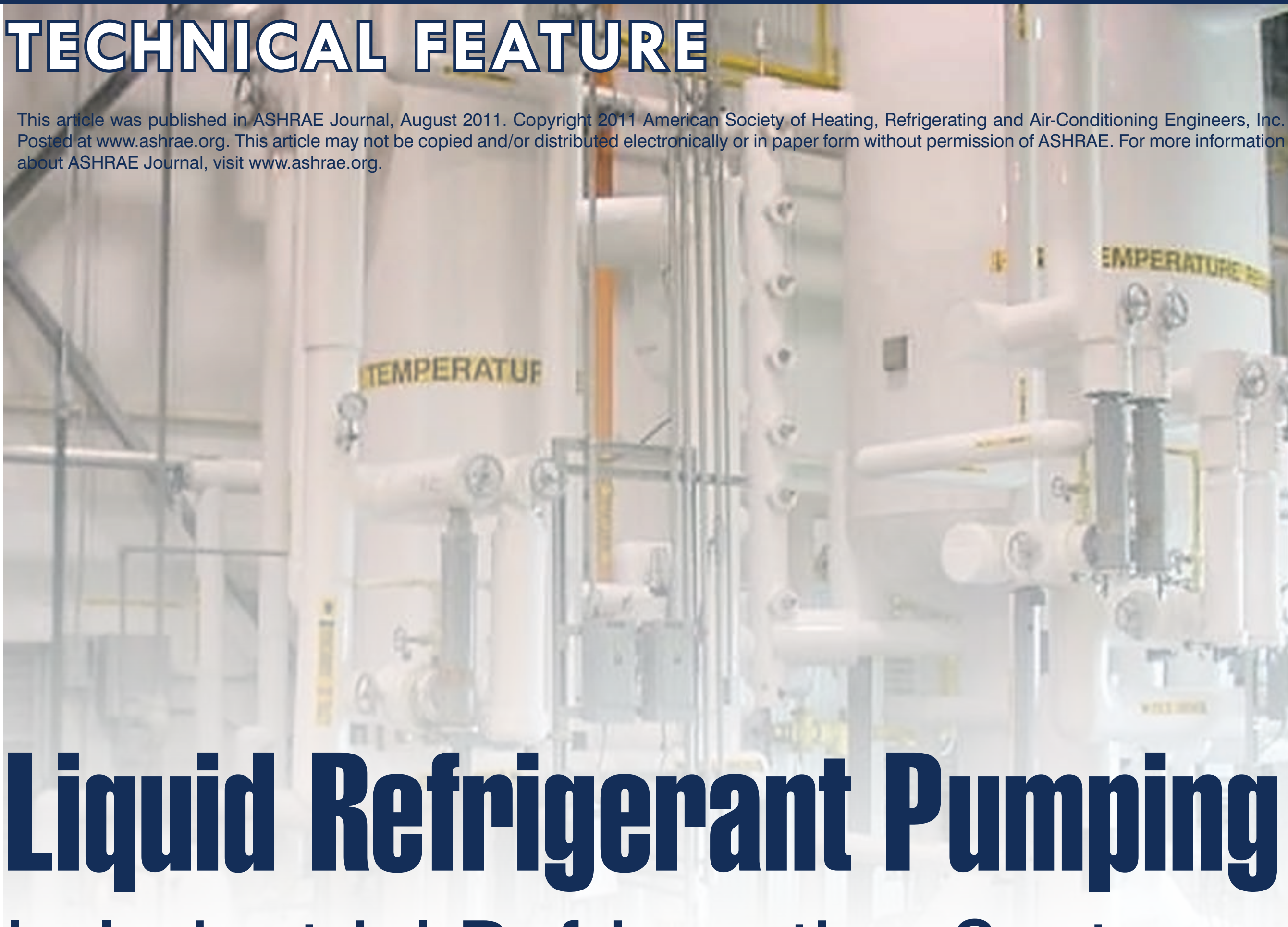


# Liquid Refrigerant Pumping

## In Industrial Refrigeration Systems

By **Todd B. Jekel, Ph.D., P.E.,** Member ASHRAE, and **Douglas T. Reindl, Ph.D., P.E.,** Fellow ASHRAE

