

ICE CRYSTAL SLURRY TES SYSTEM USING THE ORBITAL ROD EVAPORATOR

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Abstract

A novel ice crystal slurry thermal energy storage (TES) system has been developed for both HVAC and process cooling applications. The system uses an orbital rod evaporator (ORE), a vertical shell-and-tube heat exchanger with mechanical heat transfer augmentation, as a dynamic ice maker to generate liquid ice. Ice forms continuously without accumulation in the ORE and is compatible with conventional condensing units, storage tanks, and pumps. Dilute glycol or inorganic brine solutions promote formation of ice crystals, and the resulting liquid ice may be pumped or gravity fed to a storage tank. The cooling load circuit can be hydraulically decoupled from ice production at the storage tank. Stored liquid ice provides consistently low solution supply temperatures over significant portions of the ice melt period and may be melted very rapidly. With its characteristic high evaporator temperatures and high heat fluxes, ORE TES systems have the potential for significantly lower capital and operating costs than static ice or ice harvesting technologies.

Key Words

Orbital Rod Evaporator, Ice Crystal Slurry, Dynamic Ice, Ice Thermal Storage, Thermal Energy Storage.

Introduction

Thermal Energy Storage (TES) systems store "heating" or "cooling" energy produced in high availability periods (e.g. off-peak hours) for use in high utilization conditions (e.g. peak load, high demand charge). For example, ice or chilled water produced at night can be used to meet the comfort cooling needs of a building during the daytime. TES systems offer several advantages over HVAC systems sized to handle the peak load: reduced electricity demand charges, lower energy cost with off-peak power, better comfort due to lower humidity and secondary construction cost savings (reduced duct and fan sizes) with low temperature air distribution systems (Dorgan and Elleson, 1993). Because of the favorable impact on their electrical generating load profile, many electric utilities offer financial incentives to customers installing TES systems.

Ice storage systems use smaller tanks compared to chilled water TES systems (1/4 to

1/5 the volume) because of the high latent heat released when water freezes (144 BTU/lbm compared to 1 BTU/lbm/°F sensible capacity for water storage). Static ice systems form thick layers of ice on pipes and plates or freeze an encapsulated water or solution. Static ice systems use standard chillers, but require large amounts of secondary heat transfer surface because of the high insulating value of ice accumulating on that surface. For that same reason, static ice systems also suffer from relatively low ice melting rates and require more energy to produce the low evaporator temperatures required. Despite these deficiencies, static ice systems are popular for their simplicity.

Dynamic ice harvesting systems avoid thick layers of ice on the heat transfer surface by periodically releasing the ice. No secondary heat transfer surface is required, but there is usually a penalty in energy and capacity for hot gas defrost needed to break the ice bond to the evaporator surface (Knebel, 1995). Upon release, the ice falls by gravity into large, open tanks. Very high melting rates are possible by direct contact of warm return solution with the stored ice (Stewart, Gute, and Saunders, 1995). The ice harvester can be used as a chiller to effectively pre-cool extreme loads. Dynamic ice systems are commonly used in larger buildings where the savings in tank cost and the elimination of a secondary heat transfer surface make them more attractive than static ice systems.

The use of ice crystal slurries in dynamic ice systems offer inherent advantages in energy efficiency, capacity, and ice transportation. The ice crystals do not adhere to the evaporator surface or are continuously removed from the surface by mechanical means (Krepchin, 1994), so a hot gas defrost circuit is not required (hence the compressor delivers its full capacity to the load at a consistently high efficiency). Furthermore, the ice slurry can be pumped, so the location of the ice maker is not restricted to the top of the tank, reducing the structural requirements and storage tank costs. Despite these advantages, previous indirect ice slurry generators have seen limited use due to their high cost heat exchangers. Similarly, direct contact ice crystal slurry generators require either expensive vacuum tanks (triple-point-type systems) or pollution mitigation (refrigerant injection into solution). Indirect contact ice slurry systems have been more commercially successful than the direct contact systems in the HVAC and process cooling markets, but still cost more than conventional static ice builders or ice harvesters.

