Thermal energy storage: the role of the heat pipe in performance enhancement

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Abstract

Heat pipes and thermosyphons—devices of high effective thermal conductivity—have been studied for many years for enhancing the performance of solid, liquid and phase change material (PCM) heat stores. However, as the applications of heat storage widen, from micro-electronics thermal control to concentrated solar heat storage and vehicle thermal management, and even for chemical reactor isothermalization, the challenges facing heat storage increasingly are moving from those associated with the 'standard' diurnal storage, in itself a problem for low thermal conductivity materials, to response times measured in a few hours or even minutes. While high thermal conductivity metals such as foams can be impregnated with a PCM, for example, to increase local conductivity, the rapid heat input and removal necessitates a more radical approach—heat pipes, possibly with feedback control, with innovative PCM interfaces. This paper reviews the use of heat pipes in conventional and rapid response PCM and liquid or cold storage applications and introduces some novel concepts that might overcome current limitations.

Keywords: thermal energy storage; heat pipes; thermosyphons; heat transfer enhancement; applications

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1 INTRODUCTION

Currently, the most common thermal energy storage (TES) systems involve a solid or a liquid as the 'core' of the store, or employ phase change materials (PCMs)—the latter normally being associated with materials that transform from liquids to solids and vice-versa. Steam accumulators (liquid to vapour phase change systems) are used in some industries for meeting peak load demands, particularly as boilers are now frequently undersized for meeting peak demand excursions. Solid heat stores are used on a massive scale in some building applications, and are also popular as 'compact' storage radiators (or convectors) in some domestic heating systems, together with liquid-based convectors. The domestic hot water storage tank is gaining increasing attention as heat pumps and solar thermal systems grow in popularity.

While the liquid/vapour heat storage systems do not suffer from thermal inertia problems due to poor heat transfer, one of the most common challenges associated with liquid/solid storage using PCMs is the perceived low thermal conductivity of the material, particularly when melting needs to be initiated. It is also not uncommon for solid (single-phase) and some liquid-phase stores to require assistance with heat removal and addition using passive methods.

Heat pipes and thermosyphons—devices of high effective thermal conductivity based upon an evaporation/condensation cycle—have been studied for many years for enhancing the performance of solid, liquid and PCM heat stores. However, as the applications of heat storage widen, from micro-electronics thermal control to concentrated solar heat storage and vehicle thermal management, and extending to areas such as chemical reactor isothermalization, the challenges facing heat storage increasingly are moving from those associated with the 'standard' diurnal storage, in itself a problem for low thermal conductivity materials, to response times measured in a few hours or even minutes. While high thermal conductivity metals such as foams can be impregnated with a PCM, for example, to increase local conductivity, the rapid heat input and removal necessitates a more radical approach—heat pipes, possibly with feedback control, with innovative PCM interfaces.

In Figure 1, the thermosyphon on the left only functions with gravity assistance to return the condensate to the evaporator,

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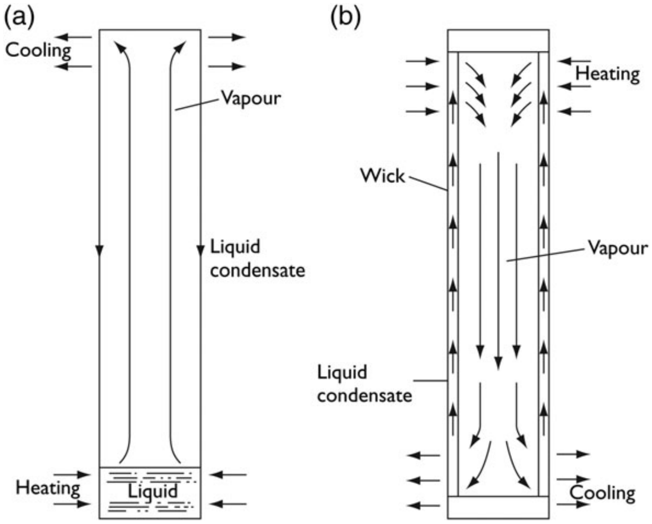

Figure 1. *A thermosyphon (**a**) and heat pipe (**b**).*

while the heat pipe (Figure 1b) can use various passive (and in some cases active) methods for taking the liquid back to the evaporator. It can therefore operate, with some limitations, in any orientation and in zero gravity. Most common wick forms, used to generate the capillary action to drive the liquid from the condenser to the evaporator, are sensitive to heat pipe orientation, and do not perform so well if the heat removal section (condenser) is vertically below the evaporator. Other variants such as loop heat pipes and capillary-pumped loops [1] can overcome this drawback.