Early practitioners of industrial refrigeration systems found they could increase the capacity of evaporators by supplying excess liquid refrigerant to the unit (overfeeding). In evaporators configured to operate with overfeed, the quantity of liquid refrigerant supplied is greater than the minimum amount required to meet the cooling loads as it undergoes the phase change from liquid to vapor. In this case, a mixture of low temperature liquid and vapor leaves the evaporator and returns to a vessel designed to separate the liquid from the vapor prior to the vapor being recompressed.

Within limits, the cooling capacity of an overfed evaporator increases due to the tendency for more of the evaporator's interior surfaces being wetted with saturated liquid refrigerant.[1,2] *Figure 1* shows a simple liquid overfed system typical of those designed and used today for large built-up industrial refrigeration systems.

In a mechanically pumped overfeed system, a centrifugal pump draws low temperature saturated liquid refrigerant from a vessel referred to as a "pumped recirculator," "pumped accumulator," "recirculator," or "low-pressure receiver" and raises the pressure of the liquid for delivery to one or more evaporators having a common refrigerant temperature requirement. Once pressurized by the pump, the saturated liquid becomes subcooled as it leaves the pump discharge and enters the "recirculated liquid supply line." As individual evaporators call for cooling, local controls simply open a liquid feed solenoid valve, which allows low temperature pressurized liquid from the liquid supply line to flow into the evaporator. Manually adjustable hand-expansion (i.e., metering) valves are used at each evaporator as a means of balancing the supply of

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liquid flow to individual evaporators throughout the system. The hand-expansion valves are adjusted to achieve appropriate liquid overfeed rates as-required for given evaporator designs.

Leaving each unit will be a mixture of saturated vapor produced by absorbing heat from the refrigeration loads and saturated liquid that was overfed. The two-phase mixture is carried back to the same pumped recirculator vessel through the "recirculated liquid return" or "wet suction return." The recirculator vessel separates overfed liquid from vapor and liquid falls to the bottom of the vessel to be pumped back out to the evaporators while the saturated vapor is directed to the compressors through the "dry suction" line. Liquid is made up to the recirculator vessel from a high pressure part of the system to replace the liquid that is evaporated to meet the refrigeration loads; the recirculator vessel separates the flash gas formed as a result of this throttling process just as it separates the two-phase mixture returning from the evaporators.

