Industrial Heat Pumps:

The Renewing of Rejected Heat

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Introduction

Industrial food and beverage processors consume considerable energy from two primary utilities in the production of their products. Mechanical refrigeration applied in the processing and preservation of products consumes electrical energy, while the hot water supplied for cleanup and cooking employs mostly fossil fuel energy.

The considerable energy absorbed by ammonia in industrial refrigeration is usually discarded to the atmosphere as wasted heat. As an engineering community we readily acknowledge this standard practice of wastefulness with the use of the phrase Heat of Rejection. The entering flow of gas or oil used to produce hot water, bypasses the significant energy potential of the exhausted heat of rejection from refrigeration.

Although the rejected heat is a significant amount, it is usually condensed at temperatures ranging from 70°F (21°C) to 95°F (35°C). These low temperatures are considered to be of poor quality, and little use, compared with the 140°F (60°C) to 190°F (88°C) water temperatures required by processors, so the rejected heat is often discarded.

Fortunately, emerging technologies now allow end-users to harness their heat, rather than reject it. For example, heat pump technology is widely applied and accepted in commercial and residential HVAC applications, providing both cooling and heating from the single energy source of electricity. Heat pumps capture the heat extracted from a low temperature medium, and together with the additional heat from the work of mechanical compressors, reject the combined heat to a higher temperature medium for beneficial heating purpose. This allows industrial processors to take advantage of the rejected heat and avoid unnecessary wastefulness, also affording a potential economic payback of approximately 20 months based on average industrial energy costs.

With a growing interest in conserving energy and renewing refrigeration systems' wasted heat of rejection, industrial processors are tapping into recent screw compressor developments to bridge the energy gap between refrigeration and heating in industrial processes, making the most of their energy resources. These end-users are realizing the potential of applying industrial heat pumps to their processes and converting their waste heat into useable heat.

Moving Heat

Mechanical vapor compression systems are utilized mostly for their

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ability to produce a cooling effect. Cooling is obtained by the removal of heat from a variety of foodstuffs in blast and spiral freezers, chillers, processing rooms and cold storage spaces, by extracting heat from meat, poultry, dairy, seafood and beverage products. Heat is also removed by vapor compression in the production of ice for rinks, ice for consumption, air conditioning, district cooling, wood drying and chemical/pharmaceutical processing.

The cooling effect is actually achieved by the absorption of heat through the evaporation of a working fluid, such as ammonia, through a heat exchanger. Work performed by the compressor contributes an additional 20 percent to 25 percent of heat to the ammonia. The combined heat from evaporation and compression is discharged from the working fluid through condensing and oil cooling heat exchangers.

The theoretical coefficient of performance (COP) for cooling is the ratio of heat removed to the energy consumed, or ΔOPcooling = ΔQcold/ΔW. The COP of a heat pump for heating is the ratio of the sum of the heat removed plus energy consumed to the energy consumed, or COPheating = (ΔQcold+ΔW)/ΔW. If 4.0 kWh of heat is removed by using a compressor that consumes 1.0 kWh of energy, its cooling COP is 4.0. For this same system, its COP for heating is 5.0. Most heat pump COPs fall in the range from 3.0 to 6.0.

Burning fossil fuels to produce hot water is a straightforward solution to a hot water need, simply by piping the fuel to a heater or boiler and burning it. Although it is easy to design, pipe and operate a gas or oil heating system, energy-wise it is wasteful. The COP of fossil fuels cannot be greater than 1.0, since the only source of heat is from the fuel itself. In burning such fuels to heat water, not all of the energy potential of the fuel is transferred to the water due to efficiency losses. Hot water systems generally operate with an efficiency of 80 to 95%, corresponding to a COP of 0.80 to 0.95. Although it has been used as a default solution for the heating needs in most processing plants, water heaters and boilers have a very low COP compared with the renewed heat available from heat pump systems.

Although utilized for its cooling ability, a greater amount of heat is exchanged from the high temperature, heating side of a vapor compression system than from the low temperature, cooling side. Refrigeration systems that beneficially absorb heat and then uselessly reject it to atmosphere, utilize less than half of their full potential. Tapping into both the cooling and heating aspects of a vapor compression system, releases its full capabilities, and with higher COPs than fossil fuels, heat pump systems consume less energy overall.