Heat pipe operating temperatures are determined solely by the source/sink temperatures—these defining the heat pipe operating temperature range. For very high temperature duties, a liquid metal can be used as the working fluid (e.g. sodium at 800°C) while water is eminently acceptable between ∼40°C and 200°C vapour temperature in the unit. For lower temperatures, ammonia is ideal. The fluid must be chemically compatible with the container and stable. A desirable feature is a high latent heat of vapourization.

So the selection of heat storage media and heat pipe working fluids has several features in common!

2 WHAT CAN A HEAT PIPE OFFER TO THERMAL STORAGE SYSTEMS?

In general, applications come within a number of broad groups, each of which describes a property of the heat pipe. Those most relevant to storage, discussed in more depth later in this section, are:

(i) Separation of heat source and sink
(ii) Temperature flattening, or isothermalization
(iii) Temperature control
(iv) Thermal diodes and switches

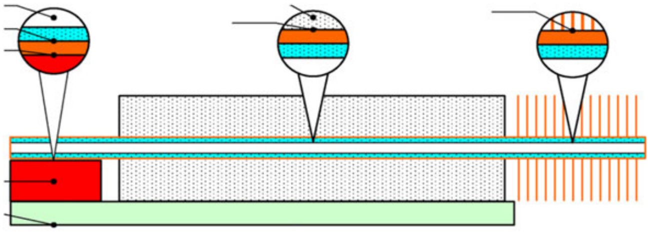

Figure 2. *Separation of the heat source and heat sink—in this case with an intermediate heat storage 'buffer' for electronics thermal control. The electronics is on the left, the storage buffer in the centre and the heat sink on the right [2]. Reprinted from Weng* et al. *[2] with permission from Elsevier.*

2.1 Separation of source and sink

In the context of heat storage, the high effective thermal conductivity of a heat pipe, e.g. 1000s of W/mK, enables heat to be transferred at high efficiency, if necessary over considerable distances. For example, heat dissipation from a high-power device within a module containing other temperature-sensitive components would be implemented by using the heat pipe to connect the component to a remote heat sink located outside the module. Thermal insulation could minimize heat losses from intermediate sections of the heat pipe. In the case of buffering of power semiconductor heat dissipation, a PCM can be located between the heat pipe evaporator and condenser (Figure 2).

2.2 Temperature flattening

The second property listed above, temperature flattening, is closely related to source–sink separation. As a heat pipe, by its nature, tends towards operation at a uniform temperature, it may be used to reduce thermal gradients between unevenly heated areas of a body. Heat pipes 'immersed' in a batch chemical reactor could assist uniform reaction rates by taking heat from more exothermic regions to less active parts of the reactants and of course imagine a low thermal conductivity PCM—putting heat pipes in solely to isothermalize the melting procedure could have a similar effect as in Figure 3. This is discussed in the context of a PCM later.

2.3 Temperature control

The third area of application, temperature control, is best carried out using the variable conductance heat pipe (VCHP). This type can be used to control accurately the temperature of devices mounted on the heat pipe evaporator section. This is done by controlling the amount of heat removed from the heat pipe condenser by releasing or blocking off internal surface. The basic VCHP is shown in Figure 4. By adding active or passive feedback control, the rate of heat removal can be accurately controlled. While the VCHP found its first major applications in spacecraft, it has now become widely accepted in many more mundane applications, ranging from temperature control in electronics equipment to ovens and furnaces.

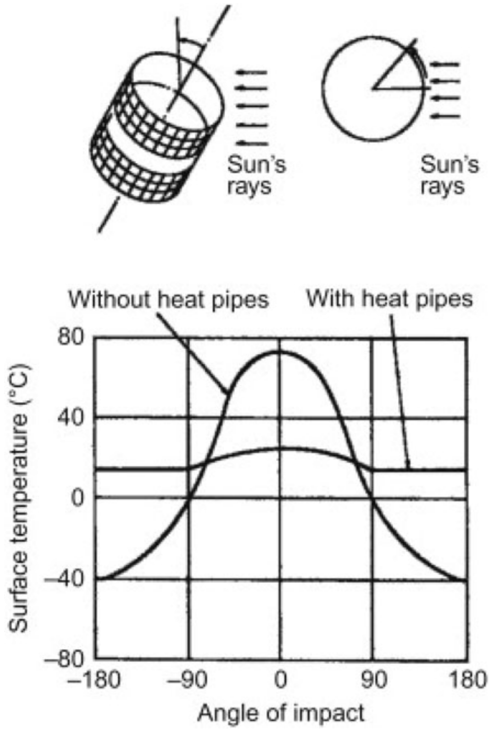

Figure 3. *Isothermalization: these data are from a space satellite application, but are also applicable to chemical and phase change storage. Reprinted from Zhang* et al. *[3] with permission from Elsevier.*

