Principles of Fluid Chillers

Design Criteria for Reliable Operation

Designing a high reliability process chiller requires an in depth understanding of chiller system dynamics and associated components, their limitations in specific cooling applications, and how they affect overall chiller performance. Described here is a tutorial of a single-stage recirculating fluid (or liquid) chiller with emphasis on the factors that determine reliable operation. Refer to Figure 1 below while reading about chiller component types and functionality.

The basics: A process chiller removes heat from a heat source where temperature must be maintained within a narrow region, on a continuous basis. Examples of environments that need continuous cooling include semiconductor fabrication, industrial machinery, chemical processing, and medical imaging. These applications are collectively referred to as the process, hence the name Process Chiller.

Fluid chillers remove heat based on the immutable principle that heat will move from a hotter source to a colder source – from the process to a conditioned fluid. They comprise two main parts called circuits – a refrigeration and a fluid circuit. The two circuits work in concert to transfer heat away from the process and maintain a reasonably constant process temperature.

There are several types of chillers– they are categorized based on the heat transfer medium used (air, gas, fluid) and their use depends on the application. A fluid chiller, the most common, is a closed-loop system that recirculates its fluid.

A fluid chiller works by generating low temperatures in a refrigeration circuit. A heat transfer fluid flows between the refrigeration circuit and the process where it carries heat away from the process. The warmer fluid absorbed from the process is pumped through a heat exchanger, transferring heat back to the refrigeration circuit and, finally, expelled by a condenser:

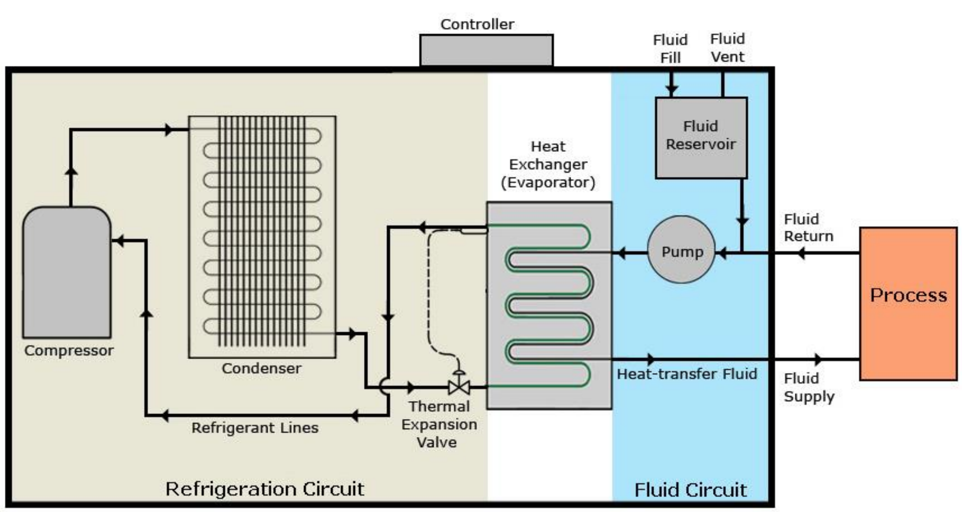

Figure 1. Simplified diagram of a single-stage recirculating fluid chiller, showing direction of flow and heat removal.

- An air-cooled condenser expels heat (end of the heat-removal process) by blowing cool air across the condenser, moving heat into the atmosphere.
- A water-cooled condenser expels heat by circulating cool water through lines in the condenser. The water moves the heat to an external cooling apparatus.

A word about Chiller systems and reliability: The desired output temperature and cooling capacity of a chiller (typically specified in Watts) are the critical parameters that will influence the size and number of components used in a particular design. When process cooling requirements specify low- and ultra-low temperatures (-40 to -110°C) chiller designs will increase in form and complexity.

Chillers operating from -40°C to ambient typically use a single-stage refrigeration design such as the one shown in Figure 1. As temperature requirements drop below -40°C, chillers incorporate additional refrigeration circuits (called two-stage and three-stage systems) with multiple refrigerants. These low-temperature units are collectively known as cascade refrigeration systems.

Every element of a chiller – compressor, pump, valves, refrigerants, tubing, controls and more – is critical to the long-term reliability of chiller operation. In fact, the weakest link among these components can bring down the entire cooling system. Thus, reliable operation begins at the design stage. It involves not only matching component capacity to process cooling requirements but also building in a safe set of operating parameters that factor in operation at the worst possible conditions.

Figure 2. Modeling and simulation are essential to designing a reliable process chiller, especially as the need for cooling capacity increases.