To make ice crystal slurry systems commercially viable, the cost of the heat exchanger must be substantially reduced and the heat flux capabilities greatly expanded. A novel ice crystal slurry technology has been developed that promises to accomplish these mandates, producing a competitive alternative for HVAC and process cooling thermal storage applications.

Orbital Rod Evaporator

The Orbital Rod Evaporator (ORE) is a breakthrough technology in ice crystal slurry generation that incorporates agitating rods to enhance the heat transfer effectiveness of

multiple-tube heat exchangers (see [Figure 1](#)). An offshoot of research on compact heat exchangers for seawater desalination (Li and Ho, 1987), the ORE is a vertical-tube falling film heat exchanger with refrigerant on the shell side and solution to be chilled or frozen on the tube side. The ORE tube bundle may contain hundreds of tubes, each having a metal rod rolling around (translation with rotation) its internal circumference. As shown in [Figure 2](#), the effect of this rolling whip rod is to push a wave of fluid around the circumference of the tube. This agitation enhances the tube side film coefficient by mixing the falling film solution, producing a highly turbulent flow (Buonopane, Huang, and Zhang, 1991). It is hypothesized that the mixing is sufficient to produce a supercooled liquid that is subsequently relieved by the formation of ice crystals. Thus, the agitated flow generated by the rolling whip rod in the tube prevents the adhesion of ice crystals to the heat transfer surface.

Centrifugal force keeps the whip rods rolling along the internal surface of the tubes. Rods are pushed only at their upper end because the curvature of the tube exerts a strong "straightening" effect, keeping the rod axis parallel to the tube axis. In wetting the surface, the solution acts as a lubricant ensuring that the whip rod does not contact the tube. Thus, the whip rod motion is inherently self-adjusting, minimizing wear and allowing relaxed tolerances (as opposed to tight tolerance bearings at each end of the evaporator tube).

The whip rods are hung by a "nail-head" from a countercrank (rotary cap) in the top of each tube (single-point control). The countercranks rotate by the orbiting action of the drive plate when it is driven by an electric motor. The countercranks allow multiple tube evaporators to be balanced, virtually eliminating vibration. The countercranks allow the rods to "center" in the tube in the case of a tube freeze-up, preventing damage to both the tube and whip rod.

The entire whip rod drive assembly (excluding the drive motor) is enclosed in a plenum space above the heat exchanger. The entire drive system is simple, reliable, and readily accessible. Component wear is minimal due to the lubricating and cooling effects of the low temperature solution, which continuously floods all moving components.

ORE TES System

As illustrated in the schematic of the ORE TES system in [Figure 3](#), solution is pumped from the bottom of the storage tank to the ORE, where it floods the plenum above the upper tubesheet. The feed rate is controlled by a flow control valve. Solution passes evenly through the holes in the drive plate and countercranks into each tube, where it is distributed as a falling film. As sufficient heat is removed by the refrigerant, fine ice crystals form in the falling film, resulting in liquid ice that can be pumped or gravity fed back into the storage tank.

As shown in [Figure 4](#), liquid refrigerant floods the shell side of the ORE where it absorbs the sensible heat and heat of fusion from the solution. Saturated liquid and vapor refrigerant are overfed into a low pressure receiver, where the two phases are separated, with the liquid refrigerant gravity fed back to the ORE. Suction gas is compressed and condensed in the condensing unit, and returned as a liquid refrigerant to the ORE. The first commercial systems use conventional R-22 condensing units, with subcooling control or level control–type expansion valves.

The liquid ice delivered to the storage tank is quite fluid and self-leveling. As ice crystals concentrate in the storage tank, they separate into a floating ice pack of uniform thickness. The ice pack is initially soft and slushy, but becomes harder and drier over time. The ice accumulation in the storage tank is monitored by a temperature sensor that signals the compressor to shut down at a preset solution temperature (based on initial additive concentration), corresponding to a full tank of ice. When the tank is full of ice, about one-half of the liquid has been frozen.