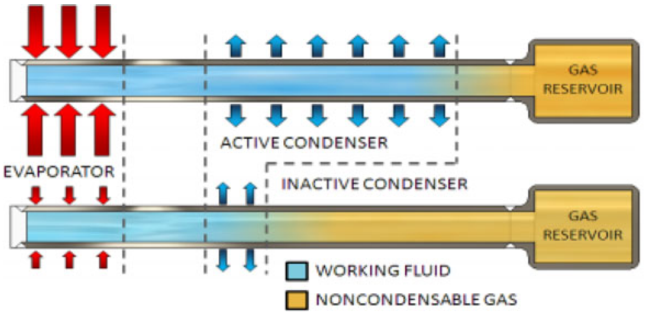

Figure 4. *The basic VCHP. In the context of a PCM, it can be used to control the rate of heat extraction.*

2.4 Thermal diode operation

The heat pipe (or thermosyphon) thermal diode has a number of specialized applications where heat transport in one direction only is a prerequisite. Preservation of permafrost—in itself an energy storage use—is the classic example, recognized in the support posts for the trans-Alaska oil pipeline, but the Tibet–Qinghai highway is a more recent example (Figure 5) [3].

In the storage application shown in Figure 6 [4], the heat pipes (operating as thermosyphons here) transfer the ground heat to the ambient in winter which freezes the soil. When the temperature rises in the spring, the heat is not transmitted from the ambient to the ground (thermal diode), inhibiting soil melting.

Figure 5. *Permafrost preservation—in this case to stop subsidence of a road—will increase in importance as global warming affects the permafrost 'table'. Reprinted from Zhang* et al. *[3] with permission from Elsevier.*

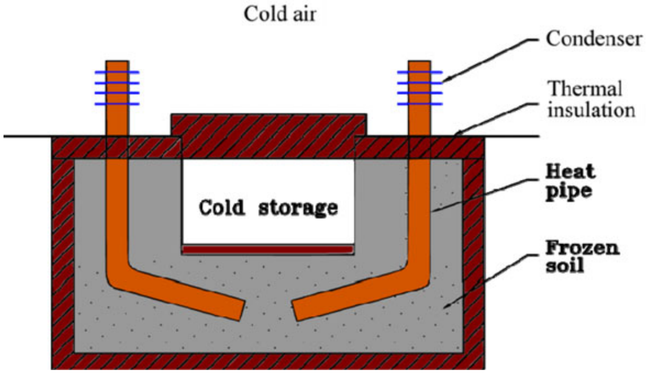

Figure 6. *Thermal diode heat pipes used to maintain a cold store by inhibiting leakage from the ground in warmer seasons.*

As with any other device, the heat pipe must fulfil a number of criteria before it becomes fully acceptable in applications in homes and industry.

(i) Reliable and safe with an acceptable lifetime.
(ii) Satisfy a required performance.
(iii) Cost-effective.
(iv) Easy to install and remove.

In the context of heat storage, aspects to consider include the chemical compatibility between the heat pipe wall and the storage material, the method of charging/discharging the heat pipe/store combination, and heat pipe orientation—interestingly, in some CSP (concentrated solar power) uses, the heat pipes operate in different orientations, implying different duties, discussed later. As shown in Figure 7, the range of heat pipe working fluids readily matches the likely temperatures encountered in TES.