Refrigeration Circuit

As mentioned earlier, a process chiller contains two main circuits – refrigeration and fluid. The refrigeration circuit is the primary system that generates low heat and expels higher heat. Thus it must keep pace with removing the heat generated by the process.

While this tutorial centers on single-stage refrigeration there are many more reliability factors when considering multi-stage system designs. For this reason, it is worth taking a diversion to briefly explain multi-stage systems.

A two-stage refrigeration system, for example, has two independent refrigeration circuits allowing heat to be transferred from the second stage to the first. This type of system requires more components – additional compressor, heat exchanger, valves, switches, sensors, filters, and regulation loops that must be managed by the chiller's controller. A three-stage system for ultra-low temperature applications adds third refrigeration circuit to the design mix.

The capacity specifications of components, especially compressors, are not only critical to the work they do within their respective circuits but also need to handle the heat load from stages closest to the process. While refrigeration stages are closed loop circuits, reliability depends on each stage's ability to keep pace with overall heat removal demands of the process chiller. Let's talk about these components.

Compressor: The compressor is the heart of the refrigeration circuit; it compresses refrigerant gas to perform work. The temperature and pressure of the gas increases at the outlet of the compressor, and its heat content is expelled by the condenser.

Figure 3. Compressors run continuously and need sufficient horsepower to maintain overall process chiller performance.

Hermetically sealed compressors are leak proof and usually maintenance free. The type of hermetic compressor used depends on the application with consideration for required horsepower (Hp), noise level and footprint. Typically, hermetically sealed reciprocating compressors are smaller, used in applications that require less than 2 Hp. Scroll compressors are used in applications requiring more than 2 Hp, low noise levels, or extended operation periods.

Compressors also need constant lubrication, typically fulfilled with oils. However, at low temperatures oils will become dense and difficult to move. These systems mix a small amount of refrigerant with the oil. An oil separator and management system ensures that the oil remains in the compressor to avoid causing problems elsewhere in the refrigeration circuit

Condenser: The condenser removes heat from the refrigeration circuit and releases it using air or water as the transfer medium. During the heat removal process, the refrigerant condenses, changing its state from gas to liquid. The condenser should be sized to the application; air-cooled condensers are physically larger than water-cooled condensers for the same load duty because air is a less efficient heat transfer medium than water.

Refrigerant Lines: Refrigerant lines are usually built with copper tubes and fittings that carry the refrigerant through the refrigeration circuit. The manufacturing process of these lines is critical to the health of components and the system, especially those with moving parts, and thus a chiller's overall reliability.

Fully brazed (metal-joining process) refrigerant lines with hermetically sealed solenoid valves prevent leaks and contamination from external sources. Additionally, each refrigeration circuit should undergo a cleaning process, which removes unwanted chemicals and debris from the system. Finally, every refrigeration circuit should be leak tested.

Refrigerants: Many common refrigerants are available for use in cooling systems. They provide a wide range of physical properties important to refrigeration systems including boiling and freezing points at a specific pressure. HFCs (HydroFluor-Carbons) should be used whenever possible as they are the most environmentally safe refrigerants for low temperature use. Oftentimes, refrigerants are blended to achieve an optimal cooling environment.

Heat Exchanger (Evaporator): The Heat Exchanger (also referred to as an Evaporator) moves heat away from the process similar to the condenser. It absorbs heat from the fluid circuit. The Thermal Expansion Valve on the inlet of the Heat Exchanger creates a pressure drop for expansion of the liquefied refrigerant as the refrigerant enters the Heat Exchanger. This pressure drop forces the refrigerant to evaporate (i.e. changes from liquid to a mixture of boiling liquid and gas).

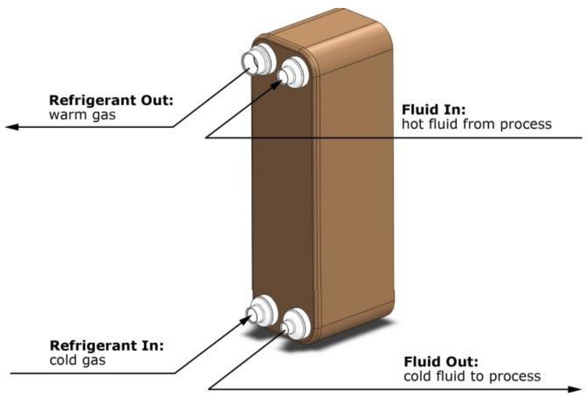

Figure 4. A heat exchanger removes heat from the fluid circuit.

As the refrigerant evaporates, it expands and becomes very cold and thereby ready to absorb heat. The cold gas lines run next to the fluid lines in a counter-flow direction – the coldest parts of the refrigerant line interfaces with the hottest parts of the fluid line. This counter-flow configuration ensures maximum heat transfer from the fluid as it exits the Heat Exchanger.