In the cooling circuit (refer to [Figure 3](#)), the stored cooling capacity is utilized as low temperature liquid from the bottom of the tank. Chilled solution is pumped to the cooling load then returned through a spray distribution system located in the top of the tank. The warm return solution is cooled by direct contact with the concentrated ice crystals, providing a continuous, low temperature heat sink to the cooling load. Due to the large surface-area-to-volume ratio of the fine ice crystals, a low solution temperature is provided until the ice inventory is nearly depleted. A heat exchanger is typically utilized to dissociate the TES system from the cooling load circuit.

It is necessary to use an additive to promote formation of fine ice crystals in the ORE. Dilute solutions of both glycol (ethylene or propylene) and inorganic brines (calcium magnesium acetate, NaCl, CaCl₂, NaHCO₃) have all proven successful. The first commercial ORE TES systems use 7% propylene glycol solution, which depresses the freezing point of the solution to about 28°F (-2.2°C). The freeze point of the solution continues to drop as ice inventory increases, with the tank being full of ice at a temperature of roughly 25°F (-3.9°C).

The ORE TES system is marketed for HVAC and process cooling applications under the registered trade name "MaximICE." The MaximICE Liquid Ice TES system contains an Orbital Rod Evaporator assembly, which houses the ORE, low pressure receiver and solution, and refrigeration piping and control devices. Mated to the ORE assembly is a conventional condensing unit, comprised of a single or multiple compressors; a pumpdown receiver and an air-cooled, water-cooled, or evaporative condenser; and a storage container manufactured from polyethylene, steel, fiberglass, or concrete, and containing a spray distribution system. A plate-and-frame type heat exchanger separates the MaximICE system from the load.

Performance

The overall heat transfer coefficient for the ORE is quite high due to enhanced film coefficients from the whip rod agitation. In ice-making operations, the coefficient varies as a function of the heat flux. Compared to ice harvesting systems, the ORE produces heat transfer coefficients ten to fifteen times higher.

The overall heat transfer coefficient for ice making varies with both whip rod orbiting velocity and heat flux. The variation with orbiting velocity results from improved film coefficients on the freezing side of the ORE at higher speeds, consistent with classical analysis of wiped film heat exchangers (McCabe and Smith, 1976). The variation with heat flux results from improved boiling side film coefficients at higher temperature differences, consistent with classical analysis of nucleate boiling plus reduced percentage of hydrostatic suppression (Hewitt, Shires, and Bott, 1994). The overall heat transfer coefficient for chilling is somewhat lower.

The design day performance of the refrigeration unit is directly proportional to the efficiency of the compressor. The ORE system's high efficiency is achieved through low nighttime ambient temperatures (low compressor discharge temperatures) and high evaporation temperatures (high suction pressure).

The characteristics of the liquid ice storage tank have been qualified from initial test results and field data, which indicate that the stored liquid ice can absorb any instantaneous discharge (ice melting) rate seen in HVAC applications. This is due to the high surface area of the ice crystals and the consistent accumulation of ice crystals in the storage tank, which greatly reduces the burn-through potential. Process applications are more demanding than HVAC, but even at very high melt rates, the ORE TES system's return temperature remains around 34°F (1.1°C) until the tank is 90% discharged.

Economics

At less than \$550/ton for applications requiring more than 100 tons ice-making evaporator capacity, the ORE is the lowest cost dynamic ice generator available. Thus, the ORE TES system has the potential of significantly reducing the cost of thermal storage systems. The three major system components (ORE, condensing unit, and storage tank) each enjoy lower unit cost as capacity increases. This economy of scale contrasts with the relatively constant cost per unit capacity for static ice systems.

In HVAC service, the ORE TES system delivers a solution supply temperature that is about 4°F (2.2 K) lower than static ice systems. The lower return temperature can reduce the cost of cold air distribution systems, as well as improve dehumidification. Also, the stored liquid ice absorbs instantaneous load spikes, commonly seen in processing facilities, at a substantially higher rate than static ice systems.

ORE TES systems also offer operating cost advantages because of the high evaporator temperature. Since refrigerant compressor power consumption is proportional to lift (difference between saturated suction and discharge temperatures), higher evaporator temperatures translate directly into energy savings. Since there is no build up of ice crystals on any heat transfer surface, this energy savings is realized over the entire ice generation cycle.

