Front. Energy 2011, 5(1): 20–42
DOI 10.1007/s11708-011-0139-9

FEATURE ARTICLE

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Revolutionizing heat transport enhancement with liquid metals: Proposal of a new industry of water-free heat exchangers

Abstract Water is perhaps the most widely adopted working fluid in conventional industrial heat transport engineering. However, it may no longer be the best option today due to the increasing scarcity of water resources. Furthermore, the wide variations in water supply throughout the year and across different geographic regions also makes it harder to easily access. To address this issue, finding new alternatives to replace water-based technologies is imperative. In this paper, the concept of a water-free heat exchanger is proposed and comprehensively analyzed for the first time. The liquid metal with a low melting point is identified as an ideal fluid that can flexibly be used within a wide range of working temperatures. Some liquid metals and their alloys, which have previously received little attention in thermal management areas, are evaluated. With superior thermal conductivity, electromagnetic field drivability, and extremely low power consumption, liquid metal coolants promise many opportunities for revolutionizing modern heat transport processes: serving as heat transport fluid in industries, administrating thermal management in power and energy systems, and innovating enhanced cooling in electronic or optical devices. Furthermore, comparative analyses are conducted to understand the technical barriers encountered by advanced water-based heat transfer strategies and clarify this new frontier in heat-transport study. In addition, the unique merits of liquid metals that could lead to innovative heat exchanger technologies are evaluated comprehensively. A few promising industrial situations, such as heat recovery, chip cooling, thermoelectricity generation, and military applications, where liquid metals could play irreplaceable roles, were outlined. The technical challenges and scientific issues thus raised are summarized. With their evident ability to meet various critical requirements in modern advanced energy and power industries, liquid metal-enabled technologies are expected to usher a new and global era of water-free heat exchangers.

Keywords heat exchanger, liquid metal, water resource, heat transport enhancement, coolant, thermal management, process engineering, energy crisis, chip cooling

Received November 3, 2010; accepted December 16, 2010

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1 Introduction

Limited energy and water resources are two major issues that mankind has to face over this century. Along with the impending energy crisis, water problems are also substantially worsening. Meanwhile, water and energy, as exemplified by heat transport, are closely interrelated; hence, water shortage can potentially lead to more serious energy problems [1]. Heat transport is one of the most fundamental processes in nature, and it has been playing a significant role in modern power and energy industries. In these industries, heat transport is generally enabled by water-based heat exchangers. As such, the current scarcity of water resources is leading to an energy shortage.

The 2006 United Nations Human Development Report [2] warns against an unprecedented crisis in the coming years as a result of the growing scarcity of freshwater per inhabitant in developing countries. As a vital resource that supports all forms of life, water is not evenly distributed across seasons and geographical regions. Some parts of the world are prone to drought, and in these parts, water is particularly a scarce and precious commodity [3]. Desert areas receive an average annual rainfall of less than 250 mm (10 in) annually; they lose more water by evaporation and transpiration than what can be replenished by precipitation [4]. Deserts occupy approximately one fifth (20%) of the Earth's land surface, and they are still continuously expanding. Antarctica is the world's largest cold desert (also known as "polar desert"), and Sahara is the largest hot desert (Table 1). The largest non-polar deserts are presented in Fig. 1.

Table 1 Largest deserts on earth [4]

Rank	Desert	Area/km^2
1	Antarctic Desert (Antarctica)	13829430
2	Sahara (Africa)	9100000+
3	Arabian Desert (Middle East)	2330000
4	Gobi Desert (Asia)	1300000
5	Kalahari Desert (Africa)	900000
6	Patagonian Desert (South America)	670000
7	Great Victoria Desert (Australia)	647000
8	Syrian Desert (Middle East)	520000
9	Great Basin Desert (North America)	492000

Water is essential to life. About 600 million of the 6700 million people around the world are already experiencing chronic water scarcity, and over 1 billion people lack access to safe drinking water. Furthermore, unsafe water and poor sanitation cause 80% of all the diseases in developing countries. Groundwater tables are falling, thereby seriously affecting about one third of the global population. Groundwater resources are increasingly being exploited because nearly all surface water resources are already in use in many parts of the world [2]. If the present trend continues, two out of three people on Earth will be living in water-stressed areas by 2025 [5]. Arid developing countries will be worst hit; the average water availability per person will only be about 15% of the per capita availability in 1950 [2]. With an estimated global population growth of 95% in cities and their surrounding areas [3], the need for solutions is even more pressing. Therefore, water supply for the burgeoning global population is one of the greatest challenges that mankind is facing today [6].

Water scarcity is already a serious global problem, and it will become critical in the first half of this century [1]. Unfortunately, most industrial heat transport processes are still water based because water is readily available and its use is rather convenient. It should be noted that in most industrial purposes, freshwater is needed because saltwater corrodes metals. Globally, 22% of the total water use is accounted by industries; water is used for fabrication, processing, washing, and cooling. Moreover, water is used by smelting facilities, petroleum refineries, and industries producing chemical products, food, and paper products. High-income countries account for 59% of the total industrial water use, whereas low-income countries only account for 8% [7,8]. These figures are expected to increase with industrial production, making the issue of water scarcity even more pressing. Freshwater resources are likely to be more constrained in the future; hence, developing new alternatives to replace water-based technologies, especially conventional heat exchangers, must be prioritized. Potential alternatives must have favorable basic characteristics, such as low melting point, low viscosity, high thermal conductivity, and high heat capacity. Research has shown that the use of liquid metals with a melting point at around room temperature is one of the most efficient and effective solutions. Although the cost of liquid metals is generally higher than that of most conventional technologies, a strong global effort in fundamental research, practical development, and device demonstration could rapidly bridge the existing cost gap. In fact, certain liquid metals, such as NaK alloys, are already cheap enough. Most importantly, escalating water

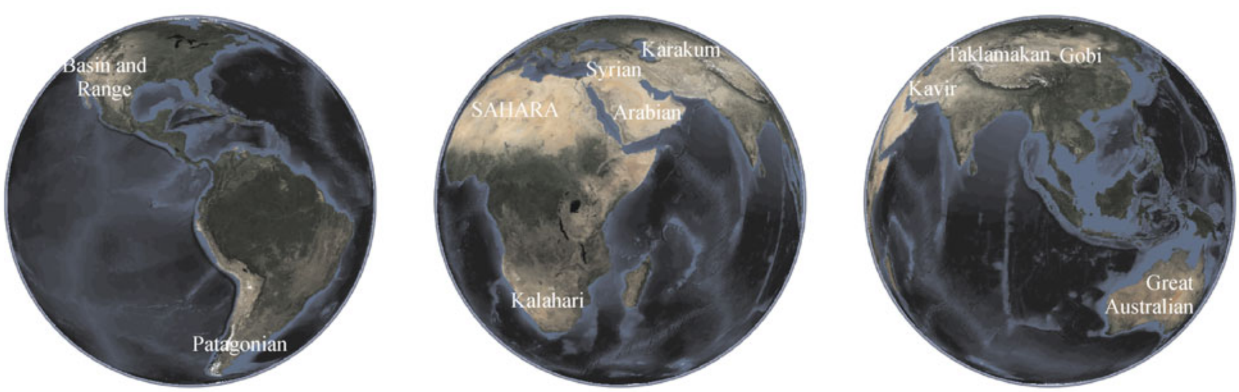


Fig. 1 Largest non-polar deserts on earth [4]

scarcity and the environmental costs of existing technologies make the development of water-free technologies not just an option but a necessity. Based on this consideration, we propose the concept of water-free heat exchangers for the first time, and we systematically explain the basic features, applications, and challenges of water-free heat exchangers.

As shown in Fig. 2, water and liquid metals have different physical and chemical properties [9, 10]. For a long time, liquid metals with melting points at room temperature have largely been ignored in the field of general heat transfer. However, it is doubtless that such metals have important applications in various industries. Recently, Liu and Zhou [11] opened up a new area of liquid-metal-based chip cooling, which has significantly sparked widespread academic and industrial interests. Compared with conventional working fluids, liquid metals have unique advantages in enhancing thermal performance and saving energy. However, to date, few data on liquid metals are available. We only have a rather limited practical experience in the fields of nuclear [12–14] and IT [11,15,16] concerning liquid metal applications. Liquid metals are expected to be useful in a wide range of areas, especially in those areas where water resources are limited, such as in the desert-based petroleum industry. At this stage, high cost and technical complexity serve as significant barriers to the general application of liquid metals in industries. These barriers are brought by the lack of related research proving the feasibility of using liquid metals and by a general failure to appreciate the tremendous value that this new technology could provide. To push forward research and development in the newly emerging field of liquid metal engineering, we outline the profile of a group of liquid-metal-based heat exchangers and evaluate the potential benefits of using liquid metals as working fluids. First, the basic innovative features of major heat exchangers are compared in terms of their advantages and disadvantages. Meanwhile, the merits of liquid metals in heat transfer application are identified. After the discussion, several promising and important liquid metal applications are clarified for the first time. This paper is expected to fill the research gap in many fields.

2 Features of mainstream heat exchangers

Fluids in heat exchangers may be single-phase streams, such as gases and liquids, whereas others may be two-phase, such as vapors and gases or liquids with particles/slurries. The kind of heat-exchange fluids, the range of applied temperature, the range of applied pressure, and the kind of application sites make particular demands on the material, geometry, compactness, and weight of heat exchangers. Consequently, heat exchangers are manufactured with different structures from metal and nonmetal materials. Therefore, diverse types, shapes, arrangements, and combinations of heat exchangers are used by industries.