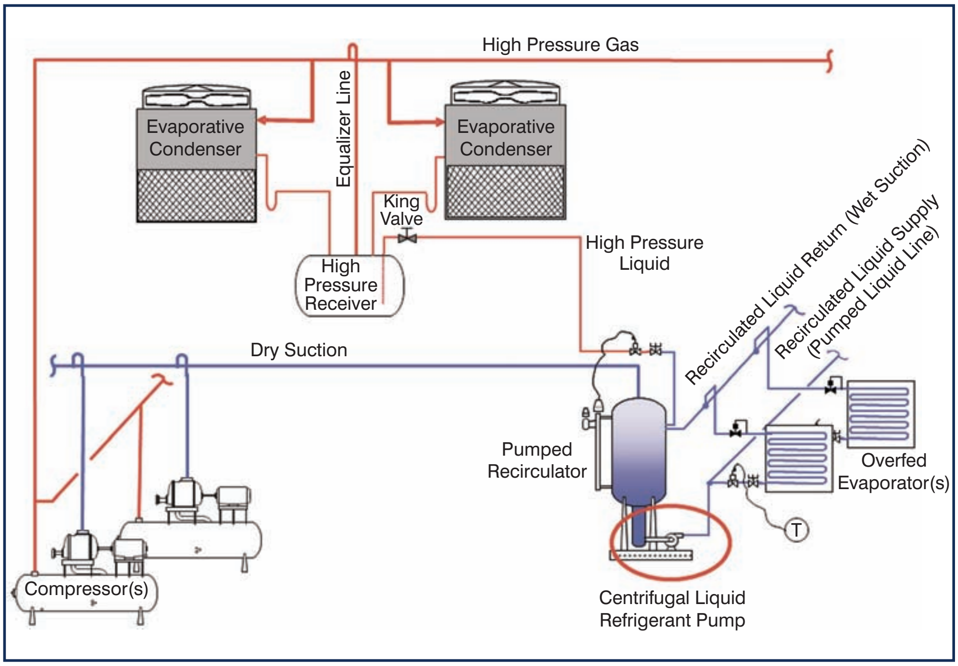


**Figure 1:** Mechanically pumped liquid overfeed system arrangement.

### How Much Liquid Refrigerant Needs to Circulate?

For industrial refrigeration systems using ammonia as the refrigerant, the flow rate of liquid refrigerant delivered by the pump to connected evaporators is relatively low due to the refrigerant's high heat of vaporization. The total pump flow rate will depend on the minimum mass flow rate required to meet the aggregate capacity of connected evaporators and the recommended overfeed rate for the evaporators. The minimum mass flow rate of liquid required to meet the aggregate refrigeration load is given by:

$$\dot{m}_{refrigerant,\,min} = \frac{Q_{load,total}}{h_{fg}} \tag{1}$$

where $\dot{m}_{refrigerant,min}$ is the minimum liquid refrigerant that must be supplied to all connected evaporators to meet their aggregate load in lb/min (kg/s), $Q_{load,total}$ is the aggregate refrigeration load in Btu/min (kW), and $h_{fg}$ is the enthalpy of vaporization for the refrigerant at the operating pressure of that suction level in Btu/lb (kJ/kg). The overfeed rate (*OR*) is the ratio of liquid mass flow rate to vapor mass flow rate leaving the evaporator:[1]

$$OR = \left(\frac{\dot{m}_{liquid}}{\dot{m}_{vapor}}\right)_{wet\ return} \tag{2}$$

where $\dot{m}_{liquid}$ is the mass flow rate of liquid-phase refrigerant leaving the evaporator in lb/min [kg/s] and $\dot{m}_{vapor}$ is the mass flow rate of vapor-phase refrigerant leaving the evaporator in lb/min [kg/s].

The total liquid refrigerant mass flow rate the pump needs to deliver is then:

$$\dot{m}_{refrigerant,\,pumped} = \dot{m}_{refrigerant,\,min}\left(OR+1\right) \tag{3}$$

where $\dot{m}_{refrigerant,pumped}$ represents the mass flow rate of liquid refrigerant the pump must supply to the connected overfeed evaporators expressed in lb/min (kg/s). The term (*OR*+1) is commonly referred to as the *circulating rate*, $N_r$. The circulating rate represents the mass ratio of liquid pumped to the evaporators to the amount of vaporized liquid in the evaporators.[1] *Table 1* shows the required recirculating liquid flow rate expressed in gallons per minute of liquid flow for each ton of refrigeration load over a range of saturation temperatures and circulating rates (*OR+1*).

*What overfeed rate is required for an individual evaporator?* Evaporator manufacturers typically publish recommended overfeed rates based on the unit's specific design. Deviating significantly from the manufacturer's recommended overfeed rate can lead to lower operating capacity of the evaporator. Too low of a refrigerant flow rate will starve the unit but excessive liquid supply will cause the evaporator to brine. Excessive supply of liquid refrigerant flow also increases the likelihood of pump cavitation. Finally, excessive overfeeding of liquid to evaporators increases the difficulty associated with returning the unused liquid to the recirculator when the return path involves a vertical riser. In this case, there is an increased tendency for liquid to accumulate or log up in evaporators.

