Meet the heat

Edward Cass, Paratherm Heat Transfer Fluids, USA, details the use of thermal fluid systems technology for the process heating industries.

When it comes to process heating technology, no conversation can exclude the role that liquid-phase heat transfer systems play in industrial heating technologies. Heat transfer fluids, also known as thermal oils, thermal fluids etc, are engineered fluids that are used to generate high operating temperatures at low system pressures. They are used in a multitude of manufacturing processes that require uniform, responsive heating to maintain the production of an asset. Thermal fluid systems provide years of reliable service when properly engineered and maintained. They are an economical alternative to steam and direct-fired technologies, allowing more application flexibility as well as gentle, uniform heating. While thermal fluid systems have been in use for over half a century, continuous advances in material science have paved the way for improved operational safety, capacity/capability, versatility, and reliability of these systems. This article describes some of the technology inside a typical high-temperature thermal fluid system.[1]

System technology

Thermal fluid systems consist of one or more thermal fluid heaters, circulation pump(s), flow control valves, isolation valves, temperature and pressure gauges/sensors, and process unit operations. The primary circulation pump moves the fluid across a heat source, capturing the thermal energy and releasing it to one or more process users downstream (reactor, reboiler, column, tank, etc) before returning it to the circulation pump. In most industrial designs, an expansion tank is piped off the return line to allow for thermal expansion of the oil as it heats up to the desired temperature.

Thermal fluid pumps

Most high-temperature systems utilise centreline-mounted cast steel centrifugal pumps with air-cooled tungsten carbide mechanical seals, water/air cooled bearings, seal flush and inerting configurations. Sealless pumps are also commonly used, particularly for service > 625˚F (330˚C) or where the thermal fluid is being operated above its normal boiling point. Sealless pumps consist of canned-motor pumps, and mag-drive pumps. These designs offer the advantage of leak free performance (low maintenance), however they are generally much less tolerant to contaminants, cavitation and dry running. In the absence of rotary joints, the thermal fluid pump is the component of the system that requires the most maintenance. The pump must be properly sized, selected and installed to provide the desired pressure, head and flow rate for efficient heat transfer and reliability. Mechanical stresses on the pump and piping should be minimised, with provisions for centreline mount designs, proper pump support, expansion joints and minimum 300# raised face ANSI flanges. The typical pressure and temperature limitations on high-temperature thermal fluid pumps is 35 bar at 400°C (500 psi at 750°F). For optimal seal performance, the seal should be kept under 204°C (350°F).

Thermal fluid heaters

The thermal fluid heater is the primary component of the system. It is a complex piece of equipment, comprised of a fire box, refractory, thermal fluid coil(s), burner(s), blower(s), fuel train(s), relief device(s), heating elements, probes/sensors, control panel, etc. Larger thermal fluid systems commonly employ fuel-fired heaters (natural gas, diesel, oil, biomass, etc) while small to medium sized systems may employ electric heaters. A well-designed thermal fluid heater will have optimal efficiency (combustion, power draw, etc), minimal differential between outlet temperature and film temperature, and sufficient capacity to provide temperature control over the expected operating range of the process.

Liquid-tube fired heaters work on the principle of both radiant and convective heat transfer. Radiant heat transfer occurs on the flame side of the coil(s), while convective heat transfer occurs by virtue of the combustion gases passing over the coil surfaces. Depending on the heater design, more than 50% of the heat transfer may occur in the radiant zone. Serpentine coil designs are the oldest design in the industry, and consist of straight piping with 180˚ bends to form a continuous s-shape around the wall of the combustion chamber. A major benefit of serpentine designs is that the heat flux is spread over a larger surface area, minimising excessive film temperatures. These are available in both vertical and horizontal configurations.

Helical coil heaters feature one or more continuously-wound coils which frame the combustion chamber. The radiant zone of helical designs is determined by the diameter of the coil, relative to the flame. Concentric coil designs offer optimal heating efficiency by allowing for three convective zones of redirected combustion gas. In general, helical coil heaters offer the advantage of compact design, with vertical/horizontal configurations, as well as top-fired or bottom-fired burners.