Heat exchangers may be categorized based on the following factors: transfer processes, number of fluids, surface compactness, flow arrangements, heat transfer mechanisms, type of fluids (e.g., gas-gas, gas-liquid, liquid-liquid, gas-twophase, and liquid-twophase), and application areas [17]. Moreover, they can be classified according to their construction and process functions, as outlined in Fig. 3 [17]. More information can be found in Shah and Mueller [18]. It should be noted that the use of liquid metals is suitable for most heat exchangers. Meanwhile, liquid metals are not advisable in the case of welded and brazed heat exchangers because chemical reactions may occur when liquid metals come in contact with the metal flux, thereby increasing the probability of leakages and accidents. Thus, special safety considerations should be adopted when liquid metals are used in these cases.

(a)

(b)

Fig. 2 Appearance of (a) water [9] and (b) liquid metal [10]

2.1 Classification of heat exchangers by geometry and structure

2.1.1 Shell-and-tube heat exchangers

Many industrial applications, such as chemical, petrochemical, food, refrigeration, and power station applications, utilize shell-and-tube heat exchangers because of their relatively simple manufacturing process and their adaptability to different operating conditions. Shell-and-tube heat exchangers, which contain a number of parallel tubes inside a shell, are used when a process requires large amounts of fluids to be heated or cooled. Due to their

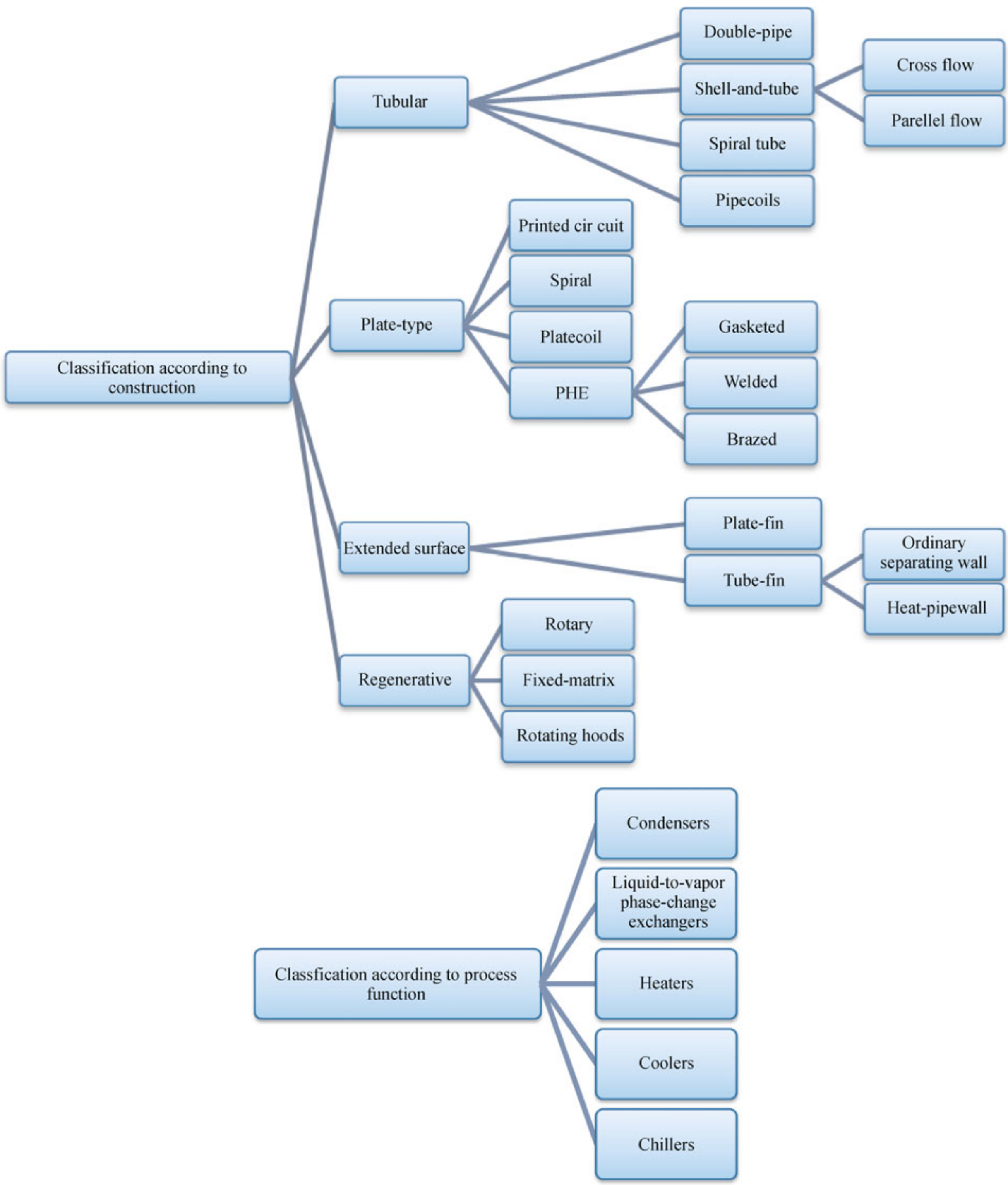


Fig. 3 Classification of heat exchangers according to construction and process functions [17]

design, shell-and-tube heat exchangers offer a wide heat transfer area and a high heat transfer efficiency. Moreover, they can ensure a stable heat transfer through the multiple passes of one or both fluids. Various types of shell-and-tube heat exchangers have been constructed and put into operation. They serve as reboilers, evaporators, condensers, heaters, and coolers [19,20]. According to construction styles, they are divided into fixed tubesheet, U-tubesheet, and floating tubesheet exchangers [21]. Figure 4 presents a typical shell-and-tube heat exchanger [22,23].

Although shell-and-tube heat exchangers have some advantages, such as a wide heat transfer area and a high heat transfer efficiency, they also have several limitations. For instance, for systems that shut down at night and weekends, secondary water temperature can be low at start-up in a cold winter morning. This can cause internal corrosion, mechanical stress due to distortion, and water hammer noise. Liquid metals, which cover a wide range of working temperatures, offer an excellent solution to these problems. For example, tightly sealed mercury (melting point = −38.87°C) can be used as a feasible alternative.

2.1.2 Plate heat exchangers

Plate-type heat exchangers were initially developed for hygienic applications, such as dairy, brewery, and food processing industrial applications. Today, they are also applied in modern power and process industries because of their manifold advantages, such as compactness, flexibility, easy installation, capability to recover heat with extremely small temperature differences, and smaller hold-up volume (hence quicker response to control operations) [24–28]. Hence, much research has been focused on this particular type of heat exchangers [29–34].

A plate heat exchanger consists of a pack of thin corrugated metal plates with portholes for the passage of fluids, as illustrated in Fig. 5 [31]. Each plate contains a bordering gasket, which seals the channels formed when the plate pack is compressed and mounted on a frame. The hot and cold fluids flow in alternate channels and heat transfer takes place between adjacent channels. The corrugation of the plates promotes turbulence inside the channels and improves the mechanical strength of the plate pack [35, 36]. The number of plates, their perforation, the type and position of the gaskets, and the location of the inlet and outlet connections at the covers characterize the plate heat exchanger configuration and define flow distribution inside the plate pack. The flow distribution can be in parallel, in series, or in any of their various possible combinations.

Compared with tubular exchangers, different flow arrangements can conveniently be accomplished in plate exchangers to meet specific demands. They are especially suitable for heat exchange among more than two fluid streams that may not be mixed. The plates are easy to remove; hence they are easily cleaned and replaced when necessary. However, freeze and frost cracks during winter are still problematic when water is used as coolant. This can be resolved with liquid metals having low melting points (e.g., mercury).

2.1.3 Compact heat exchangers

Compact heat exchangers have a high specific surface area and a high ratio of heat transfer surface to heat exchanger volume. Heat exchangers with over 700 m^2/m^3 of the specific surface area are classified as compact one. Generally, plate-fin and tube-fin exchangers, as well as regenerators, belong to this category (Fig. 6) [37,38]. A tubular exchanger with a tube diameter of less than 5 mm may be considered compact [21].

Unlike shell-and-tube heat exchangers, compact heat exchangers can be designed to operate in a pure counter-flow mode, and they can accommodate multiple fluid streams. Moreover, compact heat exchanges have multi-stream capability, high thermal efficiency, small size, low weight, design flexibility, and energy-saving capacity; hence, they allow a reduction in the quantity of fluids in evaporators while increasing safety [39–41]. However,

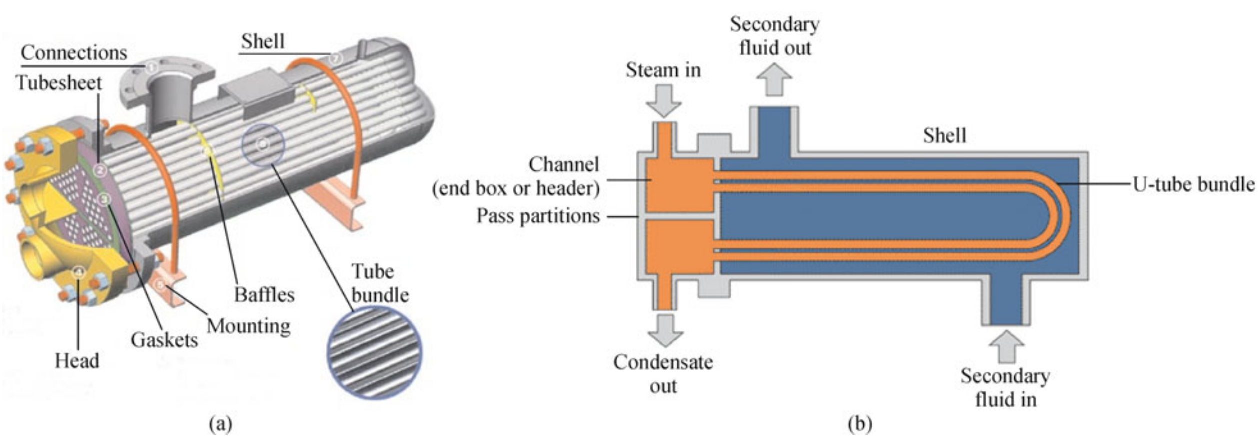


Fig. 4 Typical shell-and-tube heat exchanger: (a) prototype [22] and (b) profile [23]