Fact or Fallacy – Compressors Abhor High Pressures

Refrigeration compressors are designed to operate satisfactorily at worst-case summer design conditions, with high-side operating pressures rarely exceeding 200 psig (14 barg). With attention focused only on the cooling aspect of mechanical refrigeration, operators strive to reduce system discharge pressures to gain improved system efficiency, increased capacity and lower mechanical stress on compressors.

In heat pump duty, in order to capture the full extent of available heat from the system, compressors must discharge ammonia at pressures higher than the heated medium's desired corresponding temperature. Typical design pressures of ammonia refrigeration compressors range from 300 psig (21 barg) to 350 psig (24 barg). Yet to capture the high grade heat from condensing ammonia at temperatures ranging from 140°F (60°C) to 190°F (88°C), with a 5F° (2.8C°) approach through a heat exchanger, condensing pressures need to be in the range of 390 psig (27 barg) to 740 psig (51 barg), respectively. Further, with differential pressure allowances for safety relief, compressor design pressures will range from 430 psig (29 barg) to 820 psig (57 barg).

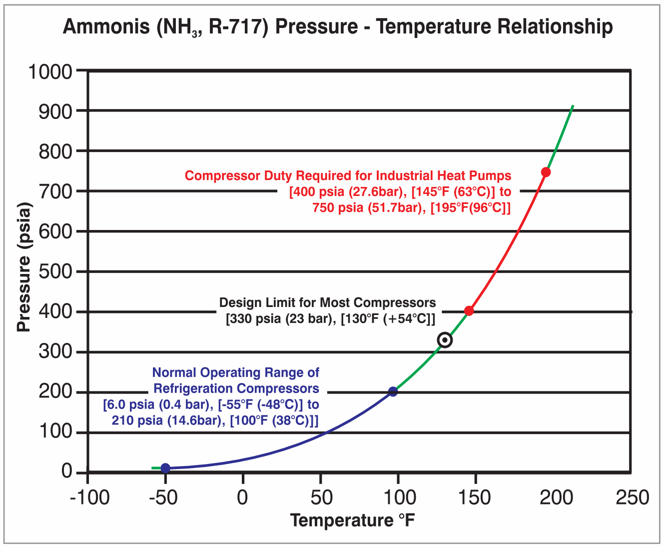

Figure 1. Ammonia pressure-temperature relationship

A few noteworthy factors are considered in the design of ammonia screw compressors intended for heat pump operation.

1. Greater forces are exerted on a compressor's casing and rotors.
2. High differential pressures should be attainable.
3. High pressures result in a high mass flow of gas through a compressor.

Various methods are employed in the design and manufacture of screw compressors to withstand pressures higher than required in refrigeration duty. The housing material of a compressor may be upgraded from cast iron to nodular (ductile) iron, or to cast steel, to contain the increased pressures. High pressure frames also incorporate heavy duty bolts and flanges, as well as o-rings in lieu of gaskets.

Twin screw compressors' male and female intermeshing rotors are supported by bearings on shafts extending from each end of the rotors. As pressure builds along the length of the screw, the unsupported midsection of the rotors can flex and distort, leading to wear and loss of performance by cascading (compression leakage). Higher pressures also increase the axial and radial thrust loads imparted on the rotor's bearings, resulting in accelerated wear and an increased frequency of overhauls. Twin rotor screw compressors may incorporate design upgrades to their bearings and rotors to withstand the increased forces exerted by higher pressures. Single rotor screw compressors, however, have balanced internal forces, inherently lower bearing loads and are capable of operating at higher pressures with standard rotors and bearing sets.

Recently developed high pressure single rotor screw models are encased in cast steel housings with a design pressure rating of 1,100 psia (76 bar) and differential pressures up to 550 psid (38 bard).

A single stage refrigeration compressor running at –43°F (–42°C) suction to 95°F (35°C) condensing, with a 186 psid (13 bard) differential pressure, would squeeze ammonia gas to a 20:1 compression ratio (10.2 volume ratio). At the opposite end of the refrigeration spectrum, compression ratios as low as 3:1 (volume ratio of 2.3) are rare. With the higher operating pressures of heat pumps, a lot of gas can be packed into small spaces. The increased gas density and high mass flow of ammonia at heat pump conditions correlates to low compression ratios and correspondingly low volume ratios (Vi).