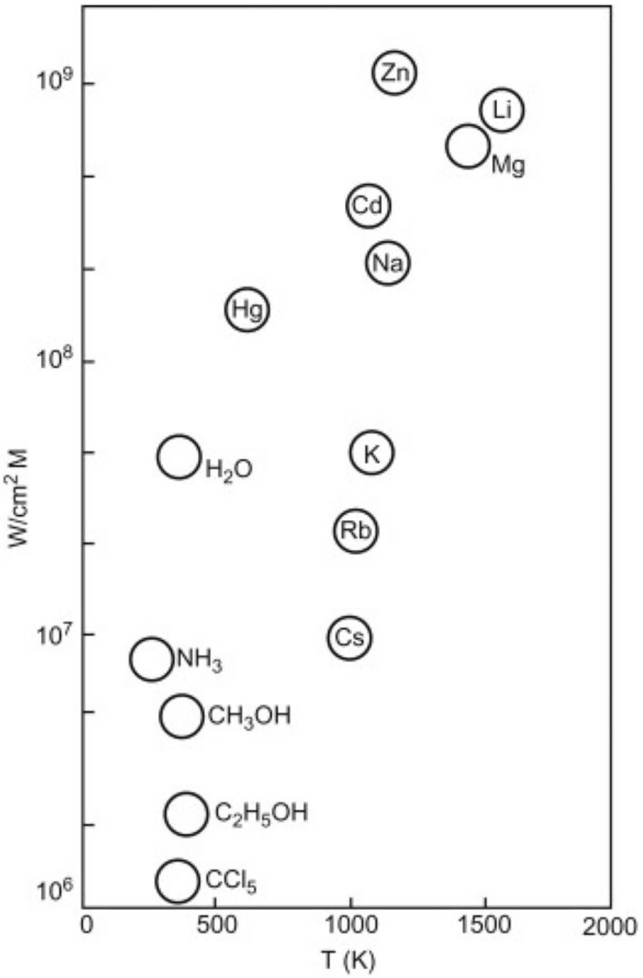

Figure 7. *The Merit Number (calculated at atmospheric boiling point) for a range of heat pipe working fluids.*

3 HEAT PIPES IN ENERGY STORAGE SYSTEMS

By their nature, many energy storage systems should lose or gain as little heat as possible during 'inactive' periods, while also delivering or taking in heat (or 'coolth') as predetermined rates, some of which may be rather high, when required to function actively. The nature of the chemicals used in some phase change storage media, in particular their low thermal conductivity, gives heat pipes an opportunity to enhance performance, although one needs to take care to 'shut off' the heat pipe when heat transport is not needed. One sensible heat 'store' that has benefited considerably from heat pipes is the ground. The use of the ground as either a heat source or a heat sink—well known to heat pump users—to deice roads using heat pipes and, as discussed below, as a sensible heat sink for underground train thermal management. The example of ground use given in Figure 5 is the one where shutting off the heat pipe is essential in high ambients. This was among the earliest mass-produced heat pipe applications.

Heat pipes have been used extensively in a variety of energy storage systems. They are suited to thermal storage systems, in particular, in the role of heat delivery and removal, because of their high effective thermal conductivity and their passive operation. As aids to temperature stratification in hot water storage tanks, to their incorporation in stores for heat or 'coolth' using PCMs, the unique properties of heat pipes can permit systems to operate in a manner not generally possible using conventional heat exchangers. The safety aspect of heat pipes, due to the two walls intervening between the evaporator and the condenser, has also encouraged their use for heat removal from nuclear fuel stores and reactors themselves.

3.1 Why use heat pipes in energy storage systems

The limitations of some thermal storage systems be they for storing heat or 'coolth' tend to be strongly dependent on the properties of the heat storage medium used, such as specific or latent heats, density and thermal conductivity. Many excellent reviews have been written on the subject, for example, Dincer and Rosen [5] and Zalba *et al.* [6]. Cost bears strongly on the choice of storage medium, and unfortunately low-cost materials tend to require the largest storage volume per watt-hour of heat stored. The materials that undergo a phase change, thus releasing latent heat—as in a heat pipe, but in this case normally changing from solid to liquid—tend to have the smallest storage volumes, but are generally more expensive, and may require special encapsulation materials, due to corrosion or toxicity. This can be a limiting factor in applications in occupied buildings, for example.

While heat may be stored at any temperature from just above ambient to in excess of 1000°C, for the storage of 'coolth' for air-conditioning applications—an important energy-saving opportunity, the temperature range is more modest. The storage medium may be expected to operate mainly within the -10 to $+25$°C band. Although the use of heat pipes for the storage at cryogenic temperatures is less known, there is no reason why heat pipes using, for example, nitrogen as the working fluid should not be employed.

A major disadvantage of many potential heat storage candidates is the poor thermal conductivity, whatever phase they are in. This can of course be overcome by 'exciting' the storage medium—fluidization, pumping, or another form of active enhancement (possibly microwaves). It is the role of heat pipes (and other 'enhanced' heat transfer devices such as compact fin assemblies) which has allowed the practical use of heat storage systems to extend into areas where limitations on internal conduction have inhibited the performance in the past. Often the heat pipe is critical to the successful operation of the unit, both in charging and discharging modes. In a number of applications, it additionally allows a compact modular unit to be developed and helps ensure separation of reactive storage media from occupied spaces, an important health and safety factor—not just for the nuclear stores!

