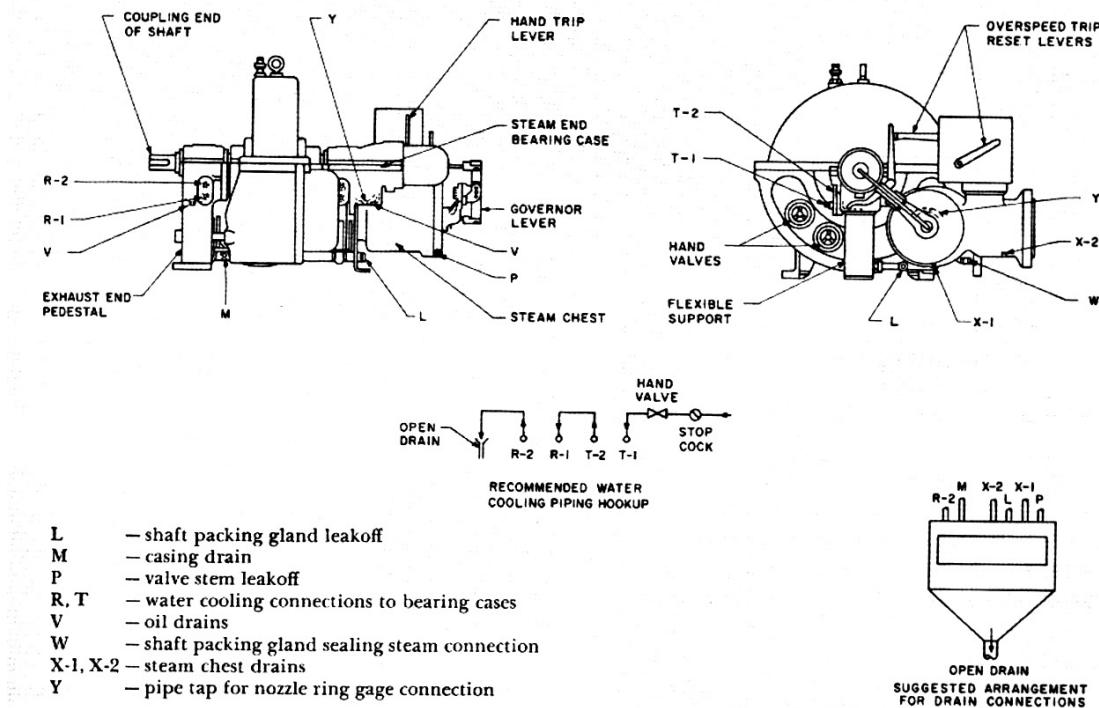


FIG. 72 – MISCELLANEOUS PIPING CONNECTIONS, TYPICAL SINGLE TURBINE

GOVERNOR

A speed governor must be employed to maintain or vary the speed. They are of two basic types, mechanical (fly-ball) or hydraulic (oil pump). This classification indicates the type of speed sensitive element. Each may be either direct acting or controlled by a relay to indicate the means of speed control.

The turbine manufacturer should recommend the type of governor for specific conditions. In general, a direct acting hydraulic governor is used for a constant or variable speed drive. However, above approximately a 5-inch governor valve size or for speeds in excess of 7000 rpm, an oil relay hydraulic governor is used.

A 35% speed reduction from design rpm covers the capacity range of a centrifugal refrigeration machine. A smaller reduction is no particular advantage. Maximum speed of the turbine must not exceed the compressor nominal speed by more than 15%

GAS TURBINE DRIVE APPLICATION

A gas turbine drive may be used to power a centrifugal refrigeration machine, and/or the exhaust from the gas turbine can be used to make steam in a waste heat boiler to operate an absorption machine or a steam-driven centrifugal machine.

Gas turbines are usually available in the large horsepower sizes used by centrifugal refrigeration equipment rather than the smaller sizes required by reciprocating equipment.