A single stage scavenging heat pump system produces 190°F (88°C) water with a design condensing pressure of 750 psia (52 bar), and drawing suction gas from the host system at 196 psia (13.5 bar); with a differential pressure of 554 psid (38 bard), the compression ratio is 3.8:1 (2.8 Vi). By splitting the heat pump into 2 stages, overall efficiency improves. The optimized intermediate pressure of 383 psia (26 bar), permits each stage of the heat pump to operate at a compression ratio of 2:1 and a volume ratio of 1.7. The low Vi requires the release of high density gas through large open discharge ports. The single discharge port of a twin screw compressor can be restrictive in releasing high density gas, with a low-end volume ratio limit of about 2.2. Limited by a Vi higher than required by the design, the internal restrictions in the compressor create an increased backpressure, and result in overcompressing the gas and consuming excess energy. A single screw compressor, with dual opposing discharge ports and slide valves optimized to handle high mass flows, is less restrictive to high density gas and is capable of operating at volume ratios down to 1.2, for peak efficiency.


Figure 2. High pressure single screw rotors

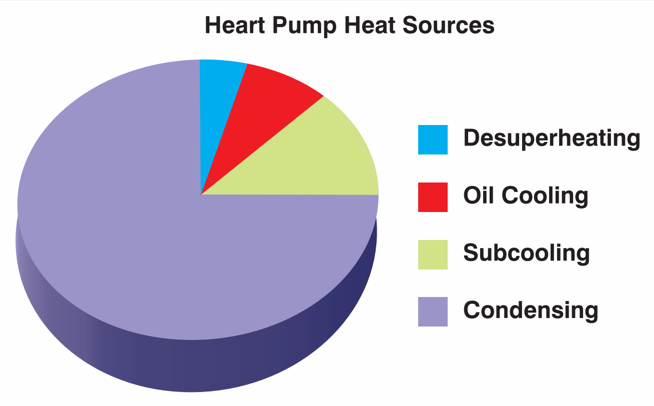

Figure 3. Heat sources of industrial heat pumps

Although most screw compressors are capable of operating at the high pressures required for heat pump duty, the inherent balance design of the single screw compressor, together with its ability to handle high mass flow gas, makes it better suited to high pressure operation than twin screws.

Capturing Heat

The total heat rejected from a screw compressor is discharged as high pressure superheated vapor and as heat absorbed by the oil circulated through the compressor. Means of capturing this heat may include oil coolers, desuperheaters, condensers and liquid subcoolers. Oil heat and superheat are often tapped for purposes of underfloor heating, snow melting in ice rinks and in preheating water. The sensible heat gain from these heat sources is marginal by comparison to the significant capacity of latent heat available in condensing, as shown in *Figure 3*.

The Best Heat Pump Configuration

Refrigeration designers may consider a variety of system designs for a given application, with two-stage or single stage compressors; recirculated or flooded liquid feed; hot gas or electric defrost, etc. Although each design aspect may contribute to satisfying the cooling load, they may have different effects on the cost of equipment, installation, operation or service and maintenance.

Likewise, a multitude of solutions are possible when designing an industrial heat pump system. One of three general heat pump configurations is initially selected, followed by the selection of multiple heat exchangers for extracting the desired heat. The three most common configurations include: 1) self-contained, 2) stand-alone and 3) scavenging systems.

Self-contained systems would be applied where the desired cooling and heating conditions fall within the acceptable operating range of a compressor or compressor set. The heat drawn from these systems would be considered relatively low grade for industrial applications, with condensing temperatures ranging from 130°F (54°C) to 145°F (63°C). Compressors are applied in self-contained systems either in a single stage arrangement, with evaporation temperatures as low as –25°F (–32°C) to –15°F (–26°C), or more efficiently in two-stage arrangements. Stand-alone systems draw energy from a heat