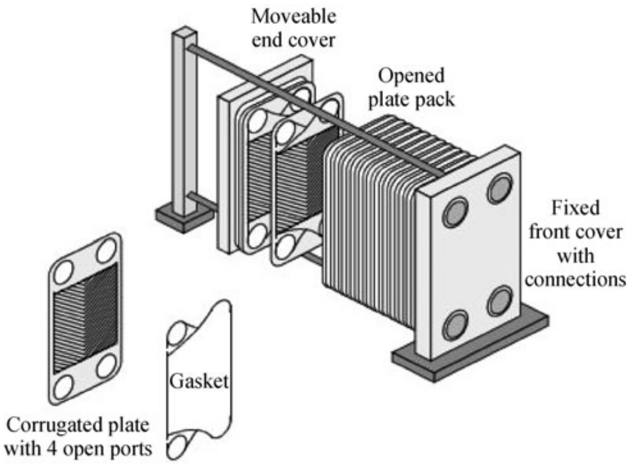


Fig. 5 Plate heat exchanger assemblage [31]

taking water as a tube-side working fluid is also restricted by the freeze phenomenon. Meanwhile, liquid metals with wide working temperature ranges can realize true single-phase liquid cooling, and consequently reduce the probability of leakages and accidents. Furthermore, their boiling points — often more than 2200°C — eliminate the need to refill coolants.

2.1.4 Heat pipe heat exchangers

In a heat pipe heat exchanger, the latent heat of vaporization is utilized to transfer heat over a long distance with a corresponding small temperature difference. This exchanger consists of individual closed tubes that are filled with an appropriate working fluid. In the operation, working fluid evaporates at the evaporation section and condenses over the other end of the tube (Fig. 7). The condensed fluid returns to the evaporator section through the capillary action of the wick or by gravitational force in the thermosyphon heat pipes [42].

Compared with other conventional heat exchangers, heat pipe heat exchangers have many advantages. Large quantities of heat are transported through a small cross-sectional area with no additional power input to the system, and the pressure drop in fluids is minimized. They have advanced maintainability, high reliability, simple structures, small volumes, small end-to-end temperature drops, and extremely wide temperature application ranges (4–3000 K). Moreover, they have the ability to control and transport high heat rates at various temperature levels [43–47].

Heat pipes have been applied in many ways since their introduction in 1964. Some of the important applications are found in the areas of spacecraft cooling [48,49], electrical and electronic equipment cooling [50], medicine and human body temperature control [51–53], and heat recovery [54–56].

Several factors, including operating temperature range, vapor pressure, thermal conductivity, compatibility with the wick and case materials, stability, and toxicity, affect the selection of appropriate working fluids. The theoretical operating temperature range of a given heat pipe is typically between the critical temperature and triple state of the working fluid [57]. Normally, water and toluene are used as working fluids inside heat pipes for low temperature ranges (30°C–200°C), whereas Dowtherm and naphthalene are used for high temperature ranges [58–60]. The heat transfer characteristics of working fluids can be expressed by Merit Number, which is defined as [57]:

$$M = \frac{\rho_1 \sigma_1 \lambda}{\mu_1}, \qquad (1)$$

where σ_1 is the surface tension of the working fluid, λ is the latent heat of vaporization, and μ_1 is viscosity.

It should be noted that the normal (dynamic) viscosity of liquid gallium is approximately 1.5 times that of water, and its mass density is approximately 6 times that of water. This means that liquid gallium can be pumped through small channels with relative ease. The surface tension and

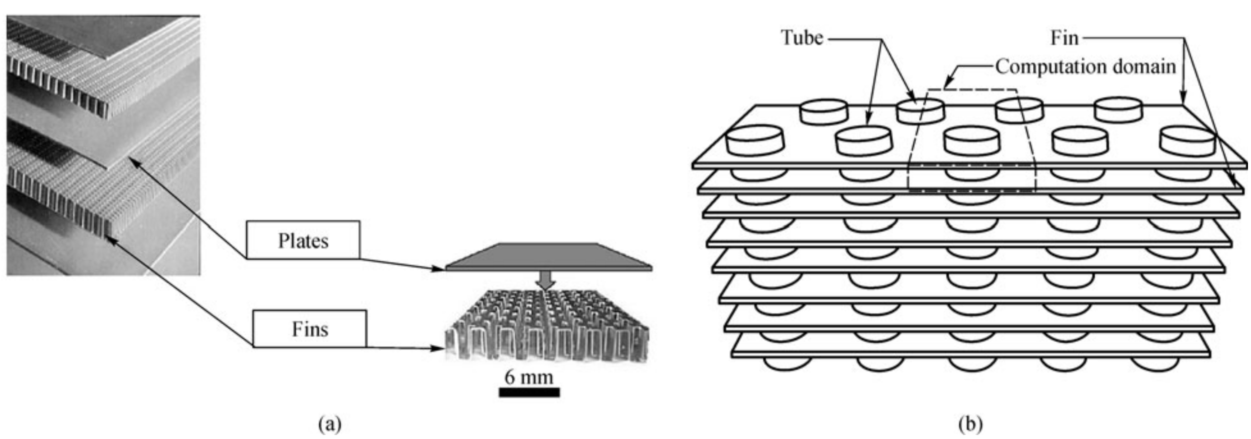


Fig. 6 Examples of compact heat exchangers: (a) plate-fin heat exchangers [37] and (b) tube-fin heat exchangers [38]

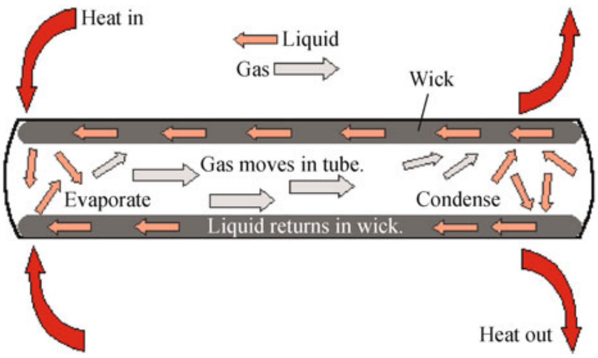


Fig. 7 Heat pipe[1)]

the latent heat of vaporization of liquid gallium are much higher than those of water. Thus, the heat transfer characteristics of liquid gallium is much better than that of water. Moreover, liquid gallium is not toxic and is relatively cheap. It has a much higher specific heat capacity per unit volume, a much lower vapor pressure at room temperature, and a much less reactive nature when exposed to oxygen and water. All these compelling properties warrant its future applications in heat pipe heat exchangers.

2.1.5 Polymer heat exchangers

Heat exchangers are commonly made from various materials, such as aluminum, stainless steel, nickel, and copper, depending on operating temperatures and pressures [40]. Nevertheless, the operating limitations of metallic heat exchangers in some applications have created the need to develop alternative designs using other materials. Polymer sparks are of interest because of their ability to handle both liquids and gases (single and two phase duties). Furthermore, they offer substantial weight, volume, space and cost savings, resistance to fouling and corrosion, and possible use in humidification and dehumidification duties [41,61]. Figure 8 presents examples of polymer heat exchangers. Milieupartners Calorplast plastic heat exchangers, as shown in Fig. 8(a), are suited for air cooling under condensing conditions [62]. A polymer plate heat exchanger with a unique extended surface pattern, as shown in Fig. 8(b), has been developed by Greenbox Co. [63].

Polymer heat exchangers have wide applications, such as in the desalination, recovery, and dissipation of heat energy in buildings. They are also used in absorption chillers and solar collectors. Moreover, polymer heat exchangers are widely applied in the food industry; refrigeration, air-conditioning, and ventilation industry; cryogenic industry; automotive industry; computer industry; and chemical industry [64–70]. They are also well compatible with liquid metals. Hence, we need to strengthen further the applications of liquid metals in the industrial heat transport process.

2.2 Heat exchange enhancement techniques

To obtain more compact and efficient units, heat transfer augmentation techniques have been successfully used in many heat transfer situations, such as in process industries, heating and cooling in evaporators, thermal power plants, air-conditioning equipment, refrigerators, radiators for space vehicles, and automobiles [71]. Heat transfer augmentation techniques are broadly classified into active and passive techniques. Passive techniques do not require

Fig. 8 Examples of polymer heat exchangers: (a) milieupartners polymer heat exchanger [62] and (b) Greenbox polymer plate units [63]

1) Definition: heat pipe. http://www.zdnet.com/topics/heat + pipe

any external power, whereas active heat transfer augmentation is conducted by utilizing the effect of external power. External power induces secondary motions that in turn cause instabilities in the thermal and hydrodynamic boundary layers, thus leading to increased transfer rates at the heat transfer surface for a given temperature. Although active techniques tend to add complexity to the system and cost to the operation, they are two to three times more effective than passive techniques. The selection of a particular technique depends on applications, the geometry of the heat transfer surface, service life, working fluid type, and operating conditions [72]. Table 2 summarizes the most common passive and active enhancement techniques [73].

Apart from developments in heat transfer enhancement techniques, some structural improvements have been introduced in both tubular and plate exchangers. New materials also inspire the invention of new heat exchangers. Currently, the proposal of using liquid metals with high thermal conductivity as an alternative to water is very promising.