## Anatomy of a Centrifugal Pump

At a fundamental level, the centrifugal pump used for circulating refrigerants is similar to the centrifugal pump used to move water or other secondary fluids. *Figure 2* shows a single-stage centrifugal pump common for moving liquids. The main feature of a centrifugal pump is the impeller, which rotates within the pump casing creating a low pressure zone near its center (the eye). This area of low pressure draws liquid into the pump where the rotating impeller increases the kinetic energy of the fluid by accelerating the liquid outward radially to the impeller tips. As the liquid leaves the impeller tips, its kinetic energy is at a maximum. The pump housing or volute surrounding the impeller then takes over to orderly collect the liquid leaving the impeller. The process of "gathering" liquid in the volute converts the kinetic energy of the fluid to pressure (potential) energy. The higher pressure fluid then leaves the pump through the discharge line.

Because a refrigerant pump is moving a volatile fluid, it is highly susceptible to cavitation during operation (see *What is Cavitation?* sidebar). To reduce the likelihood of cavitation, liquid refrigerant pumps include design details that differ from ordinary water or secondary fluid pumps to decrease the pressure loss through the pump suction.

| Circulating Rate | Recirculated Liquid Flow Rate (gpm/ton) — Liquid Saturation Temperature (°F) | | | | | |
|---|---|---|---|---|---|---|
| | –60 | –40 | –20 | 0 | 20 | 40 |
| 2:1 | 0.1117 | 0.1164 | 0.1216 | 0.1274 | 0.1340 | 0.1415 |
| 3:1 | 0.1676 | 0.1746 | 0.1824 | 0.1911 | 0.2009 | 0.2122 |
| 4:1 | 0.2235 | 0.2328 | 0.2431 | 0.2548 | 0.2679 | 0.2829 |
| 5:1 | 0.2793 | 0.2910 | 0.3039 | 0.3185 | 0.3349 | 0.3537 |

Multiply by 0.0646 to convert table values to $m^3/h$ per $kW_T$.

**Table 1:** Recirculated gallons per minute per ton of refrigeration.

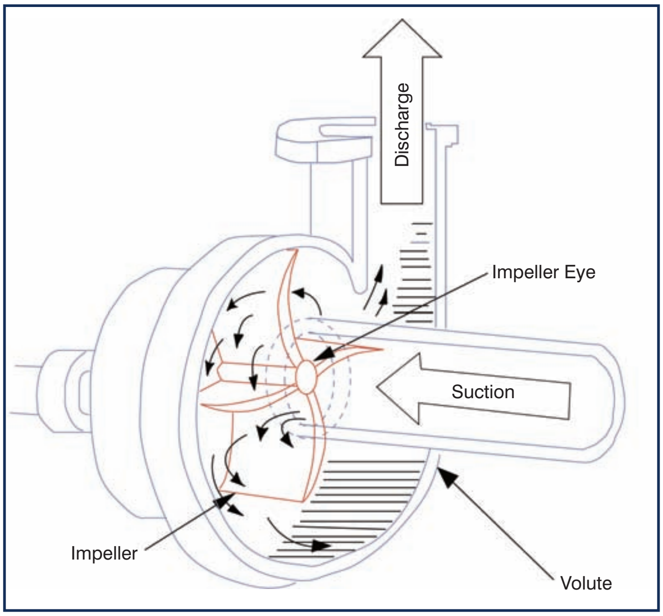


**Figure 2:** Single-stage centrifugal pump.[3]

## Liquid Refrigerant Pumps

Before discussing the operating details of centrifugal refrigerant pumps, it is important to consider a few concepts fundamental to their successful operation. One of the most important concepts is net positive suction head (NPSH). Quite simply, "suction head" represents the pressure at the pump's suction. The term "net positive" is intended to account for the balance of positive pressures (static, i.e., height, and absolute pressure above the vapor pressure of the fluid) and negative pressures (losses) attributable to fluid flow. Effectively, NPSH is the difference in pressure of refrigerant at the pump suction and the refrigerant's saturation pressure. An NPSH of 0 for a pump attempting to move a volatile liquid refrigerant indicates that the liquid will flash to a vapor state as it moves into the pump.