The benefit a heat pipe can bring to a simple storage unit is illustrated using a simple case study below. A three-dimensional

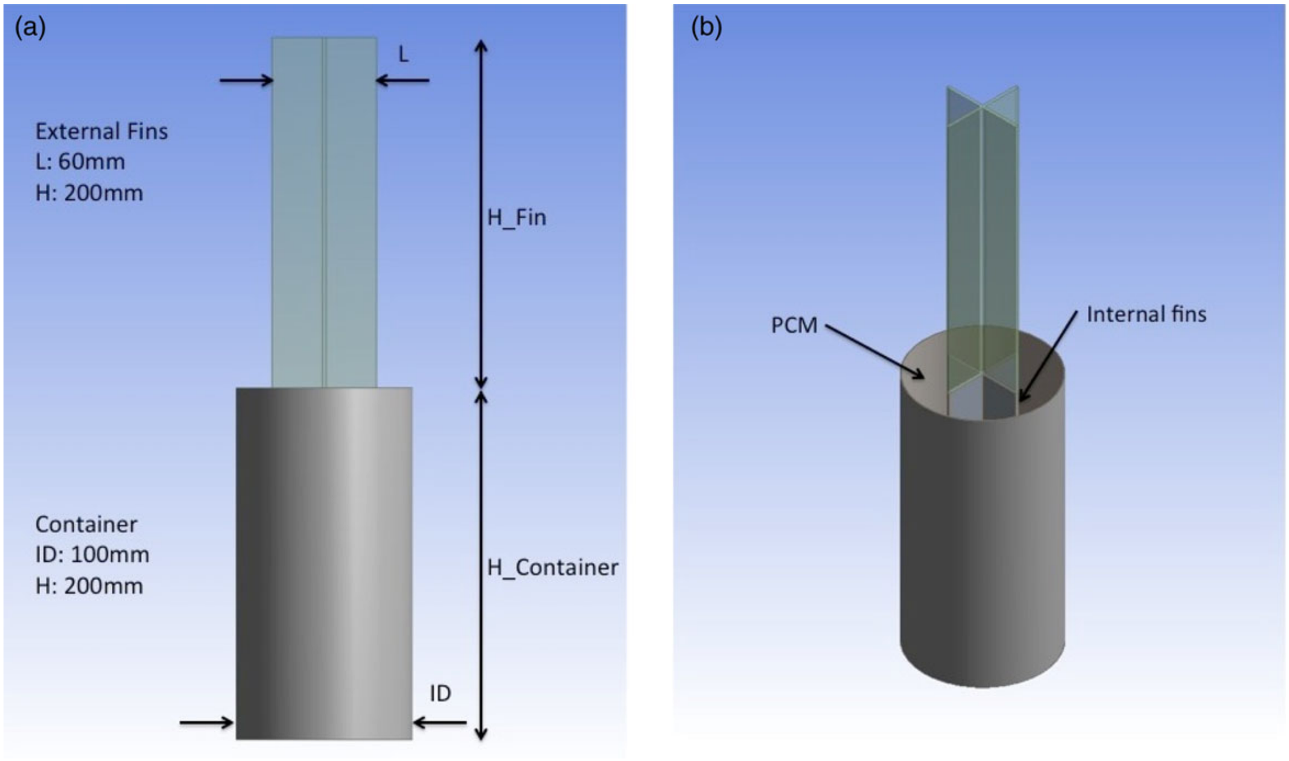

Figure 8. *Configuration of a PCM container (using Erythritol as PCM) with fins to aid heat transfer through and out of the bulk material. (**a**) Profile view showing principal dimensions and (**b**) isometric view showing the fin configurations. Note: internal fins have similar dimensions to the external fins.*

(3D) model was created as shown in Figure 8. Copper was selected as the material for the container and fins. A vertical arrangement is chosen to contain any volume change during melting for the PCM, which is ∼15% V/V_s. The model incorporates numerous coupled mesh interfaces for heat transfer to occur. All other unspecified surfaces are considered adiabatic such as the outer container wall. The dimensions of the cylindrical PCM container are: inner diameter (ID) 100 mm and height (H) 200 mm. The internal fins are submerged in the PCM, whereas the external fins are exposed to air to cool the molten PCM. Two cases of cooling were studied: natural and forced convection.