Table 2 Major passive and active enhancement techniques [73]

Passive techniques	Active techniques
Treated surfaces	Mechanical aids
Rough surfaces	Injection of suction
Extended surfaces	Jet impingement
Displaced enhancement devices	Surface vibration
Swirl flow devices	Fluid vibration
Surface tension	Rotation
Additives for liquids	Electromagnetics
Additives for gases	Electrohydrodynamics

3 Limitations of typical water-based heat exchangers

3.1 Properties of water

Water is the most abundant compound on Earth, constituting about 70% of the planet's surface. Water usually comprises 55%–78% of the human body [74]. Table 3 lists typical properties of water at room temperature.

3.1.1 Adhesion and cohesion

Water molecules are attracted to other water molecules. This is called cohesion. Water molecules are also attracted

Table 3 Typical properties of water at room temperature

Temperature /°C	20	Source
Pressure/Pa	2,338	Ref. [75]
Constant-pressure heat capacity at 100 kPa/($J \cdot g^{-1} \cdot K^{-1}$)	4.1818	Ref. [74]
Heat of vaporization/($kJ \cdot mol^{-1}$)	43.99[a)]	Ref. [74]
Density/($kg \cdot cm^{-3}$)	998.2071	Ref. [76]
Specific weight/($kN \cdot cm^{-3}$)	9.789	footnote[1)]
Surface tension/($dyn \cdot cm^{-1}$)	72.8	footnote[2)]
Electrical resistivity/($k\Omega \cdot m$)	182 [b)]	Ref. [74]

Notes: a) 25°C; b) 25°C, theoretical maximum electrical resistivity.

to other materials. This is called adhesion. The oxygen end of water has a negative charge, whereas the hydrogen end has a positive charge. Meanwhile, the hydrogen of one water molecule is attracted to the oxygen from other water molecules. This attractive force gives water its cohesive and adhesive properties [77].

3.1.2 Surface tension

Surface tension refers to the cohesion of water molecules at the surface of a water body. Each molecule in a water drop is attracted to other water molecules in the drop. This causes water to pull itself into a shape (bead or sphere shape) with the smallest amount of surface area. All water molecules on the surface of the bead are "holding one another" or creating surface tension. Water has a very high surface tension. It is sticky and elastic, and it tends to clump together in drops rather than spread out in a thin film. Surface tension is also responsible for the capillary action that causes water to stick to the sides of vertical structures despite the downward gravitational pull. The high surface tension of water allows the formation of water droplets and waves. Moreover, it allows plants to move water (and dissolved nutrients) from their roots to their leaves, and small animals to move blood through tiny vessels [77,78].

3.1.3 Specific heat

Specific heat is the amount of energy required to change the temperature of a substance. Water has a high specific heat, enabling it to absorb large amounts of heat energy before it begins to get hot, release heat energy slowly in situations of cooling, and moderate the Earth's climate and help organisms regulate their body temperatures more effectively [78].

1) Water–Density and specific weight. http://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html
2) Surface tension. http://hyperphysics.phy-astr.gsu.edu/hbase/surten.html

3.1.4 Conductivity

Pure water containing no ions serves as an excellent insulator; however, not even "deionized" water is completely ion free. Water undergoes auto-ionization in liquid state. Furthermore, because water is such a good solvent, it almost always has some solvent dissolved in it, most frequently a salt. If water has even a tiny amount of such a solvent, it can conduct electricity readily because in an aqueous solution, impurities (e.g., salt) separates into free ions through which electric currents can flow [74].

Water conducts heat more easily than any liquid, except liquid metals. This fact gives large bodies of liquid water, such as lakes and oceans, an essentially uniform vertical temperature profile [9].

3.2 Limitations of water-based heat exchangers

Water is the most widely occurring substance on earth; however, only 3% of the earth's total water volume is freshwater (the remainder is saltwater). Some two thirds of this freshwater is locked up in glaciers and permanent snow covers. The available freshwater is distributed regionally, as shown in Fig. 9 [78]. Groundwater and freshwater are useful or potentially useful to humans as water resources. Water resources are renewable (except some groundwater), with huge differences in availability in different parts of the world, and wide variations in seasonal and annual precipitation in many places. This leads women and girls in some rural areas to walk long distances and spend up to four hours daily to provide their households with water [79]. Per capita use is increasing (with better lifestyles) and the population is growing. Thus, the percentage of appropriated water is increasing. Together with spatial and temporal variations in water availability, water for human purposes is becoming scarce [78, 80].

Water is tremendously used in many industrial processes and machines, such as in steam turbines and heat exchangers, in addition to its use as a chemical solvent. The discharge of untreated water from industrial uses, including discharged solutes (chemical pollution) and discharged coolant water (thermal pollution) [80], is considered pollution. It should be noted that water freezes at 0°C under standard conditions (101.325 kPa and 0°C). Thus, the application of water in low-temperature and cryogenic industries is limited. Furthermore, metallic facilities exposed to water tend to corrode due to electrochemical reactions, and both water temperature and water flow velocity can strongly influence corrosion rates. All these factors restrict the wide application of water-based industrial heat exchangers, and imply an urgent need for an alternative to water. This paves the way for the development of water-free heat exchangers.

4 Innovating conventional heat exchangers with liquid metals

4.1 Basic features of liquid metals

4.1.1 Structures and characteristics of liquid metals

Metals have giant atomic structures held together by metallic bonds. Researchers at Lawrence Livermore National Laboratory have found that in addition to the rearrangement of sodium atoms in liquid under pressure, electrons are transformed as well. The electronic cloud gets modified, the electrons sometimes get trapped in interstitial voids of the liquid, and atomic bonds adopt specific directions [81]. Liquid metals exhibit special characteristics, as shown in Fig. 10 [81].

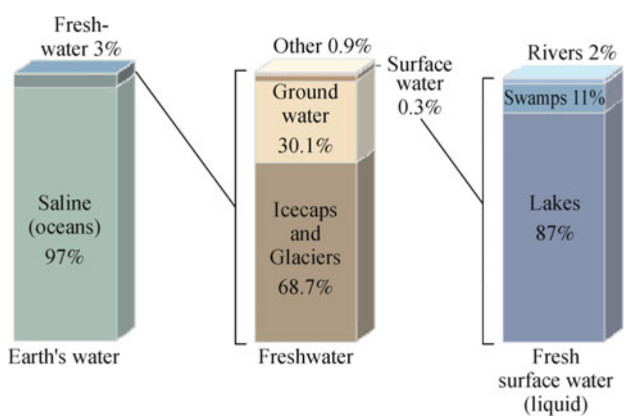


Fig. 9 Distribution of earth's water [78]

Fig. 10 Appearance of liquid metals [81]

The thermal conductivity of a metal is much higher than that of a general liquid, such as water, oil, and many organic fluids. Thus, if a certain liquid metal (or its alloys) with a low melting point is adopted as a cooling fluid, a much higher cooling capacity than that of traditional fluids can be obtained [15]. Starting from this basic point, Liu and Zhou [14] proposed for the first time the use of liquid metals or their alloys as cooling fluids for the thermal management of computer chips in 2002. Similarly, liquid metals are also a potential candidate coolant for next-generation coolants in general industrial heat exchangers because of their favorable properties, such as high thermal conductivity, high electrical conductivity, low vapor pressure, low dissolution in water, high boiling point above 2200°C, and true single-phase liquid cooling. High electrical conductivity enables the application of non-moving and compact magneto-fluid dynamic (MFD) pumps. Furthermore, the liquids can be pumped efficiently with silent, vibration-free, and low energy consumption rates because of the absence of moving components. Numerous experiments have been performed to test the properties of liquid metals or their alloys, such as tungsten [82], lead-bismuth alloy, and gallium. The typical properties of liquid metals, gathered from various studies, are presented in Table 4 [16, 83–85].

The first three metals in Table 4, namely, mercury, cesium, and gallium, remain in liquid state at or around room temperature, making them suitable for use in heat exchangers for most industrial areas, such in manufacturing, air-conditioning, and refrigeration applications. Gallium and cesium have quite acceptable melting points, just above room temperature, and good thermal conductivity. Gallium is regarded as superior to cesium because of its low working temperature range, much higher specific heat per unit volume, much lower vapor pressure at room temperature, and much lesser reactive nature when exposed to oxygen and water. Meanwhile, mercury has been used in some earlier versions of fast breeder reactors. However, a leakage in mercury cooling loops can be disastrous, even at room temperature, and it becomes even worse at an elevated temperature. Such kind of metals could easily contaminate the whole system. Furthermore, mercury vapors are hazardous to human health. Hence, it is forbidden in most accelerator environments, and unless specifically requested, its use is not recommended.

Sodium and potassium, as active alkali metals, are also very good cooling fluids. Although their operating temperature ranges are narrower than those of previously described metals, the alloy of sodium and potassium has been widely used in fast breeder reactors. Sodium is a normal coolant used in large power stations, and both lead and NaK have been used successfully for smaller generating rigs. However, they are quite reactive to air and water, are therefore considered fire hazards. This entails special safety considerations when they are really adopted as coolants. As for liquid rubidium, it has all the necessary features of an excellent coolant, but it is extremely expensive and reactive.

The other three metals — tin, lithium, and indium — are also excellent coolants. Lithium, especially, has two outstanding advantages in the task of heat transfer: a very high thermal conductivity and a very high specific heat capacity per unit volume [15]. The relatively high melting points of these metals make them suitable for high-temperature areas, such as in waste heat recovery plants. In summary, liquid metals have the potential to meet and supplement various energy requirements.