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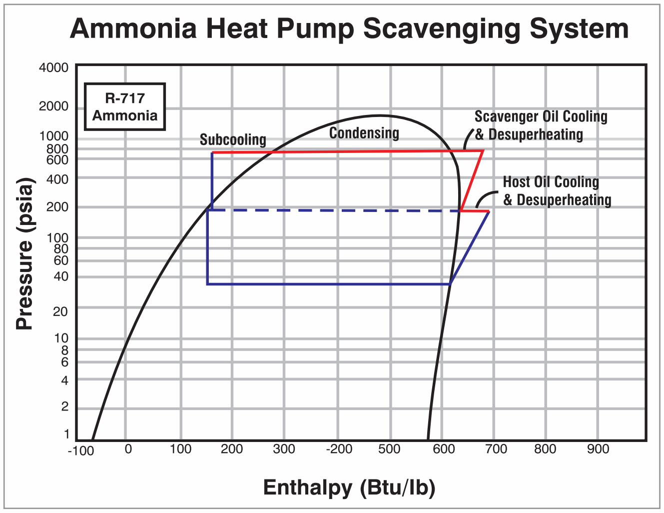

Figure 4. Heat potential of a scavenging heat pump system

sink, such as air or water, and are applied only for their heating potential, providing no beneficial cooling effect.

Similar to commercial air-source or water-source heat pump units, industrial stand-alone systems may draw heat from even larger heat source pools such as sea water.

These systems are often used for district heating applications and can be arranged in single-stage, two-stage or even three-stage systems to meet desired water temperatures and optimize efficiency. Scavenging systems capture waste heat from existing industrial ammonia plants (host systems) and convert it into useable heat.

The 'heat of rejection' is diverted from the evaporative condensers into a package that conditions the gas through a desuperheater, compresses it to a higher pressure, condenses the gas to a liquid and finally subcools the liquid down to the ammonia system's operating pressure. Scavenging packages may consist of single or multiple compressors, in single-stage or multi-stage arrangements. Two-stage scavenging packages can easily provide condensing temperatures upwards of 195°F (91°C).

After a heat pump configuration is determined, heat exchangers are selected. Heat may be extracted from a screw compressor's recirculated oil, superheat from the discharge gas of a host system's compressors (low stage and high stage), superheat from the discharge gas of the scavenging system's compressors, a condensing heat exchanger and a subcooler.

Each industrial heat pump application is unique, and with the many variables to consider and analyze, software tools developed to simplify the design process, allow engineers to define a system's operating conditions and heat load and then select heat exchangers for optimized first cost and system efficiency.

A scavenging system is dependent on the operation of the refrigeration system for its supply of heat. There may be conditions where hot water is required at times when the refrigeration system is operating at little to no capacity.

Analysis of the hot water consumption load profile and the refrigeration system load profile will reveal if hot water storage or supplemental heating is necessary.

Ancillary Benefits

Scavenging heat pump systems divert the flow of discharge gas away from condensers. A reduced condenser load affords incremental savings in fan and pump energy, make-up water for evaporation and blow-down, reduction of water treatment chemicals and prolonged condenser life. The costs and maintenance required of a fossil fuel fired water heater are also reduced or eliminated.

Economic Example

An example of the benefits of a heat pump system can be found in dairy processing plants. One such dairy processing plant uses ammonia refrigeration in the cooling and storage of its milk and dairy products. Large volumes of hot water are used in the cleaning of the facility's processing and storage tanks. Waste heat from the refrigeration system is discharged to a scavenging heat pump system in which 55°F (13°C) water is heated to 155°F (68°C). Hot water is consumed throughout the day in various batches and cycles, averaging a flow rate of 95 GPM (360 LPM).

In any example, utility prices have to be taken into account when calculating the payback of switching from the boiler to heat pump. For this analysis, current average industrial costs of energy are used: $0.08/kWh electric, $0.90/therm gas. The