Another configuration, employing a heat pipe, was developed (Figure 9). The 12.7 mm o.d. heat pipe is designed to transport 100 W (nominal) at 118°C, the PCM melting point, a relatively low power value, just for comparison purposes with the non-heat pipe configuration. The heat pipe is modelled as a solid copper bar with 6000 W/m K thermal conductivity, in line with an example in the literature [5]. As a comparison, copper has a thermal conductivity of 384.7 W/m K.

In Figure 10, the solidification of the PCM with natural and forced convection cooling of the fins above the container, with and without the heat pipe, is shown. The natural convection cases show mediocre results compared with forced convection cases for both configurations. For natural convection, times for complete solidification are 16.85 and 12.00 h for non-heat pipe and heat pipe configurations, respectively. For forced convection, times for complete solidification are 6.47 h for non-heat pipe and 2.71 h for heat pipe configurations, respectively. Therefore, in both natural and forced convection, embedding a heat pipe, which is a passive enhancement method, is an excellent way to achieve rapid PCM cooling. Bear in mind that the heat pipe simulated is of low wattage value at 100 W. Increasing its diameter from the present value of 12.7 mm (0.5″) to e.g. 25.4 mm (1.0″) would increase the heat pipe power and hence, could decrease the solidification time further. In addition, the nominal values of heat transfer coefficient input: 10 and 100 W/m^2 K for natural and forced convection, respectively, are conservative.

The benefits of embedding the heat pipe can be seen in Figure 11—the forced convection cases are illustrated. One of its advantages is isothermalization. The snapshot is from the onset of full solidification. It can be seen that the temperature gradient within the PCM is greatest without a heat pipe (A—Section 2) compared with the heat pipe configuration (B—Section 4). The exposed external fins also show a thermal gradient difference between the two configurations—Sections 1 and 3. The thermal gradient occurs due to convective heat transfer within the PCM, thus the heat pipe assists this mode of heat transfer by channelling the heat from the hot spots to cold spots more efficiently.

A large proportion of PCM applications that employ heat pipes function in the above manner.

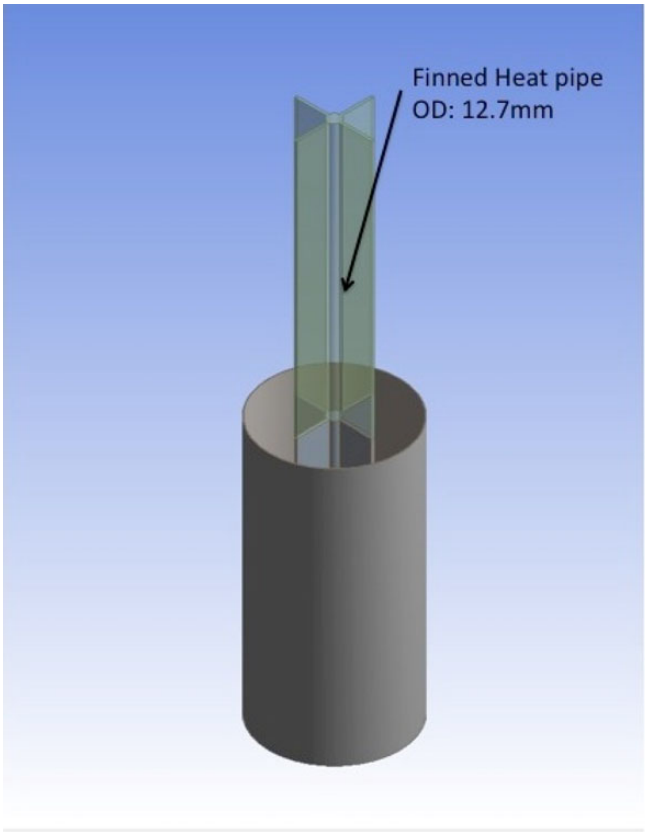

Figure 9. *The addition of a heat pipe (operating in the 'thermosyphon' mode) to improve heat transfer along the finned section outside the PCM container.*

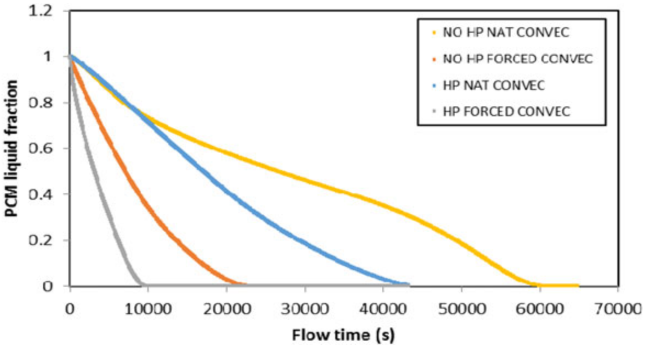

Figure 10. *PCM solidification rate with and without the heat pipe.*

Additionally, the storage medium does not have to be a PCM to benefit from the use of heat pipes and thermosyphons—an early example using a solid store being described below.