DESCRIPTION

The gas turbine cycle (Fig. 73) consists of a compressor section where ambient air is compressed to approximately 60 psia at about 350 F. This compressed air passes into the combustion chamber where it is heated to 1350-1500 F by burning fuel directly in the air stream. From the combustion section the air and combustion products flow into the expansion turbine section where they expand to atmospheric pressure. The energy extracted from the gas stream in the expansion process is used to drive the compressor and produce the power for the output shaft.

A split-shaft arrangement is usually used for refrigeration compressor drives. This arrangement divides the expansion turbine into two sections. The first section or high pressure turbine expands the gas to an intermediate pressure and drives the air compressor; the second section or low pressure turbine drives the power output shaft.

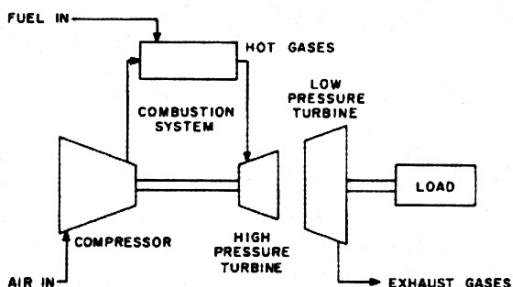


FIG. 73 – SPLIT-SHAFT GAS TURBINE CYCLE

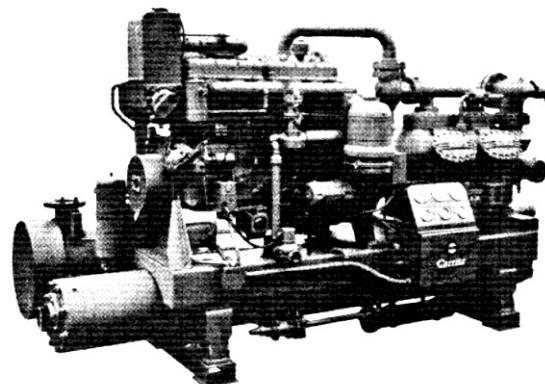


FIG. 74 – GAS ENGINE DRIVEN RECIPROCATING WATER CHILLER

STARTING

The gas turbine may be started by an electric motor, air turbine, steam turbine or gasoline engine depending on the means available. The starter is normally disconnected after the turbine is operating.

AIR INTAKE

Provision must be made to supply combustion air to the gas turbine: This amount approximates 15 cfm/bhp. The air should be filtered before entering the compressor.

LUBRICATION

Lubrication is generally supplied by a pump driven from the main drive shaft during normal running. During startup or shutdown lubrication is supplied by a motor-driven auxiliary pump.

GOVERNOR

A hydraulic governor is usually used to position the fuel control valve to maintain speed as the load changes.

SAFETY CONTROLS

Safety controls are provided to shut down the unit for the following causes:

1. Low oil pressure
2. Overspeeding of the unit
3. Low fuel pressure
4. High bearing temperature
5. Loss of flame

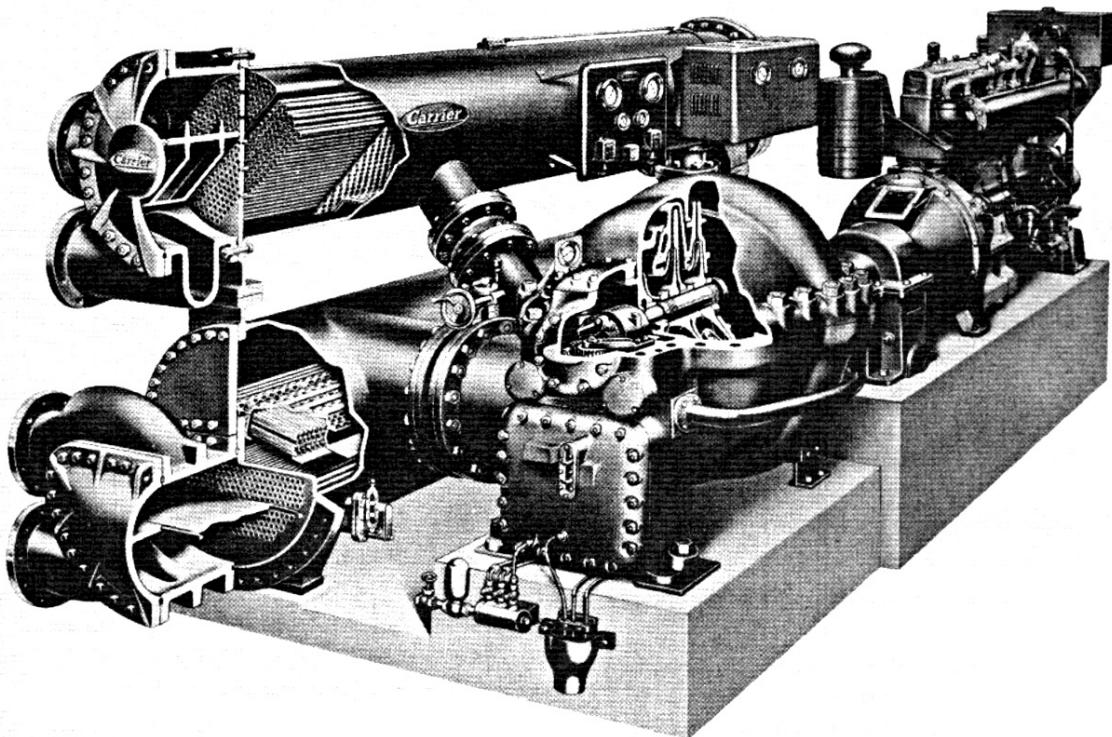


FIG. 75 – GAS ENGINE DRIVEN CENTRIFUGAL REFRIGERATION MACHINE

GAS ENGINE DRIVE APPLICATION

A gas engine drive may be used when gas is available at a cost which provides a saving in owning and operating costs. Gas engines are used to provide power to drive reciprocating (Fig. 74) or centrifugal refrigeration machines (Fig. 7) and may also indirectly supply steam to operate an absorption refrigeration machine by using the heat rejected from the engine cooling system and exhaust system.

STANDARDS AND CODES

Gas engines should be installed to conform to all codes, standards and regulations concerning internal combustion engines.

SELECTION

Gas engines used for driving refrigeration equipment should be selected for continuous duty service. This means that the unit should be selected to operate at 80% of the maximum corrected horsepower. Thus, if a compressor requires 100 bhp, the gas engine is selected

for 100/80 or 125 maximum rate horsepower. The reduced output and lower speeds are a major consideration in attaining a longer engine life.

ATMOSPHERIC CORRECTIONS

The maximum rated horsepower of a gas engine is given for an air temperature of 60 F and an air pressure of 29.92 in. Hg (sea level average).

Deduct 1% from the maximum rated horsepower for every 10 degree increase in ambient temperature above 60 F. For every 1000 feet in elevation above sea level, deduct 3% from the maximum rated horsepower.

HEAT REJECTION

The heat rejection of a gas engine to the water jacket circuit is approximately 50-60 Btu/hp/min. This represents about 30% of the input to the engine. Another 30% of the input is given up to the exhaust system, and about 10% is given up as radiation losses.

COOLING SYSTEMS

Any type of cooling system must meet the following

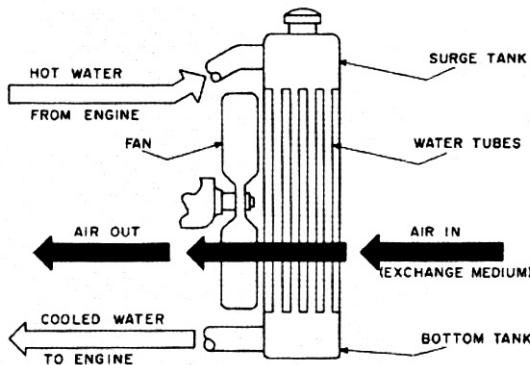


FIG. 76 – FAN AND RADIATOR COOLING

requirements for satisfactory engine operation:

1. Ample flow of water.
2. Minimum temperature differential between inlet and outlet.
3. Jacket temperature high enough to prevent condensation inside the case.
4. Jacket temperature low enough to prevent steam formation.
5. Soft water to prevent scale formation.
6. Clean water to prevent clogging of the engine jacket passages.
7. Positive pressure on the entire system to prevent entry of air.