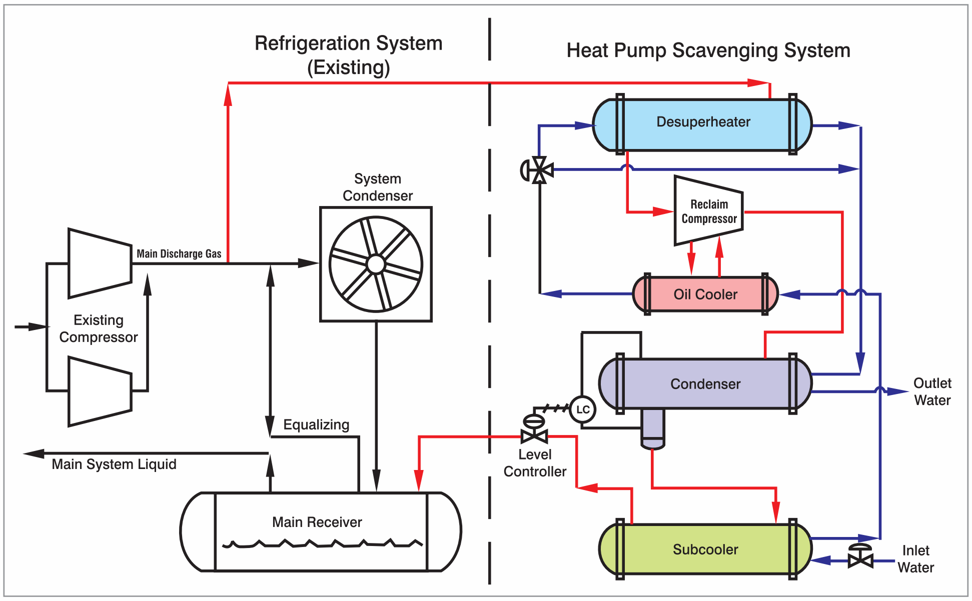

Figure 5: Scavenging heat pump system schematic

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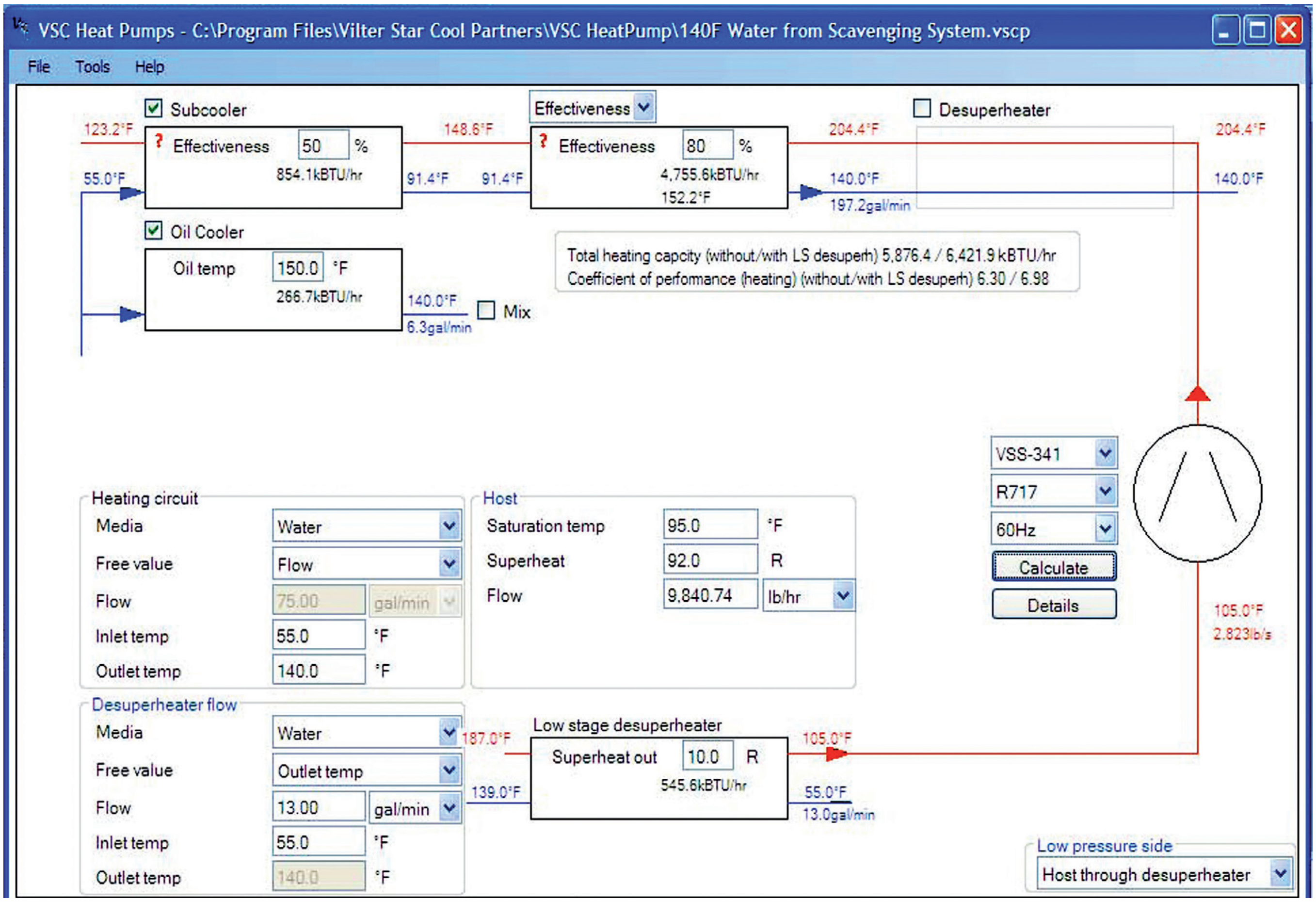