4.1.2 Potential application of liquid metals

The use of liquid metals offers an outstanding and competitive heat transfer performance. Much of the initial

Table 4 Thermal properties of typical metals with low melting points [16, 83–85]

Liquid metals	Melting point/°C	Evaporation point/°C	Evaporation pressure/mmHg	Specific heat /$(kJ\cdot kg^{-1}\cdot K^{-1})$	Density/$(kg\cdot m^{-3})$	Thermal conductivity /$(W\cdot m^{-1}\cdot °C^{-1})$	Surface tension /$(N\cdot m^{-1})$
Mercury	−38.87	356.65	1.68×10^{-3} a)	0.139 a)	13 546 a)	8.34 a)	0.455 a)
Cesium	28.65	2023.84	10^{-6} d)	0.236 d)	1796 d)	17.4 d)	0.248 d)
Gallium	29.8	2204.8	10^{-12}	0.37 n)	5907 n)	29.4 n)	0.707 n)
Rubidium	38.85	685.73	6×10^{-6}	0.363 m)	1470 m)	29.3 m)	0.081
Potassium	63.2	756.5	6×10^{-7}	0.78 m)	664 m)	54.0 m)	0.103 d)
Sodium	97.83	881.4	10^{-10}	1.38 d)	926.9 d)	86.9 d)	0.194 d)
Indium	156.8	2023.8	$< 10^{-10}$	0.23	7030 c)	36.4 c)	0.55 m)
Lithium	186	1342.3	10^{-10}	4.389 b)	515 b)	41.3 b)	0.405 b)
Tin	232	2622.8	$< 10^{-10}$	0.221	7.3 d)	15.08 b)	0.531 m)

Notes: a) 25°C; b) 200°C; c) 160°C; d) 100°C; n) 50°C; m) at melting point.

interest in the application of liquid metals has been in the nuclear industry. The transmutation of waste blankets cooled with liquid metals has been proposed to reduce the amount of the long-term toxicity contained in nuclear wastes consigned to geologic repositories. This process aims to separate uranium from the fraction of transuranic (TRU) elements and fission products in the spent light water reactor fuel [86]. Liquid metal cooling is also used in accelerators. Fast reactors typically use liquid metals as primary coolants to cool the core and heat the water, which is subsequently used to power electricity-generating turbines. Sodium is a normal coolant for large power stations, whereas both lead and Na-K alloys have been used successfully for smaller generating rigs. Meanwhile, mercury has been used in some earlier fast breeder reactors. One advantage of using mercury and Na-K alloys is that they both always exist in liquid state at room temperature. They are convenient for experimental rigs, which are less important to full-scale power stations. The advanced photon source (APS) at Argonne has pioneered the use of liquid metals as cooling fluids for X-ray optics in high-intensity synchrotron beam lines [87]. Blackburn and Yanch [88, 89] introduced liquid metal jet impingement to improve the performance of their accelerator target for boron neutron capture therapy (BNCT). Another agency, Argonne [85], is devoted to the development of liquid metal cooling for the high heat load X-ray optics of next-generation synchrotron facilities.

Compared with sodium-cooled fast reactors, fast reactors cooled by heavy liquid metals (lead or lead-bismuth) have adopted relatively open fuel lattices without wire spacers. Tak et al. [90] performed a sub-channel analysis of lead-bismuth-cooled fuel assemblies with ducts. Using the modified SLTHEN code, they investigated thermal hydraulic characteristics with emphasis on the turbulent mixing between sub-channels and interior assembly heat transfer.

Using liquid metal lithium as a coolant in the mixed breeder blanket has the merits of excellent thermal properties, neutron moderation, tritium breeding effect, and simple construction. Farabolini et al. [91] presented computations linking tritium release rates to the characteristics of lithium-lead and helium cooling circuits. The effects of tritium permeation on helium coolants in blanket modules, lithium-lead circulation rate, tritium extraction unit efficiency, tritium permeation in the steam generator, helium coolant leak rate, and helium purification unit maximum flow rate and efficiency were evaluated.

Galinstan — a family of eutectic alloys that mainly consist of gallium, indium, and tin — is liquid at room temperature and freezes typically at −19°C (−2.2 °F) [92]. It is used as a replacement for many applications that previously employed toxic liquid mercury or reactive NaK (sodium-potassium alloy) because of its low toxicity and the low reactivity of its component metals. Galinstan is difficult to use for cooling fission-based nuclear reactors because indium has a high cross-section for thermal neutrons, thereby efficiently absorbing neutrons and inhibiting fission reaction. Meanwhile, galinstan is being investigated as a possible coolant for fusion reactors. Unlike other liquid metals that are used in this application, such as lithium and mercury, non-reactivity makes galinstan a safer material to use [93].

Recently, a new area in the IT industry has emerged since Liu and Zhou [14] proposed the use of liquid metals or their alloys as cooling fluids for the thermal management of computer chips. A number of works have been conducted, promising the exciting future of this thermal management frontier [15, 16, 94, 95]. The applications of liquid metals and their alloys in nuclear and IT industries start to reveal a realistic potential for wider industrial applications.

4.1.3 Advantages of liquid metals over water

As a very promising coolant, liquid metals have some merits over water, as demonstrated in Fig. 11. First, compared with water, liquid metals with high thermal conductivity quickly transfer heat away, and the probability of leakage and accident is low because of single-phase liquid cooling. Second, these electrically conductive liquids can be driven efficiently with silent, vibration-free, non-moving, and energy-saving magneto-fluid dynamic (MFD) pumps. Third, although water is comparatively cheaper, liquid metals have more excellent characteristics, and they can potentially meet and supplement various energy requirements.

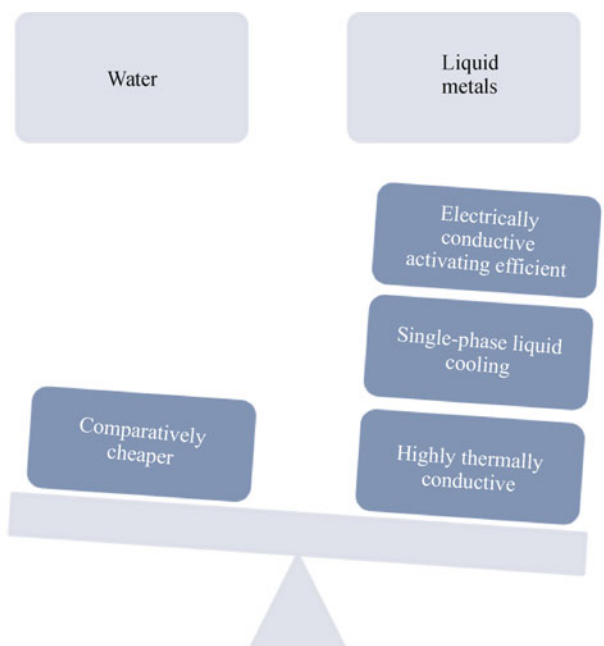


Fig. 11 Comparison between water and liquid metals

We take gallium as an example. Its physical and chemical properties are listed in Table 5[1)][96,97] and compared with those of water under normal conditions, unless otherwise indicated.

Table 5 Selected physical and chemical properties of gallium and water under normal conditions

	Gallium	Water
Melting point/°C	29.8	0
Boiling point/°C	2403	100
Vapour pressure/mmHg	10^{-12}	17.54
Mass density/$(kg \cdot m^{-3})$	5907 [a)]	987.7 [a)]
Viscosity/(mPa·s)	1.2 [b)]	1.002
Thermal conductivity/$(W \cdot m^{-1} \cdot °C^{-1})$	29.4[a)]	0.6
Specific heat/$(kJ \cdot kg^{-1} \cdot K^{-1})$	0.37[a)]	4.183
Surface tension/$(N \cdot m^{-1})$	0.707[a)]	0.072

Notes: a) 50°C; b) 77°C.

Generally, the boiling points of many metals are high. This guarantees a low working pressure for liquid metals used as coolants at normal temperatures. The low working pressure in coolant loops improves reliability and safety, simplifies the design and the fabrication of equipment, and makes easy the operation of equipment. Compared with water cooling, liquid metal cooling is more advantageous. First, it has much less possibility of burning out, thus significantly reducing leakage. Second, the coolant can be guaranteed as a truly single-phase fluid because of its high boiling point. Third, it promotes stable cooling by avoiding abrupt changes in pressure while flowing.

The dynamic viscosity of water is 1.002 mPa·s at 20°C, whereas that of liquid gallium is only slightly higher (1.2 mPa·s at 77 °C) [97], suggesting that the normal (dynamic) viscosity of gallium is approximately 1.5 times that of water. Hence, gallium can be pumped through small channels with relative ease.

It is easy to notice that the thermal conductivity of liquid metals is generally several dozen times higher than that of water, which is approximately 0.6 W/(m·°C). With about several dozen times higher thermal conductivity compared with water, liquid metals, such as gallium or its alloys, quickly transfer heat away.

The heat capacity of water is 4200 J/(kg·K), whereas that of liquid metal gallium is 370 J/(kg·K). Although the heat capacity per mass of many metals is much smaller than that of water, their specific heat capacity per unit volume is close to that of water [e.g., 2158 kJ/$(m^3 \cdot K)$ for liquid gallium and 4200 kJ/$(m^3 \cdot K)$ for water]. Gallium has a high specific heat capacity per unit volume, making it a promising coolant in the industrial heat transport process. Furthermore, it can be used for heat exchangers with compact structures.

The surface tension of liquid gallium is much higher than that of water; hence, it is immune to the presence of small cracks or channels in imperfect seals, which cause serious leakages when water is used as cooling fluid. The surface tension of liquid metals can be measured with a vacuum electrostatic levitation furnace above or below the melting temperature [98]. Moreover, liquid gallium is not toxic and is relatively cheap. All these compelling properties warrant its future applications in the industrial heat transport process.

4.2 Innovating conventional heat exchangers with liquid metals

Water is one of the most widely applied conventional energy source worldwide. However, its sustainable potential is limited. Recently, industrial applications have been consuming too much water annually, and there has been a growing awareness of the need to save energy, which calls for more efficient coolants.