Fan and Radiator

This system depends on cooling the engine jacket water by an engine-driven fan creating a flow of air over a finned tube radiator to dissipate the heat to the atmosphere (Fig. 76).

The advantage of this system is that it is self-contained, and does not depend on external water sources.

Ductwork must be provided for discharge of the hot air and openings provided for the entry of cool air. An extra 10-30 hp must be supplied by the engine to power the fan. The jacket water is pumped to the radiator by a pump driven by the engine.

Shell-and-Tube Heat Exchanger

This system uses a heat exchanger to cool the jacket water with a separate water source which may be wasted or cooled in a cooling tower (Fig. 77). When the engine is applied to a refrigeration machine, the same water used for condensing the refrigerant can be used to cool the jacket water. The condenser and heat exchanger are generally connected in parallel.

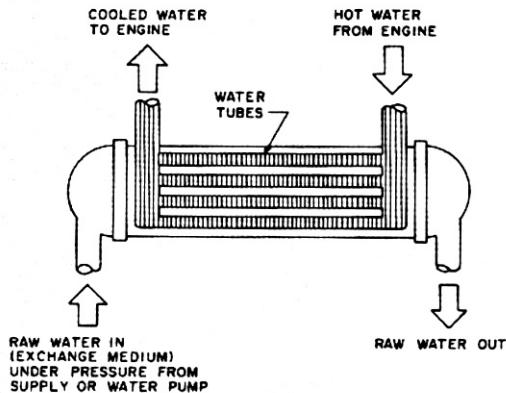


FIG. 77 – SHELL-AND-TUBE COOLING

The water temperature range for jacket cooling is recommended to be 10 to 12 degrees with an inlet temperature of approximately 180 F.

Another method of jacket cooling is called ebullition cooling which is actually a boiling of the jacket water (Fig. 78). The jacket is kept completely filled with water which circulates because of differences in temperature. The jacket water temperatures are in the boiling range. The concept of this cooling is that a large amount of heat can be picked up at the surface of the metal without increasing the engine temperature because 970 Btu are required to evaporate one pound of water at 14.7 psia. The engine heat is removed in the form of steam which is passed into a separator where the water is removed and any entrained solids are allowed to settle. The steam