The ORE TES system offers excellent flexibility in both system operating strategy and equipment layout. Consistent with dynamic ice systems, the ORE TES system can supply liquid ice to the storage tank, while simultaneously delivering a low temperature solution to the cooling load. Since the liquid ice is pumpable, the ORE can be located remote from the storage tank, significantly reducing the structural requirements of the storage tank (compared to the ice harvester). Since the ORE assembly has a very small footprint (about 0.5 ft²/ton), it requires very little floor space, allowing for its more effective use.

The economic benefit of the ORE TES system can be quantified by comparison to an ice harvester system. Compared to a 200-ton ice harvester, a comparably sized ORE TES system uses 90% less heat transfer surface, 15-20% less power consumption, 60% smaller footprint, 75% less design operating weight, lower cost, no restrictions regarding the proximity of the ice maker to the storage tank and lower, more consistent return solution temperatures.

Product Development

Presently, the ORE TES system is offered to the HVAC and process cooling markets in 3, 25, 50, and 100 ton nominal ice-making capacity increments, utilizing conventional R-22 condensing units. The complete product offering will expand this in 100 ton increments to 400 ton with units being combined to address much larger applications. A single ORE can be utilized over a range of ice-making capacities dependent on the condensing unit size to which it is mated. Industry standardization on alternative refrigerants will direct future offerings ORE TES system product.

Development is underway for an ORE TES system that will utilize R-717 refrigerant in a pumped liquid overfeed system. It is expected that a product offering spanning a comparable range of ice-making capacities will be provided for processing facilities that have central ammonia plants.

Utilization of the ORE TES system is expected in traditional TES markets such as HVAC, process cooling, gas turbine inlet cooling, and district cooling. There are non-TES applications that appear to be well suited for ORE applications, such as juice concentration, produce pulldown cooling, low temperature cooling, fish harvesting, and

others.

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Figure 1 - Orbital Rod Evaporator Components