Two types of NPSH that need to be considered to ensure proper pump operation: net positive suction head *required* or $NPSH_r$ and net positive suction head *available* or $NPSH_a$. $NPSH_r$ is the minimum net positive suction head required to prevent the liquid refrigerant from flashing to a vapor. It is a characteristic of each given pump and varies with the pump's operating point (head and flow) as provided by the pump manufacturer.

$NPSH_a$ is the *available* net head at the pump suction accounting for those factors that effectively increase head (static head to the liquid elevation ahead of the pump suction, subcooling of liquid refrigerant within the vessel) and decrease head (frictional losses, heat gains, and form losses). To prevent pump cavitation, the NPSH *available* to the pump must be *greater* than the minimum *required* by the pump.

$$NPSH_a > NPSH_r \tag{4}$$

If a refrigerant pump is cavitating, several options can remedy the situation. First, determine the pump impeller diameter from original equipment installation documentation or from the data tag on the pump. Next, read the pressure on the discharge side of the pump during operation and compare with the vessel's pressure to determine that the pump is developing a pressure rise and note the magnitude (estimated by difference between the gauge reading and the vessel pressure). Then obtain the pump curve for that specific model pump and impeller diameter (see the next section).

With this information, look at the manufacturer's pump curve and determine the pump's flow rate and the required net positive suction head ($NPSH_r$) corresponding to that operating point on the pump curve. If the pump is cavitating due to operating "out on the curve" (toward the right side of the pump curve), one approach to cure this cavitation is to

## What Is Cavitation?

Cavitation is the formation of vapor bubbles within a pump followed by their rapid collapse. The formation and collapse of vapor bubbles produces a distinct audible signature that sounds as if the pump is circulating gravel.

Although cavitation can occur in the process of pumping any liquid, refrigerant pumps are more susceptible to cavitation because fluid being pumped is at or near saturation conditions (i.e., its boiling point). When cavitation occurs, the pump loses its ability to consistently move liquid and to develop pressure lift. The loss of pump capacity (flow) can starve evaporators leading to a loss of refrigeration capacity. The action of vapor bubbles collapsing in the pump causes erosion of the pump impeller with subsequent degradation of pump capacity and efficiency. For semi-hermetic pumps, the reduction in refrigerant flow can result in a reduction of electric motor cooling leading to premature motor failure.

Preventing cavitation requires keeping the pressure of the liquid refrigerant above the saturation pressure corresponding to the refrigerant's temperature as it enters the pump. This is accomplished by ensuring the refrigerant being pumped has adequate net positive suction head (NPSH).

reduce down (close) the hand-expansion valves on the liquid overfed evaporators being served by the pump. Adjusting down on, or more, hand-expansion valves will increase the discharge head on the pump; thereby, decreasing its flow rate and the corresponding $NPSH_r$. This process should focus on the largest evaporators first since they have the greatest impact on liquid demand. If cavitation-free pump operation cannot be achieved by this approach and the recirculator is equipped with a capacitance probe for liquid level sensing/control, it may be possible to raise the vessel's liquid operating level to increase the available net positive suction head ($NPSH_a$). However, raising the operating level will reduce the capacity of the recirculator vessel for surge (i.e., unexpected return of liquid) from the system. Another possible reason for pump cavitation is excess parasitic heat gain between the vessel and the pump suction. Visible frost on the suction piping, as shown in *Photo 1* is an indication of a loss of insulation integrity, which increases the heat gain to the refrigerant. To remedy this it will require reinsulating the pump suction piping.