Electric heaters are available in numerous configurations and capacities. Cabinet style heaters are self-contained units with the heater, circulation pump, controls, valves, and expansion reservoir all inside the cabinet. Cabinet style heaters have low to medium thermal capacities, but offer excellent operational flexibility. Circulation heaters typically have higher capacities vs cabinet style, and are often sold as integrated skid-style systems complete with pumps, expansion tank, valves and controls. In both designs, the fluid is circulated past the heating elements, which should be carefully designed such that watt density does not exceed 25 – 30 W/in^2. Depending on the application, electric heaters may offer better economics vs fired heater designs.

While heater design has not changed drastically in the last 30 years, combustion control technology and remote sensing technologies have been adapted to the equipment. Combustion and emission controls allow for optimised burner efficiencies, lower pollution, safer work environments, and more reliable production. Remote temperature, pressure and flow transmitters allow for real-time monitoring of system parameters from multiple access points, making anomalies easier to spot before they become bigger problems.

Expansion tank

An often-overlooked component of the heat transfer system, the expansion tank is the vessel that allows thermal fluid systems to operate at high temperatures with low pressures. The expansion tank accommodates thermal expansion volume of the oil as it is heated to operating temperature. No matter the application or equipment, this component plays several distinct roles in the thermal fluid system:

- It ensures that the system is fully flooded, and provides adequate net-positive suction head (NPSH) to the main circulation pump.
- It acts as the reservoir to accommodate fluid expansion volume as it is heated to operating temperatures.
- It allows for the separation of air, water and/or volatiles from the thermal fluid.

The expansion tank is typically the highest point of the system and is sized to accommodate the expansion volume to be 66 – 75% full at normal operating temperature.[2] A double-drop leg arrangement allows for circulation of fluid through the tank, and is the most practical design for ease of degassing the system (separate deaerator vessels are also used). For high-temperature systems, provisions should be made for inert gas blanketing (N_2(g), CH_4(g), etc) to eliminate oxidation and suppress boiling of the fluid if applicable.

A fully-instrumented expansion tank might include inert gas pressure/back pressure regulators, pressure control valves, pressure relief valves, pressure gauges, manual vent(s), low and high-level switches/interlocks/alarms, drain valve(s), and relief and drain piping. During the design phase, careful consideration should be given to the expansion and drain plans. The addition of low-point drain valves, isolation capabilities, and appropriate drain and discharge containment goes a long way when the system inevitably needs to be drained.

Fluid technology

The chemistry of a given heat transfer fluid dictates its specific physical properties and operating range. Historically, heat transfer fluids have been divided into two categories: mineral oil-derived (organic hydrocarbons), and synthetic hydrocarbons. Mineral oil is a catch-all term, which includes different grades and purities of paraffinic oils, naphthenic oils, and blends thereof. Synthetic is also a catch-all term, collectively accounting for benzene-derived fluids with favourable heat transfer characteristics.

Mineral oil fluids are generally considered cost-effective robust choices for applications operating to a maximum 288 – 316°C (550 – 600°F), though some high-grade organics are suitable to 332°C (630°F) provided the heat flux is sufficiently low. Synthetic fluids are generally more expensive, but can provide fill-for-life performance in the mineral oil operating range in a well-designed and maintained system. Synthetic fluids are usually the obvious choice when operating above 316°C (600°F), and tend to be superior in terms of low-temperature performance.

Mineral oil heat transfer fluids

Mineral oil heat transfer fluids (aka 'hot oils') are those formulated from the base oils produced in refining processes. The American Petroleum Institute (API) classifies petroleum base oils into three groups:

- Group I: base oils with a viscosity index[3] of 80 – 120, and containing less than 90% saturated hydrocarbons and/or more than 0.03% sulfur.
- Group II: base oils with a viscosity index of 80 – 120, and containing at least 90% saturated hydrocarbons and no more than 0.03% sulfur.
- Group III: base oils with a viscosity index of 120 minimum, minimum 90% saturated hydrocarbons, and maximum 0.03% sulfur.