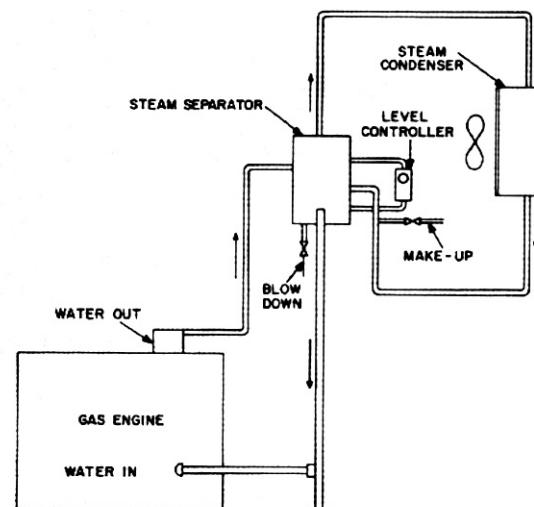


FIG. 78 – EBULLIENT COOLING SYSTEMS

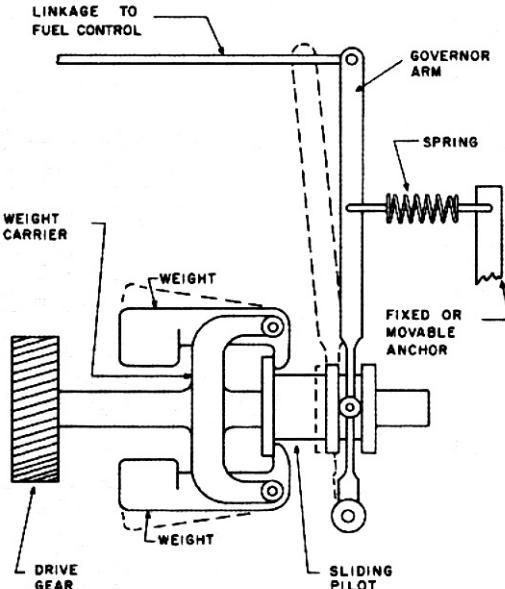


FIG. 79 – SCHEMATIC OF CENTRIFUGAL GOVERNOR

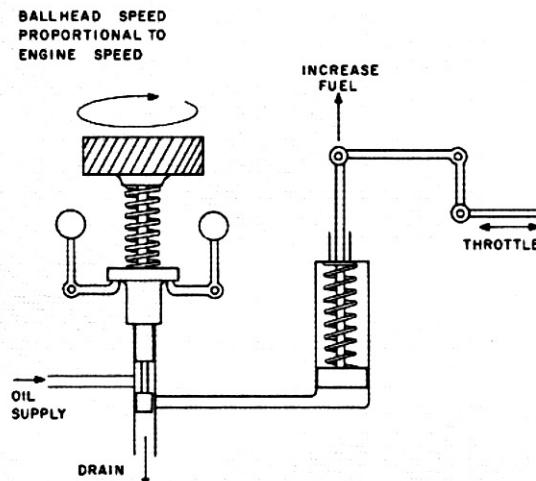
passes on to a steam condenser or some other equipment. The condensate then returns to the separator and the engine.

AIR INTAKE SYSTEM

The gas engine requires two to five cubic feet of air per minute per horsepower for combustion. This is important because this amount of air may upset the heating and ventilation calculations of an air conditioned building. An intake should be located to provide the cleanest air possible with the least contaminants, especially flammable vapors, tank vents, or other explosive wastes because the natural induction of this material may cause a runaway engine.

EXHAUST SYSTEM

Provision must be made to dispose of the exhaust gases from the engine with a minimum of restriction or back pressure. Excessive back pressure causes a loss of power, poor fuel economy, excessive valve temperatures and jacket water overheating. The exhaust pipes should be independently supported to prevent strains on the engine manifolds. Exhaust pipes can get red hot when the unit is heavily loaded; thus expansion must be provided as well as provision for disposing of the radiant heat given off by the exhaust pipe. One method of removing the heat is to install sheet metal ductwork around the pipe with an inch or two of space between



SCHEMATIC OF HYDRAULIC GOVERNOR SHOWS WEIGHTS CONTROLLING VALVE WHICH IN TURN CONTROLS HYDRAULIC PRESSURE. THEORETICAL GOVERNOR ABOVE IS NOT WORKABLE BECAUSE CORRECTIVE ACTION IS FASTER THAN THE ENGINES ABILITY TO RESPOND. THIS MAKES IT UNSTABLE.

FIG. 80 – SCHEMATIC OF HYDRAULIC GOVERNOR

them to create a chimney effect. Sometimes water-cooled exhaust piping is used for this purpose.

Attention should also be given to adequate silencing of the engine to prevent objectionable noise.

GOVERNOR

Governors are used for adjusting the power output of the unit to match the load and to maintain the speed. The governor measures the engine speed and provides power to move the throttle. The two main types are centrifugal governors (Fig. 79) and hydraulic governors (Fig. 80).

DIESEL ENGINE DRIVE

This drive is similar to the gas engine drive; the difference is the fuel used. The compression ratio of a diesel engine is greater than that of a gas engine; the engine may be either a four cycle or a two cycle.

Selection, type of cooling systems, exhaust systems, governors, etc., are identical to the gas engine drive.



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