4 EXAMPLES OF HEAT PIPES IN THERMAL STORES

4.1 Heat pipes in sensible heat storage devices

One of the most common uses for heat pipes associated with storage is to absorb solar energy and transfer it to water, either static or flowing. Solar collectors employing heat pipes are made by several manufacturers. The concept is described in one early form by Azad *et al.* [7]. The use of individual heat pipes linking to water stores is also cited by Polasek [8].

Work on heat pipes and their terrestrial applications in the Former Soviet Union (FSU) was, and in some CIS members continues to be, perhaps more prolific than anywhere else in the world. One of the laboratories most involved with such uses is the Luikov Heat and Mass Transfer Institute in Minsk, Belarus. Many years ago, Vasiliev [9] and his team (see e.g. Caruso *et al.* [10]) examined the performance of a heat store that used horizontal heat pipes to transfer heat into and out of the store. The store was charged with dry sand or pebbles—used in houses and greenhouses, often located under the building to capture solar heat or heat in warm air or warm water. The heat pipes were found to be an effective way for heat transfer during both charge and discharge processes. The mean energy transfer of the pipes was 200 Wh/m, and a 6 × 5 × 2 m tank had 10 6 m long heat pipes 1 m apart. Each discharge interval gave ∼100 W per pipe.

A second system developed in Belarus [9], illustrated in Figure 12, employed electric heating elements, using 'off-peak' electricity, to raise the temperature of storage bricks within the unit to around 500°C. The heat pipes, with evaporator sections in the lower half of the unit and condensers in the central finned section above the core, allowed heat discharge to take place over a 24–48 h period, with a boost being provided by fan-assisted heat transfer. The upper diagram shows the 'internals'—the heat pipes, the controller and the finned heat sink.

4.1.1 Tunnel structures and earth as a heat 'sink' or store

The London underground railway system—the 'tube'—was designed and largely constructed in the Victorian era. Tunnels in many cases are deep and small in diameter, passenger loads are increasing and modern air-conditioning systems are rarely used—in fact air-conditioning underground can of course lead to local heat gains, depending upon the location of the condenser. The New York City Transit Authority calculated that the operation of underground railway systems can generate sufficient heat to raise the tunnel and station temperatures by 8–11 K above the ambient. In London, where ambients can reach 30°C or more, temperatures of over 37°C have been recorded on some trains, making passenger comfort difficult to achieve.

London South Bank University (LSBU) [11] has identified heat pipes as one option for removing heat from the tunnels. The tunnel structure and the surrounding earth tend to have a moderating influence on the underground railway air temperatures, taking in or rejecting heat, depending upon the air temperatures in the tunnels. This is called the 'tunnel heat sink effect' and ways investigated by the LSBU team of enhancing this effect included the use of heat pipes.

Heat pipes can enhance the tunnel heat sink effect by modifying the thermal conductivity of the ground surrounding the tunnel—analogous to the effect on sensible heat stores of other types. It was demonstrated that if the thermal conductivity of the ground can be increased by an order of magnitude from 5 to