Compared with common working fluids, such as water, the thermal conductivity of liquid metals is much higher. Aside from improving the performance of heat exchangers at the same heat transfer area, heat transfer enhancement considerably decreases the size of heat exchangers without sacrificing performance. The reduced physical size of heat exchangers leads to the use of fewer materials in their manufacture, and the construction of associated equipment and buildings. Furthermore, liquid metals allow less dependence on conditions. Unlike water, they are not restricted by variations in scale at different times of the year and across geographical regions.

In water-cooling heat exchanger systems, mechanical pumps are most frequently used to circulate water. However, the use of mechanical pumps involves high energy costs because of their vibration and noise. It is worth mentioning that liquid metals can be driven by the magneto-hydro-dynamic (MHD) pump (also called EM pump or MFD pump), which produces no noise because it has no moving parts. Therefore, the significance of liquid metals can be seen in high energy cost savings. In some situations, liquid metals can be driven using waste heat. In a sense, this leads to a technique with zero net energy input [99]. Furthermore, the fact that the system has no moving mechanical parts eliminates tough issues, such as leakage, wearing out, and sticking.

In short, high thermal conductivity, high volume-specific heat capacity, low kinematic viscosity, very low vapor pressure, and an appropriate working temperature range make liquid metals, especially gallium or its alloys, very promising heat transfer media. Liquid metal coolants can absorb heat more rapidly, making them excellent for

1) Water–Thermal properties. http://www.engineeringtoolbox.Com/water-thermal-properties-d_162.html

some nuclear reactors that are mainly cooled with liquid sodium or potassium. Moreover, they may be used in the manufacture of high-quality machine components, such as gas turbine blades, which are rapidly cooled to 660°C with molten aluminum to prevent defects. The dream of a new world with water-free heat exchangers will certainly come true when liquid metals are widely used as working fluids in industrial heat transport processes.

5 Major strategies leading to liquid-metal-based heat exchangers

Although liquid metals have been mainly used as coolants in nuclear reactors in the past few decades, it should be noted that both the technology and the definition of industries in the past are far different from those of today. Currently, extending liquid metal applications to various industrial situations is not clearly recognized. To clarify this extremely important issue, we present a serious discussion covering the emerging uses of liquid metals from civilian to military applications, and from the ground to the aerospace. Figure 12 illustrates several potential applications of liquid metal cooling [100–103].

5.1 Chip cooling

With rapid improvements in computer performance, tremendous heat generation in computer chips becomes a major thermal management concern. Therefore, over the last four decades, the thermal management of electronic devices, such as super computers, has kept challenging system designers to develop feasible ways of keeping the junction temperatures of electronic components below 85°C [104]. To guarantee safe initiation, as well as smooth and proper working conditions, it is expected that a perfect coolant would always stay in liquid state within 0–100°C. A conventional liquid cooling solution is presented in Fig. 13 [105]. Liquid metal coolants offer a unique solution to cooling high-density power sources and spreading heat in a highly confined space. These two principal advantages lie in the superior thermo-physical properties of liquid metal coolants for extracting heat, and in their ability to pump these liquids efficiently with silent, vibration-free, low-energy, non-moving, and compact MFD pumps. This is achieved with the high electrical conductivity of liquid metals [94,106].

Liquid metal gallium and its alloys are the best coolant candidates. With about several dozen times higher thermal conductivity compared with water, liquid metals, such as gallium and its alloys, exhibit a very good performance in quickly transferring heat away. High thermal conductivity, high volume specific heat capacity, a wide working temperature range (remaining in liquid state at or around room temperature), and a very low vapor pressure are the features that warrant the future applications of liquid metals in the chip cooling area.

There are several special ways to drive liquid metals, and the use of MHD pumps is one of such ways. Peristaltic and electro-wetting pumps may also be used. Recently, new ways have also been developed, such as using the electro-wetting effect to drive discrete droplets of liquid metal alloys in cooling integrated cards [107].

The successful application of liquid metals in the field of IT demonstrates the feasibility of using liquid metals with low melting points as ideal coolants and motivates the application of liquid metals in other industries.

5.2 Heat recovery

The effective industrial utilization of energy is economically and environmentally important. Heat recovery is likely to be the major conservation method to be adopted in a wide range of industries, and it may involve substantial capital outlays [108]. Figure 14 presents a waste heat recovery boiler that can be used in the steel milling, metallurgy, nonferrous metal, petrochemical, chemical, and paper-making industries [109]. Heat exchangers are essential units in the heat extraction and recovery systems of many industries. Depending on the temperature of the exhaust stream and the proposed applications, different heat exchange devices, such as heat pipes and combustion equipment, can be employed to facilitate the use of recovered heat [110].

Waste heat can be recovered from various industrial processes. A distinction is made between high, medium, and low temperatures of waste heat. Table 6 summarizes the temperatures of waste gases and wastewater produced by industrial process equipment [111]. It should be noted that the low-temperature class plays a unique role, which was not fully realized previously. Harvesting such low-grade energy has been difficult both in industries and in daily life. In this regard, liquid metals with high conductivity offer a valuable way to harvest low-grade energy, and they are expected to be very useful in future energy-saving engineering.

Liquid metals with high thermal conductivity are the most attractive and efficient among working fluids. Moreover, they are suited to different temperature ranges. Gallium and its compounds have been proven to be the perfect working fluids for room-temperature appliances [16]. Tin, lithium, and indium are suited for high-temperature areas, such as in waste heat recovery plants, because of their relatively high melting points. Meanwhile, with tighter resealing, mercury can be used in low-temperature fields. Aside from being potential coolants, liquid metals, such as aluminum, magnesium, and zinc, can also be used as sensible heat storage media [112]. Furthermore, more energy can be saved by MHD pumps that are driven by the high electrical conductivity of liquid

Fig. 12 Potential application of liquid metals: (a) cellphones [100], (b) super computers [101], (c) steel industry [102], and (d) solar concentration [103]

metals and that have no moving components. Considering their high thermal conductivity, wide temperature ranges, and energy-saving advantages, the use of novel water-free liquid metal heat exchangers for the industrial heat transport process is very promising.

5.3 Energy system

Energy plays a vital role in the modern society; it enables systems that meet human needs, such as sustenance, shelter, employment, and transportation [113]. Over 85% of human energy demands are met by the combustion of fossil fuels [114]. Since mankind generated electricity on an industrial scale in 1881, hydroelectric power and coal power have been used in power plants. Meanwhile, other methods of power generation, such as natural gas, oil, and nuclear power, have been introduced lately. There are also small amounts of power from solar, tidal, wind, and geothermal sources. In 2006, approximately 15% of the total global power was generated from nuclear plants, 16% from hydroelectric plants, 68% from fossil fuels (coal, oil, natural gas), and less than 1% from renewable energy sources (solar, wind, and tides), as shown in Fig. 15.

Aside from the conventional energy sources described

Fig. 13 Liquid coolant for chip cooling [105]

Fig. 14 Waste heat recovery boiler [109]

Table 6 Typical waste heat temperature at various ranges [111]

Types of devices	Temperature/°C	Temperature range
Nickel refining furnace	1370 – 1650	High temperature range
Steel heating furnace	925 – 1050	
Copper reverberatory furnace	900 – 1100	
Glass melting furnace	1000 – 1550	
Hydrogen plants	650 – 1000	
Solid waste incinerators	650 – 1000	
Fume incinerators	650 – 1450	
Steam boiler exhaust	230 – 480	Medium temperature range
Gas turbine exhaust	370 – 540	
Reciprocating engine exhaust	315 – 600	
Heat treatment furnace	425 – 650	
Drying & baking ovens	230 – 600	
Catalytic crackers	425 – 650	
Annealing furnace cooling systems	425 – 650	
Process steam condensate	55 – 88	Low temperature range
Hot processed liquids	32 – 232	
Cooling water from:		
Bearings	32 – 88	
Welding machines	32 – 88	
Injection molding machines	32 – 88	
Annealing furnaces	66 – 230	
Forming dies	27 – 88	
Internal combustion engines	66 – 120	
Air conditioning and refrigeration condensers	32 – 43	
Liquid still condensers	32 – 88	
Drying, baking and curing ovens	93 – 230	

above, various other technologies have also been studied and developed for power generation. Solid-state generation (without moving parts) is of particular interest in portable applications. This area is largely dominated by thermoelectric (TE) devices, although thermionic (TI) and thermophotovoltaic (TPV) systems have been developed as well. Typically, TE devices, compared with TI and TPV systems, are used at lower temperatures. Piezoelectric devices are used for power generation from mechanical strain and particularly for power harvesting. Betavoltaics is another type of solid-state power generator that produces electricity from radioactive decay. Fluid-based MHD power generation has been studied as a method for extracting electrical power from nuclear reactors, as well as from more conventional fuel combustion systems. Osmotic power is another possibility in places where salt and sweet water merges. Electrochemical electricity generation is also important in portable and mobile applications.

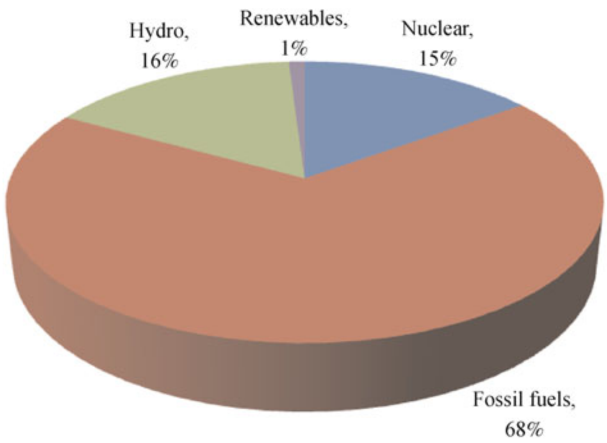


Fig. 15 Sources of global electricity in 2006[1)]

Currently, most electrochemical power comes from closed electrochemical cells ("batteries") [115], which are arguably utilized more as storage systems than generation systems. However, open electrochemical systems, known as fuel cells, have been undergoing much research and development in the last few years. Fuel cells can be used to extract power from either natural fuels or synthesized fuels (mainly electrolytic hydrogen). Thus, they can be viewed as either generation systems or storage systems, depending on their use [116].