Fully brazed heat exchangers are the most reliable and efficient design; providing the best heat transfer and leak proof protection.

Thermal Expansion Valve: The Thermal Expansion Valve (TXV) acts as a metering device that regulates the amount of refrigerant allowed into the Heat Exchanger (HTX). A bulb in the valve is filled with gas that expands and contracts based on the temperature it monitors at the outlet of the HTX. This action opens and closes the TXV as needed.

Fluid Circuit

The fluid circuit delivers fluid to the process at a specified temperature, pressure and flow rate as needed to absorb the required amount of heat generated by the process.

Heat-transfer Fluids: Fluid types vary with temperature requirements. Clean water is used at ambient and above, water/glycol mixtures for below freezing applications, and silicone oils or inert fluorinated fluids for temperature requirements between -40 and -110°C. See Table 1 below for examples of various fluids designed for heat transfer at different operating temperatures.

Refrigeration System Type	Temperature Range	Typical Heat Transfer Medium
Room Temperature - Single Stage Liquid Chiller	5 to 40°C	Water, Deionized (DI) Water
Low Temperature - Single and Dual Stage Liquid Chiller	20 to -80°C	**Above -20°C:** Glycol/Water mixture **Below -20°C:** silicone oils (Dow Dowtherm Q series, Lauda Kryo series, etc.), inert fluorinated fluids (3M Novec Series, Solvey Galden HT series, etc.), alkylated aromatic fluids (Dow Dowtherm series, etc.)
Ultra-low Temperature - Triple Stage Liquid Chiller	-80 to -110°C	inert fluorinated fluids (3M Novec series, Solvey Galden HT series, etc.)
Autocascade Gas Chiller	Down to -110°C	Clean Dry Air (CDA), Nitrogen, Argon, etc.

Table 1. Common heat transfer fluids for various heat removal temperatures.

Pump: The pump is the heart of a fluid circuit; it circulates fluid through the fluid lines. Pumping power must be sufficient to create the desired flow at the outlet of the heat exchanger. Positive Displacement Gear Pumps and Velocity Turbine pumps are typically the most reliable and best performing pumps. Choosing between them depends on the application.

Typically, Gear Pumps are used when fluids are extremely viscous and exhibit a high level of lubricity. Gear Pumps need to be lubricated; they are capable of moving viscous liquids at high pressure. Turbine pumps are used when high flow rates or low noise levels are required. Turbine pumps have fewer moving mechanical parts than gear pumps; they are quieter and require less lubrication.

Fluid Reservoir: The Fluid Reservoir holds fluid that is not circulating through the fluid circuit. The purpose of a reservoir is threefold: 1) to fill the lines initially; 2) to ensure a flooded return line for the pump; and 3) to serve as an expansion tank with fluid expansion and contraction.

The reservoir may be manually filled using Fluid Fill and Vent ports or connected to an external fluid supply that automatically refills the reservoir when levels are low. Typically, reservoirs are built with stainless steel to achieve and enhance robustness against a variety of fluids.

Fluid Supply and Fluid Return (wetted lines): Cold fluid exits the chiller at the Fluid Supply port, and is eventually delivered to the process application where it removes the heat generated by the process. With ultra-low temperatures, fluid lines may be vacuum jacketed (insulated hose) to minimize heat loss during the transfer of fluid between the chiller and the process. Warm fluid returns to the chiller through the Fluid Return port to begin the heat extraction (cooling) process again.

Flow Regulation Components: Filters and valves keep the fluid clean and control fluid flow. Filters are installed at the inlet and outlet of the pump to filter contaminates. Flow control valves, typically solenoid valves, control the flow of fluid through the fluid circuit. They are directed by the logic in the controller to open and close as needed to regulate fluid flow to the process and maintain the required temperature.

Process Material: A liquid chiller accomplishes heat removal using a variety of fluids and materials. However, their selection must be chemically compatible with the process material they will contact. For example, copper lines passing through the pump, heat exchanger and reservoir would be corrosive to cooling an aluminum-based process. Considerations for selection of wetted materials used in components making up the fluid circuit:

Process Loop Materials	Wetted Material (components used in Fluid Circuit)
Copper	Cu, Brass, Stainless Steel [2,3] Engineering Plastic
Aluminum [1]	Brass, Stainless Steel [2,3] Engineering Plastic

Table 2. Selecting wetted materials that are compatible with process materials

1. Deionized water (purified water with mineral ions removed – sodium, calcium, iron, copper, chloride, bromide) is a commonly used fluid to prevent corrosion of aluminum for temperatures above freezing.
2. Stainless steel, brass and engineering plastic tubing and joints are free of oxidative ions, reducing the possibility of corrosion.