### The Pump Curve

A pump curve is a compact, graphical representation of a pump's performance (*Figure 3*). Let's review the basics of reading a pump curve for a liquid refrigerant pump. In this case, we will consider an open-drive pump operating with ammonia (specific gravity of 0.7). The horizontal axis of the pump curve shows the pump's developed flow rate

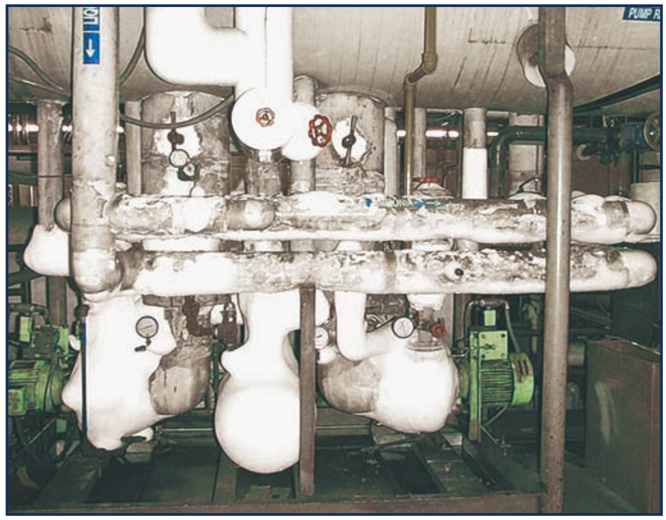

**Photo 1:** Liquid recirculator package showing excessive ice accumulation on insulation indicating the failure of the insulation system with corresponding increases in liquid refrigerant heat gain.

expressed in gal/min. The vertical axis of the pump curve shows the generated pump pressure differential (head) expressed in psi.

The lines that project horizontally from the vertical axis to the right sloping downward represents this model's pump performance with varying, but discrete, impeller diameters ranging from 8 in. (200 mm), the lowermost curve, to 10.375 in. (264 mm), the uppermost curve. The dashed lines that run on a diagonal from upper left to lower right represent the required pump power ranging from 1.5 to 5 hp (1.12 to 3.73 kW). The semicircular lines represent the pump efficiency range from 50% to 65%.

Below the upper portion of the plot (i.e., the pump curve) is an additional plot of the pump's NPSH requirement with a 10.375 in. (264 mm) impeller diameter operating with a discharge pressure of 23.7 psig (265 kPa) connected to an ammonia recirculator operating at a pressure of 8.8 in. Hg (–40°F [–40°C]). Since the system is operating in a vacuum, we must first determine the pressure developed by the pump. The saturation pressure in the recirculator vessel is 8.8 in. Hg (–40°F [–40°C]) or –4.3 psig; therefore, the total head or pressure developed by the pump is 28 psi (294 kPa). The flow delivered at that pressure differential (i.e., head) can be determined by drawing a horizontal line from the 28 psi (294 kPa) hash mark to the 10.375 in. (264 mm) diameter impeller pump curve (blue line). The intersection of this pressure with the pump curve represents the pump's operating point. Projecting a vertical line from the pump operating point down to the horizontal axis gives the flow delivered by the pump. In this case, the flow is 140 gpm (31.8 $m^3$/h). From this operating point, other operating characteristics of the pump can be obtained such as the pump efficiency (~64%) and operating power required (~4 hp [~3 kW]). The last piece of information is the $NPSH_r$, which is 2 ft (0.61 m) in this case.