VSC Heat Pumps - C:\Program Files\Vilter Star Cool Partners\VSC HeatPump\140F Water from Scavenging System.vscp

☑ Subcooler
Effectiveness 50 %
854.1kBTU/hr

Effectiveness 80 %
4,755.6kBTU/hr
152.2°F

☐ Desuperheater

☑ Oil Cooler
Oil temp 150.0 °F
266.7kBTU/hr

☐ Mix

Total heating capcity (without/with LS desuperh) 5,876.4 / 6,421.9 kBTU/hr
Coefficient of perfomance (heating) (without/with LS desuperh) 6.30 / 6.98

VSS-341
R717
60Hz

Heating circuit
Media: Water
Free value: Flow
Flow: 75.00 gal/min
Inlet temp: 55.0 °F
Outlet temp: 140.0 °F

Host
Saturation temp: 95.0 °F
Superheat: 92.0 R
Flow: 9,840.74 lb/hr

Desuperheater flow
Media: Water
Free value: Outlet temp
Flow: 13.00 gal/min
Inlet temp: 55.0 °F
Outlet temp: 140.0 °F

Low stage desuperheater
Superheat out 10.0 R
545.6kBTU/hr

Low pressure side: Host through desuperheater

Figure 6: Heat pump analysis software

analysis shows that differences in COP between the 80 percent boiler and 5.0 COP heat pump can really make a difference. Heat can be moved much more efficiently than it can be created, and if the utility rate ratio is lower than the COP ratio, quick payback may be possible.

Heat recovery capacity:

- 95 GPM of water from 55°F to 155°F
- 4,790 kBtu/hr (1360 KW) heat recovered
- 363 BHP (270 KW) shaft power required
- COP = 5.0 (1360/270)

Energy Savings and Payback

Annual Heating Requirements = 4,790 kBTU/hr * 8,760 hr / 3.413 kBTU/kW = 12.3 million kW (per year)

Annual Cost Using Boiler = 12.3 million kW / 0.80 COP / 29.3 kWh/therm * $0.90/therm = $472,270

Annual Cost Using Heat Pump (Electric) = 12.3 million kWh / 5.0 COP * $0.08/kWh = $196,800

Annual Savings = $275,470

Estimated Capital Costs = $300k (Equipment) + $150k (Installation) = $450k Investment Cost

Simple Payback = ~20 months

Discounted Payback = ~2.9 years

While energy cost savings are usually enough to justify the investment in a heat pump system, additional revenue streams may be available to enhance its viability. One potential revenue stream gaining popularity is with carbon offsets, often touted as a way to reduce greenhouse gas emissions. One carbon offset represents the reduction of one metric ton of carbon dioxide, or its equivalent in other greenhouse gases.

While the carbon markets are still evolving, many processors are preparing to take advantage of carbon offsets by reducing or eliminating their consumption of fossil fuels for alternative, renewable sources of energy. In addition, utility rebates and/ or tax incentives may be available in making heat pump projects even more attractive.

Conclusion

There are many ways to satisfy heating loads, but with recently emerging technologies it is now possible to fully harness a refrigeration system's heat of rejection and renew it into useable heat. By maximizing the refrigeration system's full potential, while decreasing consumption and dependence on fossil fuels, end-users can reap the financial benefits of stewardship with an industrial heat pump system.

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