It should be noted that all these technologies have their drawbacks. Conventional energy sources usually have environmental implications. For example, issues associated with nuclear power generation include problems on radioactive waste and accidental leakage. Large hydroelectric power plants may cause habitat degradation and fish kills. Wind power plants alter landscapes in ways that some find unappealing, and they increase bird and bat mortality [113]. Furthermore, most proposed renewable energy sources are subject to variability. The sun does not shine at night, the wind does not always blow, and the tides, waves, and currents fluctuate. Liquid metals with high thermal conductivity and electrically conductive activating features can be considered as ideal alternatives. The method of liquid metal cooling for concentrating photovoltaic cells has been evaluated, and excellent performances have been reported [117]. Therefore, liquid metals may be applied to energy systems on a large scale.

5.4 Heat transfer process engineering

In almost all process industries, it is necessary to perform heat transfer unit operations over fluid streams to either heat up or cool down fluid streams, or to produce a phase change either by vaporization or condensation through heat exchangers [118]. In most exchangers, heat transfer is enabled by convection and conduction from a hot fluid to a cold fluid, which are separated by solid walls (see Section 2 for more details).

Usually in process industries, steam and cooling water installations are centralized, serving several process units. A typical example can be found in distillation operations. Usually, the feed stream to a distillation column must be heated up before being introduced into the column. The column bottom product, in turn, must be cooled down before being sent to storage. It is possible to exchange heat between them because the temperature of the column bottom is always higher than that of the column feed [118]. Another example is the mechanical shaping process, which is typified by engraving. It should be noted that gallium corrodes various metals, especially when it is in a hot state. As the temperature of gallium is raised, it becomes increasingly and quickly reactive, corroding through thicker layers. One metal with which gallium is very reactive is aluminum. It corrodes through 0.002" thick aluminum foils within hours at room temperature, and at 500°C–1000°C, this reaction becomes much faster [10, 119]. Thus, non-metal materials, such as plastic and glass, are normally used to contain gallium. However, the corrosive property of gallium makes it suitable for engraving.

5.5 Aerospace exploration

Thermal control and heat rejection for aerospace and avionics science (Fig. 16) are more challenging than ever because of advances in space electronics (miniaturization, complexity, and integration) and the emergence of the more-electric-aircraft (MEA) concept, which makes cooling more difficult[2)]. As for aerospace equipment, the major challenges involve thermal management problems with

Fig. 16 Aerospace exploration: application of liquid metals[3)]

1) What are Some Methods of Power Generation? http://www.wisegeek.com/what-are-some-methods-of-power-generation.htm
2) Thermal management for aircraft, spacecraft and satellites. http://www.thermacore.com/industries/aerospace-avionics.aspx
3) The most experienced name in High-Speed Camera Systems for Aerospace. http://www.nacinc.com/applications/aerospace/

power higher than 100 W at the module level and with local hot spots greater than 100 W/cm^2 [120]. Each of the primary methods, such as convection (moving air), conduction (using solid materials), and the use of liquids (circulating, spray, and immersion), has its own sets of advantages and disadvantages. One can only cool approximately 1 to 1.5 watts per square inch with air. This is less than half that which can be cooled by conduction. With liquids, one can cool up to 100 watts per square inch or more [121]. Thus, liquids are the best choice. Furthermore, with about several dozen times higher thermal conductivity compared with water and being in a single liquid phase with a wide temperature range, liquid metals are no doubt appropriate candidates for aerospace applications.

5.6 Applications in large power system

Efficient cooling has been very important in large power and energy system, such as high power laser, microwave, and radar used for target acquisition and surveillance, as shown in Fig. 17 [122, 123][1)]. Many of the technologies involved in thermal solutions for aerospace and avionics science, such as liquid cooling systems or direct water injection cooling, are valuable for such applications [124]. Similar to aerospace applications, liquid metals seem to be the best choice for such situations because of their high thermal conductivity and MHD drivability.

5.7 Thermal interface material

Aside from their typical applications in heat transfer, liquid metals can also be used as thermal interface materials for conducting heat and/or electricity between non-metallic and metallic surfaces. They could remarkably reduce

Fig. 17 Applications of liquid metals in large power systems: (a) laser [122], (b) microwave [123], and (c) radar[1)]

thermal contact resistance. In this respect, IBM sets an example in photovoltaic technology, as shown is Fig. 18 (a) [125]. Researchers have applied a very thin layer of a liquid metal made of a gallium and indium compound between a chip and a cooling block. Such layer, called thermal interface layer, fills the gap between the two contacting interfaces. The layer reduces thermal resistance in the area, thereby resulting in the further maintenance of the chip at lower temperatures [125]. Another example is Coollaboratory's liquid metalpad. Its thermal interface material is a thin sheet of "dried" metal used to cool processors of high-end PC systems and game consoles, as shown in Fig. 18 (b). Furthermore, Ma and Liu proposed

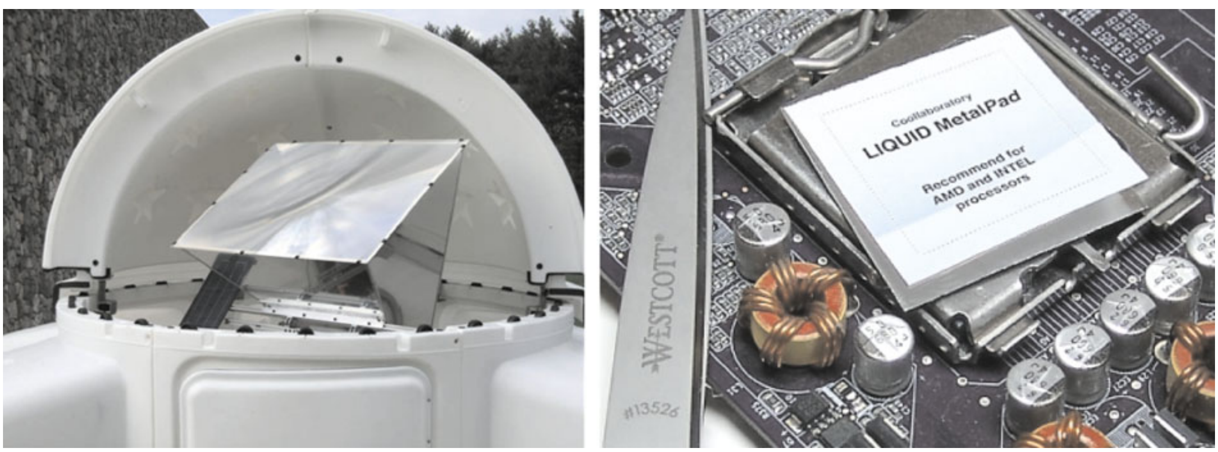


Fig. 18 Examples of thermal interface materials: (a) IBM concentrator photovoltaic cells [125] and (b) coollaboratory liquid metalpad[2)]

1) Radar. http://www.slipring.co.uk/applications/Radar.aspx
2) Coollaboratory - 3 pcs Liquid MetalPad + Cleaning Kit for AMD & Intel CPUs. http://www.sidewindercomputers.com/colimeforamd.html

the concept of a nano liquid-metal fluid, which may lead to the development of a super conductive paste [126]. Through the addition of more conductive nano particles into the base fluid of the liquid metal, the direction toward achieving the most conductive solution in nature has been identified.

5.8 More new conceptual applications

There are still more applications of liquid metals in public reports. This includes their use in fluidic dipole antennas that consist of a fluid metal alloy and eutectic gallium indium (EGaIn), which is injected into microfluidic channels that comprise a silicone elastomer. The fluidic dipole radiates at an efficiency of approximately 90% over a broad frequency range of 1910–1990 MHz. This is equivalent to the expected efficiency of a similar dipole with solid metallic elements, such as copper [127]. Park et al. introduced the microelectromechanical systems (MEMS) digital accelerometer (MDA) that consists of a amicroscale (350 nL) liquid metal droplet in a micro-structured channel etched into a photosensitive glass (Fig. 19). MDA is mainly based on high surface tension, high density, and the electrical conductivity of liquid metal droplets [128].

As perfect heat transfer media, liquid metals may go far beyond what can be imagined at this point. The day will certainly come when liquid metals are widely used in the industrial heat transfer process.

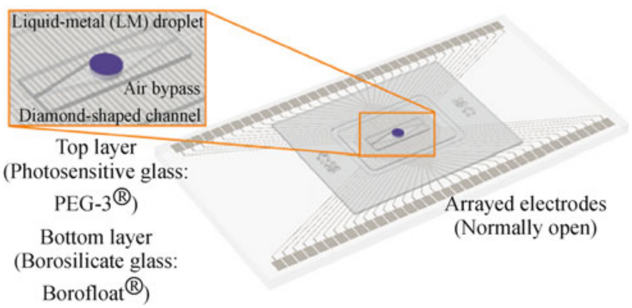


Fig. 19 Overview of the MEMS digital accelerometer (MDA) [128]

6 Technical challenges and scientific issues

The high thermal conductivity of liquid metals warrants their future applications in the industrial heat transport process. However, before their applications are approved in more heat exchange installations, many scientific and technical challenges must first be overcome.