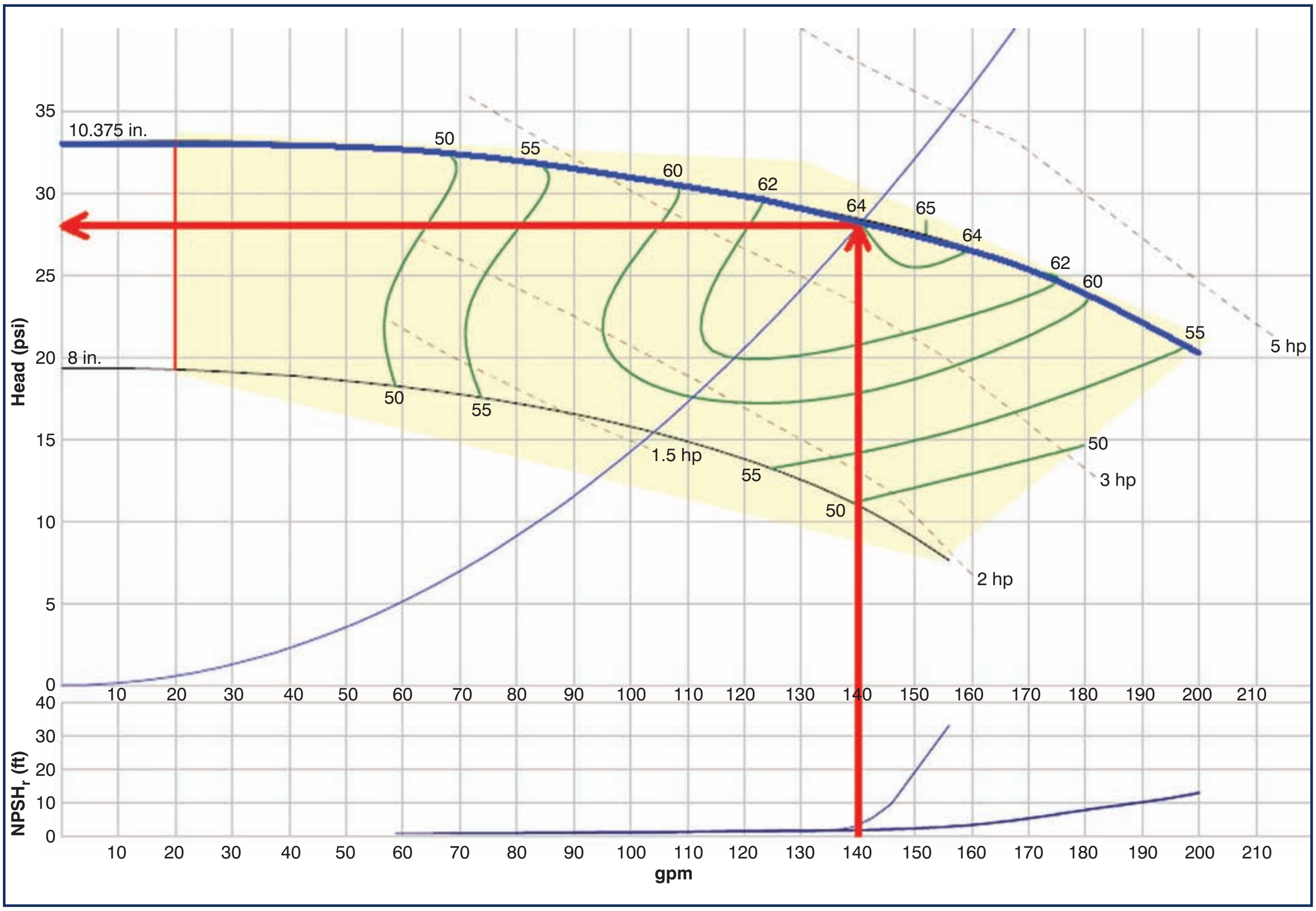


**Figure 3:** Pump curve for a liquid refrigerant pump.

## Other Considerations

**Minimum Flow Protection.** While operating, liquid refrigerant pumps always need to move some amount of liquid to avoid forming vapor within the pump due to heat addition from the inefficiency of the pump or motor (if it's a semi-hermetic configuration). The added heat at low flow conditions can also cause the liquid refrigerant in the pump to boil, leading to cavitation. To prevent this form of cavitation, a bypass (or "minimum flow") line from the pump discharge back to the pumped recirculator or recirculated liquid return is installed with an orifice (or metering valve) set at a manufacturer's required minimum flow. During normal operation, the heat gain from the pump power input is small, for the example we used earlier the heat gain would result in a temperature rise of 0.18°F (0.1°C).