Mineral oil heat transfer fluids derived from all three groups are available from various suppliers. The least expensive fluids on the market are Group I based, but these are generally considered inferior to Group II and III type fluids due to lower thermal stability and higher fouling potential. It is important to note that mineral oil heat transfer fluids are distinctly different formulations to lubricant oils. All of these oils have some similarities in base oil composition, but many commonly-used lubricant additives such as extreme pressure and anti-wear agents (EP/AW), defoamers, demulsifiers, viscosity index improvers, corrosion inhibitors, etc are not rated for the high temperatures experienced in heat transfer systems. A number of additive chemistries tend to foul heat exchange surfaces or may decompose into reactive species that can catalyse fluid degradation. For this reason, it is important to specify a heat transfer fluid from a reputable supplier offering fluids that have been specifically formulated for heat transfer service. If the supplier cannot provide thermal property data over the operating range of the fluid, it is likely that the fluid is not ideally suited for heat transfer service.[4]

Synthetic heat transfer fluids

In the heat transfer industry, synthetic fluids are also known as 'aromatics' since they are benzene-based chemistries. These fluids tend to have narrow boiling ranges vs their mineral oil cousins, so operation in both the liquid and vapour phase is possible. Synthetic aromatic fluids can offer many benefits over conventional mineral oil-based fluids, such as enhanced thermal stability, better low-temperature performance, wider operating ranges, and longer drain intervals. These fluids tend to be more hazardous in terms of handling, disposal, and environmental impact, and are typically two to three times more expensive than mineral oil fluids.

There are a wide range of synthetic heat transfer fluids available on the market, but there are fewer suppliers of these specialty fluids. Table 1 highlights the most popular synthetic varieties that are in use globally. For these fluids, maximum temperature, boiling point, and vapour pressure vary widely, and many of these fluids are suitable for operation in both liquid and vapour phase. Cost generally increases with performance, so fluids that can operate at temperature extremes or over a wide operating range tend to be more expensive. Temperature ratings for all heat transfer fluids

Table 1. Typical properties of the most commonly used synthetic heat transfer fluids

Synthetic fluids in heat transfer	Temperature range (°F)	Vapour pressure at maximum temperature (psia)	Boiling range (°F)
Hydrogenated terphenyl blends	25 – 650	Below atmospheric	> 700
Diphenylethane blends	-40 – 650	> 50	< 525
Diphenyl oxide/ biphenyl blends	60 – 750	> 100	< 500
Dibenzyl toluene blends	25 – 660	Below atmospheric	> 700
Alkylated biphenyls	-25 – 660	Below atmospheric	600 – 700
Diaryl/triaryl ether blends	10 – 715	> 20	< 600
Alkylated benzene blends	-15 – 575	Below atmospheric	> 600

should be set based on laboratory tests and established field performance.

There are a handful of other synthetic chemistries used for more niche applications such as silicones, cycloalkane blends, polyalkylene glycols, fluorocarbons, esters and polyalphaolefins, to name a few. Since their use is limited to special applications, they are not discussed here. Table 2 summarises the pros and cons of mineral oil and synthetic fluids.

Table 2. Summary comparison of mineral-oil and synthetic heat transfer fluids

Fluid type	Mineral oils	Synthetics
Pros	■ Cost effective ■ Capable to 630˚F ■ Low vapour pressures ■ High boiling points ■ High flashpoints ■ User friendly/low toxicity ■ Little to no regulatory restrictions ■ Broad material compatibility ■ Food grade available	■ High thermal stability ■ Capable to 750˚F ■ Good low-temperature performance ■ High solvency ■ Vapour phase operation ■ Soluble degradation byproducts ■ High flash and autoignition temperatures ■ More efficient vs mineral-based
Cons	■ Limited low-temperature performance ■ Low to moderate solvency ■ Insoluble degradation byproducts ■ Low boiler accumulation ■ Often re-labelled/improperly formulated ■ Higher fouling tendency ■ Less efficient vs aromatics	■ Handling and disposal ■ Regional regulatory restrictions ■ Can have high vapour pressure ■ Higher cost vs mineral-based ■ System engineering complexity ■ Narrowed material compatibility ■ Narrowed supplier options

Conclusion

Liquid phase heat transfer systems are critical production assets that must be properly designed, installed, and maintained for reliable performance. They consist of several key components, each with their own technology, specifications, and performance parameters. The components and technology discussed in this article are overviews and are in no way an exhaustive treatise of a typical high-temperature heat transfer system. Materials science and the digital transformation will continue to provide robust technologies for safer and more reliable operation of heat transfer systems.

Notes

1. The scope of this article refers primarily to liquid-phase heat transfer systems.
2. Liquid phase hydrocarbon fluids have expansion rates of 3 – 7% per 100°F depending on the chemistry.
3. Viscosity index is a unitless measure of the change of viscosity with temperature, commonly associated with lubricating oils.
4. Thermal property data includes density, viscosity, thermal conductivity, heat capacity, and vapour pressure over the recommended operating range.