3. For stainless applications, steel welds and finishes require a passivation process to restore its chromium oxide surface, preventing iron from leaching into the system.

Control System

The controller is the traffic cop that directs chiller operations – controlling temperature, monitoring sensors, and communicating data and events. Actual control is driven by software algorithms, which use data from sensors to maintain programmed set points. For example, in the refrigeration circuit the controller monitors temperature at various inlet and outlet points of the compressor, condenser and heat exchanger. The processed data results in opening and closing valves for appropriate durations.

Figure 5. Sensor feedback, responsive control and user notifications are essential to keeping a constant process temperature.

In the fluid circuit the controller measures fluid temperature at the supply and return side of the process, and at the inlet of the pump. Other measured variables include pressure to determine that flow rate has not dropped too low and reservoir level to sense high or low fluid levels.

The controller can provide notification to an operator via alarm sound, light or electronic message if a measured variable goes out of range; e.g. fluid temperature or reservoir level too high, or fluid flow too low.

Providing diagnostic information is another important function of a controller. With moving parts under continuous operation – compressors, pumps, and valves – process chiller components need to be monitored. Storing data on valve counts and component run times, for example, provides records necessary for maintaining chiller health.

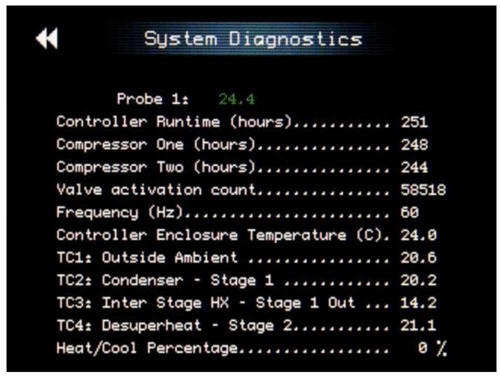

Figure 6. All moving parts have a life span. Monitoring components provides data for proactive preventive maintenance.

A controller should provide sufficient input/output capability to accommodate the functions of the sensing, control and user alerts described above. Typically, a controller is equipped with multiple inputs to connect temperature measurement devices such as thermocouples and RTDs, and other scalable I/Os to connect commonly used devices (0-10V, 4-20mA, dry contacts).

Communications to remotely monitor and control of a process cooling system, or to network multiple process chillers, can be achieved using communications protocols such as Ethernet, RS232, IEEE-488.

Summary

High reliability process chillers comprise designs with components that are well-matched to the heat removal task. Continuous operation especially at low-temperatures requires refrigeration designs that must balance overall heat-load so that each refrigeration stage can effectively manage temperature and pressure without the possibility of excess demand to overload any one component.

Every element of a chiller – compressor, pump, valves, refrigerants, tubing, controls and more – is critical to the long-term reliability of a process cooling operation. Remember, the weakest link among these components can cause the system to fail.

With proper thermal modeling and simulation, the resulting process chiller will have more robust components and require the use of fewer moving parts (e.g. valves) over other design methods without overloading any one component.

Precise and responsive chiller control is crucial to fluid chiller performance and reliability. Low- and ultra-low temperature chillers use more components, each requiring sensors that provide feedback to the controller. With each additional refrigeration circuit there are more conversions from gas to liquid to gas that need monitoring and precise regulation.

In summary, a reliable and functional fluid cooling system is a result of quality engineering and manufacturing activity. Advanced modeling, especially on low-temperature process chillers, can wring out many issues that invariably arise from trying to adapt an existing design or using poorly chosen components. When properly executed, the design phase provides the basis for long-term reliability – an ROI that goes well beyond the initial commissioning at the point of application.

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About Thermonics

Thermonics belongs to a family of temperature-related companies under the banner of inTEST Thermal Solutions. Born out of experience developed in the 1970's with designing and integrating chiller systems for the semiconductor industry, the company expanded its reach for meeting thermal management challenges to other industries. Today, these activities include energy, fiber optic, consumer product manufacturing, semiconductor and industrial markets.

Thermonics specializes in standard, custom, fluid, and gas chillers rated for temperatures from ultra-low temperatures to heating up to 300°C. Our systems feature precise temperature control and stability with cooling capacity up to 50kW.

- Ultra-low temperatures from -110°C
- Up to 50kW cooling capacities
- Air or Water cooled systems
- Custom chillers – capacity/footprint
- Rapid design to delivery
- Worldwide support
- ISO 9001:2008 registered
- All products RoHS compliant