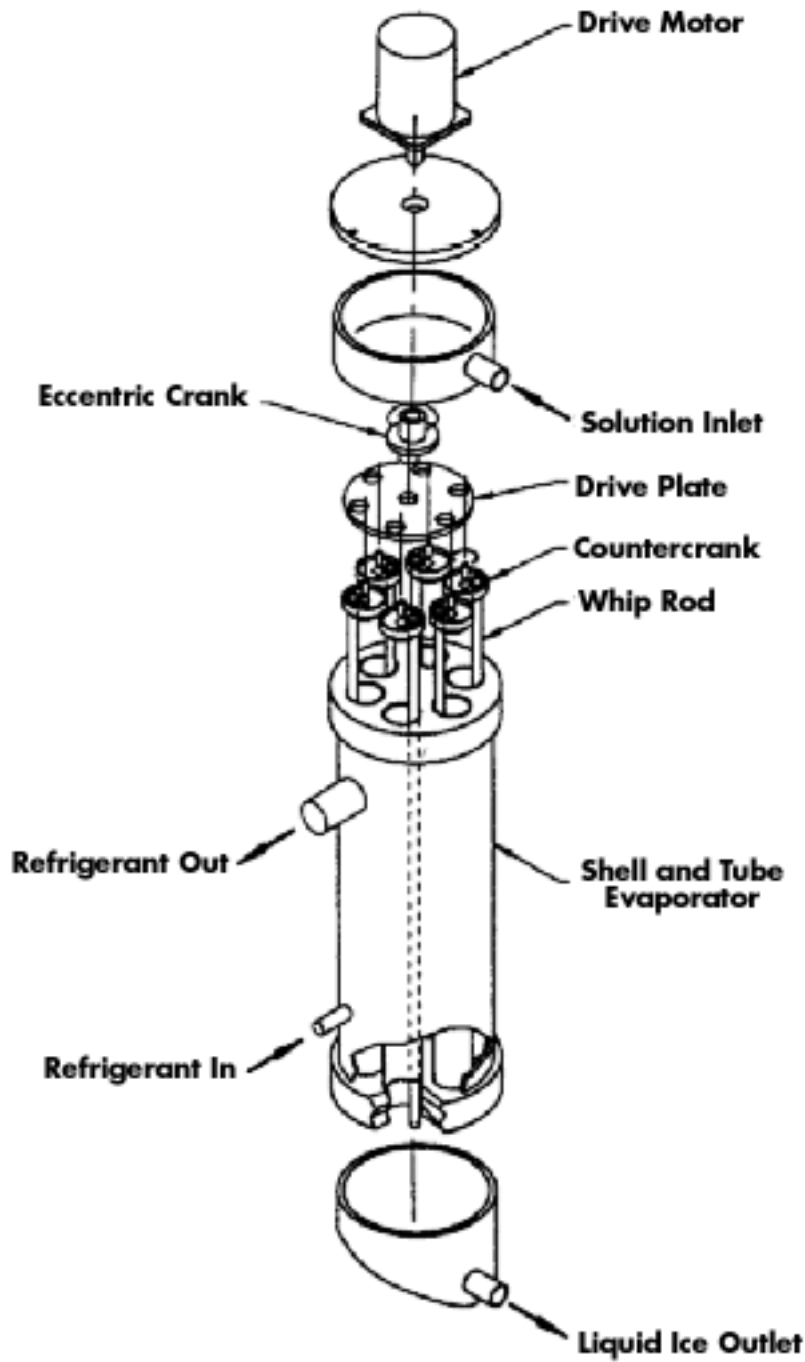


Figure 2 - ORE Whip Rod Effect

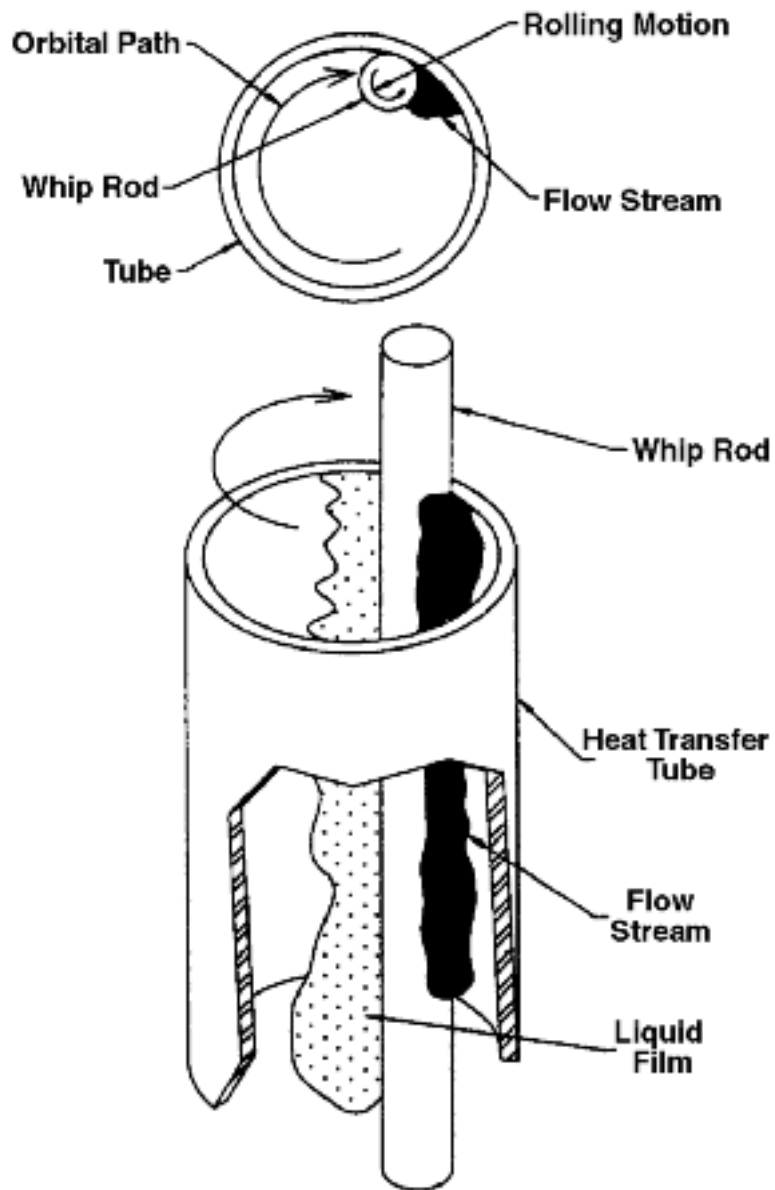