First, most liquid metals are more expensive than conventional working fluids. However, NaK is comparatively cheaper when it is sealed tightly. Second, liquid metals may be oxidized. As such, efforts must be made to prevent the leakage of liquid metal cooling systems. Third, there is a shortage of appropriate measuring techniques, which may be considered as the primary reason behind the relatively slow progress of studies on liquid metals as working fluids. Fourth, liquid metals are embrittled. In summary, the advantages of using liquid metals as coolants can be realized only if they are carefully and intelligently used.

Like other newly emerging technologies, the following are a few of the many scientific issues that must be addressed before liquid metals are widely adopted in the industrial heat transport process:

1) The known liquid metals and their alloys are still limited. They mainly lie at room temperature and high temperature ranges, as shown in Fig. 20. There is little knowledge on liquid metals at extreme and ultralow temperatures. Research is yet to determine the complete temperature range within which alloys may exist.

2) There are three general types of fluid flow in pipes, namely, laminar, turbulent, and transient. Figure 21 presents the schematic diagram of a laminar and a turbulent flow. Transitional flow is a mixture of the laminar and the turbulent flow, with the turbulence flow at the center of the pipe and the laminar flow near the edges. Turbulent or laminar flow is determined by the dimensionless Reynolds Number. In the case of water, ① laminar is when

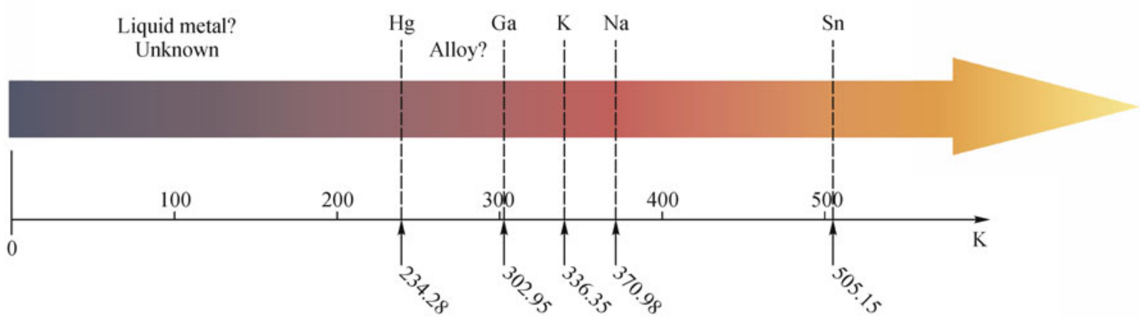


Fig. 20 Thermometric scale of some liquid metals

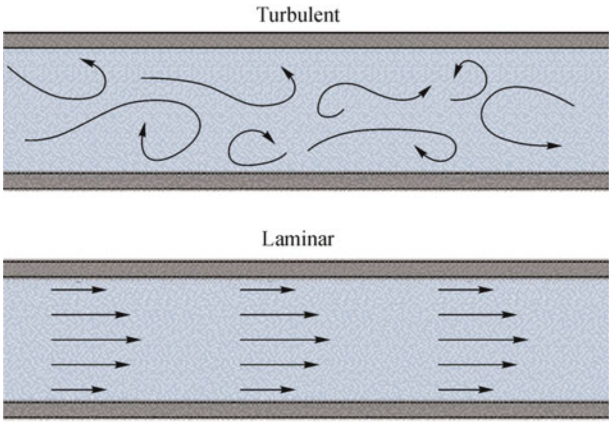


Fig. 21 Schematic diagram of laminar and turbulent flows[1]

$Re < 2300$, ② transient is when $2300 < Re < 4000$, and ③ turbulent is when $4000 < Re$. However, liquid metals have totally different properties. Their pressure loss while flowing, as well as their driving and oscillation characteristics, is still unclear. There are also other cases that need further investigation: the addition of conductive nano metal particles to the liquid metal fluid; and applications in the outer space, which is characterized by a vacuum, zero gravity, enormous temperature differences, and strong cosmic rays radiation.

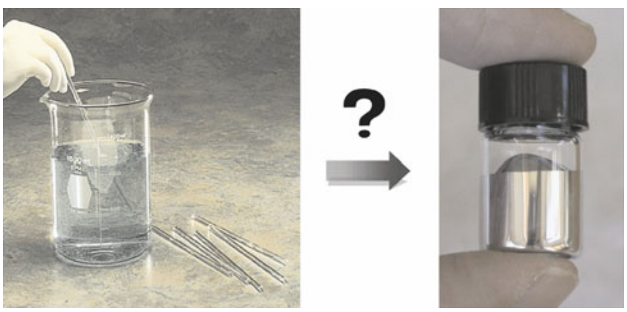


Fig. 22 Availability of heat transfer augmentation techniques (adapted from footnote[2,3])

3) Over the past decades, heat transfer enhancement technologies have been developed and widely used in heat exchanger applications. Many existing heat transfer augmentation techniques — developed in view of the characteristics of water — have exhibited good performance. However, their matching with liquid metals still remains unproved (Fig. 22). Generally, the use of nano particles as additives in modifying heat-transfer fluids to improve performance is promising [127]. Furthermore, the properties of other two-phase flows, such as liquid metal–water, liquid metal–liquid metal, liquid metal–air, and even multi-phase flows should also be investigated.

4) The size of heat exchangers is also a problem to be considered, as shown in Fig. 23. The approaches used to describe microscale heat transport may have very different physical bases from those in macroscopic phenomenological approaches. Therefore, liquid metals applied to different heat exchanger sizes should be carefully investigated.

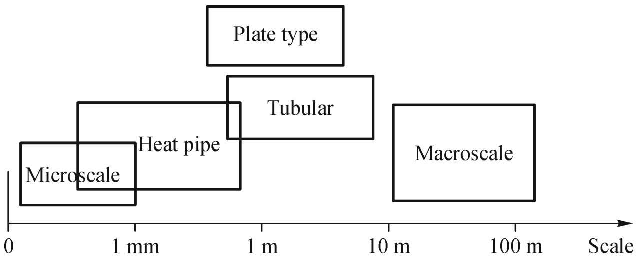


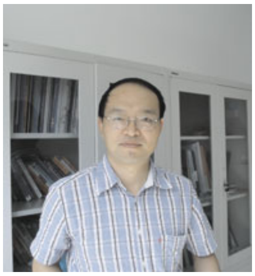
Fig. 23 Availability of heat transfer augmentation techniques

7 Summary

So far, water still remains dominant in the industrial heat transport process because it is cheaper compared with other working fluids. However, the global water supply is steadily being depleted by population explosion, business expansion, and rapid urbanization. The demand for water already exceeds the supply in many parts of the world. With climate change, environmental pollution, and poor water protection, water scarcity will hamper economic development and adversely affect human well-being. Therefore, it is imperative that we develop new alternatives to water in industrial heat transfer. Successful applications in the nuclear and IT industries indicate that liquid metals have outstanding heat transfer characteristics. This paves the way for the application of liquid metals in a wide range of industrial heat-transport areas. Liquid metals have better thermo-physical properties compared with water; hence, they offer attractive opportunities for thermal energy transportation and heat transfer enhancement for heat exchangers. Moreover, liquid metals open many opportunities for meeting and supplementing various energy requirements. This paper has comprehensively evaluated the feasibility of using liquid metals as working fluids. We expect that liquid metals will be widely adopted in the near future; they will usher a new world of water-free heat exchangers. Although they are still in their incubation stage, liquid metals — given their continuous promotion — will revolutionize advanced energy technologies for the whole world.

1) Slow is faster. February 27, 2010. http://blog.nialbarker.com/252/slow_is_faster.html
2) KIMAX® Glass Stirring Rods, Pkg. of 100. http://www.labsafety.com/KIMAX-Glass-Stirring-Rods-Pkg-of-100_s_52522/Stir-Bars—Policeman—Retrei_24550622/?isredirect = true
3) Gallium metal. https://www.scitoyscatalog.com/Merchant2/merchant.mvc?Screen = CTGY&Store_Code = SC&Category_Code = H

Acknowledgements This work was partially supported by the Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences.



Dr. Jing Liu is a professor at the Department of Biomedical Engineering of Tsinghua University and the Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences (CAS). He received his B.E. degree in Power Engineering and Control and B. S. degree in Physics in 1992, and Ph.D. in Thermal Science in 1996, all from Tsinghua University. He then served as assistant professor at Tsinghua University, a postdoctoral research associate at Purdue University, and a senior visiting scholar at Massachusetts Institute of Technology. He has been a professor at CAS since July 1999 and a professor at Tsinghua University since August 2008. Dr. Liu has authored eight popular books on cutting edge research frontiers in energy and bioengineering (among which *Micro/Nano Scale Heat Transfer* has already been reprinted five times), ten invited book chapters, and over two hundred peer reviewed journal and international conference papers. He also holds more than 90 China patents. His two latest books *Unconventional Energy Technologies* and *Advanced Technologies for Low-cost Medicine*, which have received immediate attentions, address ever tough issues facing the current scientific society. Prof. Liu pioneered the research on liquid metal cooling for the thermal management of computer chips, proposed nano-cryosurgery for tumor ablation, and invented the hybrid cryosurgical/hyperthermia system and an interventional whole body hyperthermia equipment. He contributed significantly to the bioheat transfer study through numerous conceptual innovation, methodology development and technical inventions covering both high- and low-temperature medicine and is a world-renowned expert in this area. Prof. Liu is a recipient of the National Science Fund for Distinguished Young Scholars of China, National Science and Technology Award for Chinese Young Scientist, Mao Yi-Sheng Science and Technology Awards for Beijing Youth, and the highest teaching award four times at CAS. His current research interests include thermal management, new energy, micro/nano fluidics, bioheat transfer, and thermally enabled biotechnology and medical instrumentation.

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