**Presence of EPRs on Pump Discharge Pressure Requirement.** Pumping liquid to evaporators equipped with evaporator pressure regulators (EPRs) requires special attention. First, the liquid feed pressure at the evaporator, and thus the pump discharge pressure, must be higher than the EPR set pressure to get liquid into the evaporator. Second, it is important to realize that the pumped liquid refrigerant being supplied to an EPR-fitted evaporator is *subcooled* as it enters the evaporator. The liquid refrigerant entering the evaporator is essentially at the temperature of the liquid in the pumped recirculator (plus a slight temperature rise due to heat gain in the pump and in the liquid piping). Since the liquid refrigerant supply temperature is below the saturation temperature corresponding to the EPR pressure setting, the liquid refrigerant entering the evaporator has to absorb heat to sensibly raise the refrigerant temperature until it reaches its saturation temperature corresponding to the operating pressure prior to its boiling. Evaporators operating with liquid refrigerant supply temperatures more than 10°F (5.6°C) below saturation temperature will likely result in poor evaporator performance.

**Static Head Requirements in Open Loops (Why VFDs Are Not Great For Refrigerant Pumps).** Another issue with open loop pumping circuits is that the static head requirement sets the minimum discharge pressure to get flow to the evaporators. This means that before there is any flow to the evaporators, the pressure required to lift the liquid to the roof (or to the elevation of evaporators) must be overcome. If the pressure generated by the pump is not sufficient, the pump will operate at its minimum flow with a column of liquid standing in the riser supplying liquid refrigerant to the roof. In other words, the pump is not capable of delivering flow to the evaporators. This is the main reason that variable frequency drives (VFDs) are generally not suitable applications for refrigerant pumping in liquid overfeed applications. Note that a 50 ft (15.24 m) rise in an ammonia liquid line requires a pressure difference of approximately 15 psi (103 kPa) just to lift liquid to the roof.

**Hydrostatic Lock-Up.** Hydrostatic lock-up is the trapping of subcooled (or pressurized) liquid refrigerant in a fixed volume and exposing that trapped volume to a heat source. As the trapped liquid absorbs heat, it causes an increase in temperature, which causes the trapped liquid to volumetrically expand leading to a substantial increase in refrigerant pressure and an increased likelihood of component or equipment failure. It is important to identify locations within a refrigeration system that can trap liquid and provide suitable means of overpressure protection. ASHRAE Standard 15-2010, *Safety Standard for Refrigerating Systems*, provides requirements for protection from hydrostatic lock-up. The liquid feed valve train on an overfed evaporator is a location where hydrostatic lock-up is only a danger during maintenance procedures; therefore, can be effectively managed with proper procedures and employee training. However, the liquid supply piping between the pump discharge check valve and the liquid feed solenoids on the evaporators must be protected from hydrostatic lock-up in the event of a plant-wide power failure. No amount of procedures or training can mitigate this hydraulic lock-up scenario; therefore, the installation of a hydrostatic relief device downstream of the pump discharge check valve piped back to the recirculator vessel is required.

## Summary

This article introduced concepts that are distinctive to pumping refrigerants with centrifugal pumps. In industrial refrigeration systems, the use of centrifugal pumps for supplying low temperature liquid refrigerant to loads has become quite common. Although a simple concept, the successful design, installation, and operation of centrifugal liquid refrigerant pumps does require care and attention to a number of details. One of the most common operational problems fought in the field is refrigerant pump cavitation. In a number of installations, we have found the contributing or root cause to cavitation is the excess flow of liquid through the pump due to hand-expansion valves on individual evaporators being set too far open. When cavitation occurs, cooling capacity is lost and the likelihood of premature pump (or motor) failure increases. We hope this article helps you understand and troubleshoot potential problems that may exist in refrigerant pumping systems.

## References


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