Figure 3 - ORE TES System Schematic Diagram

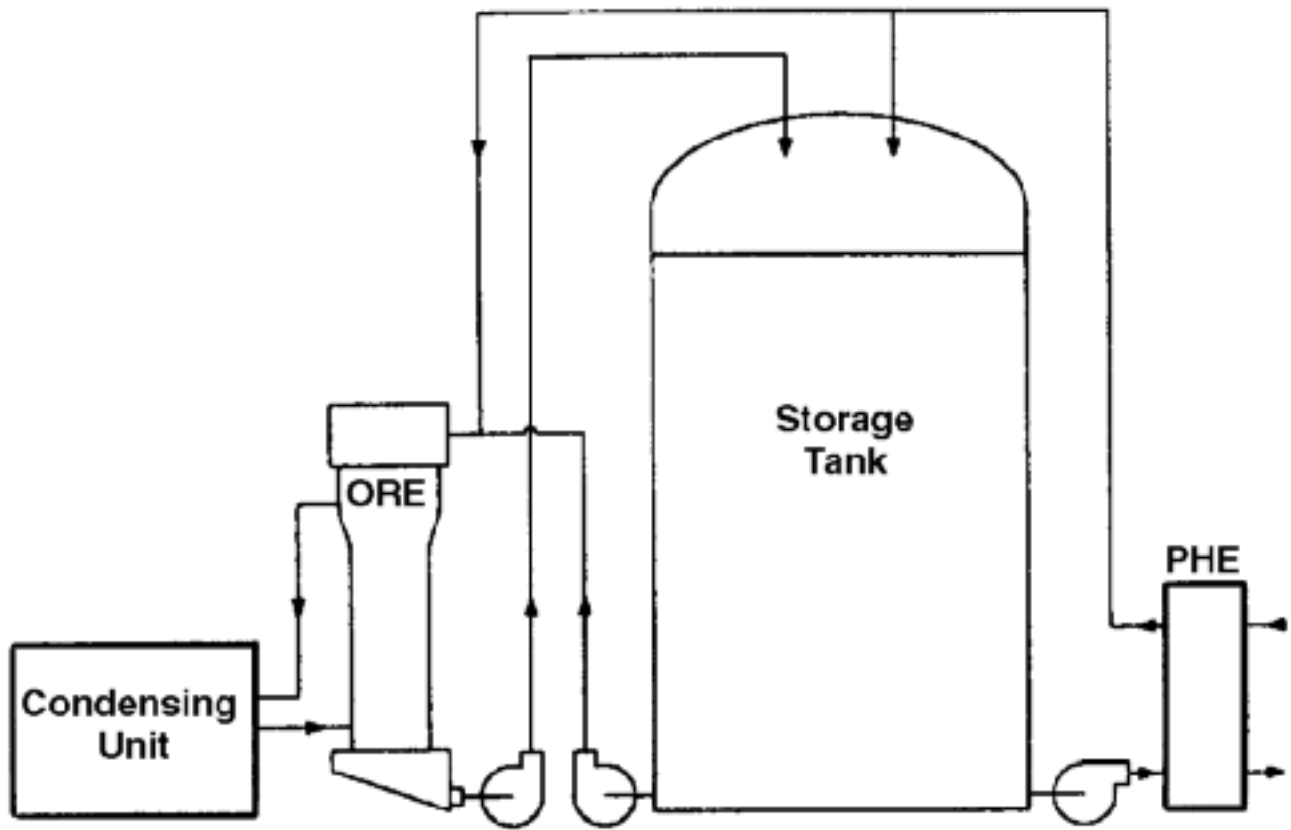
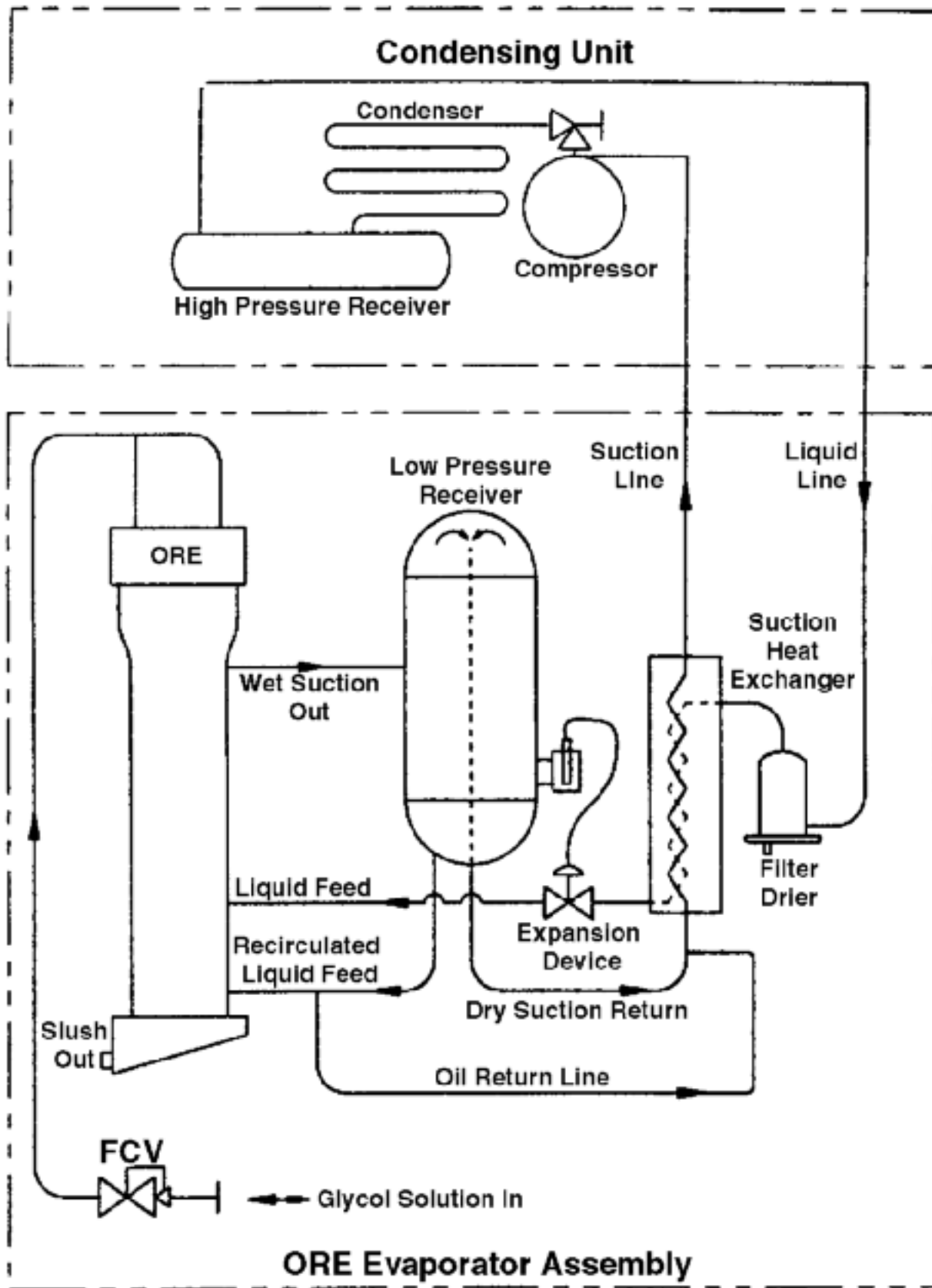


Figure 4 - MaximICE Refrigeration Schematic Diagram



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