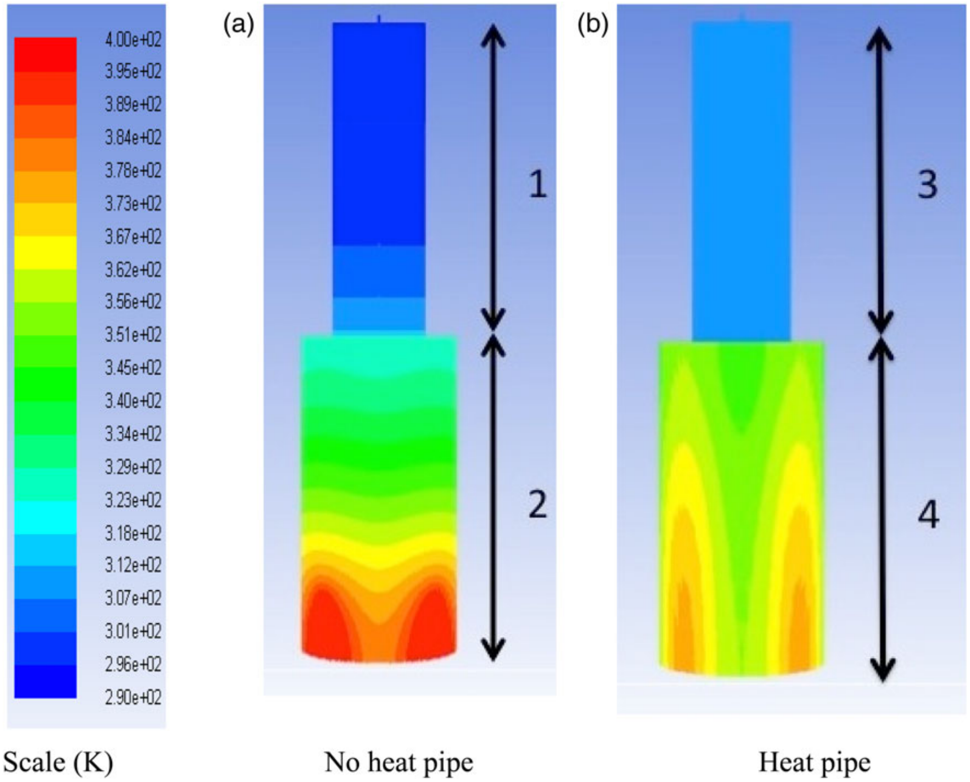

Figure 11. *Snapshot of PCM and external fins' temperature.*

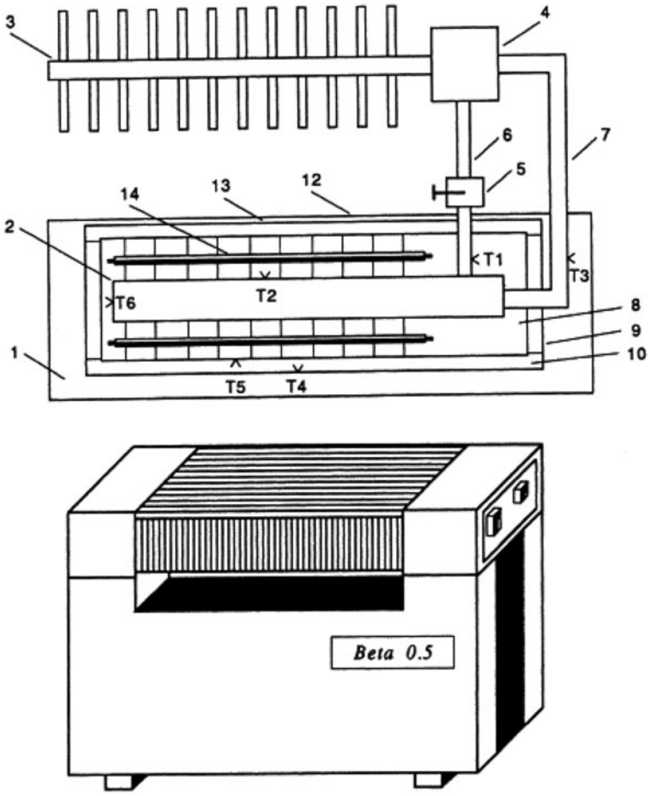

Figure 12. *The brick storage radiator developed by Leonard Vasiliev and colleagues in Minsk. Reprinted from Vasiliev [9], with permission from Elsevier.*

50 W/m K, the temperatures in the tunnel and carriages can be lowered by 12%. Data suggest that 2500 units, each of 130 W duty, would be needed per 1 km. The research team pointed out that the fitting and operation of the heat pipes should not affect the integrity of the tunnel structure.

4.2 Heat pipes in phase change stores (using PCMs)

The use of PCMs, like single-phase storage media, is beset by problems with poor thermal conductivity and unique freezing and melting profiles. Some laboratories have used metallic foils, such as that illustrated in Figure 13, foams (see Figure 14) and compact heat exchanger structures to enhance the heat transfer in PCMs. A logical development is the introduction of heat pipes into PCMs, for reasons discussed in Section 3.1.

One of the earliest studies of heat pipes in PCMs was in the 1980s, when Lee and Wu [13] examined the impact on heat transfer. This research, at the University of Ottawa, was based upon paraffin wax as the PCM (the wax variant being Sun P-116). A water thermosyphon was used to carry out heat removal.

4.2.1 The heat pipe in a passive cooling system for relieving air-conditioning loads

A system based upon the use of heat pipes to aid heat transfer into and out of PCMs (from and to, respectively, ambient air) was been developed over a number of years at Nottingham University in the UK by a team led by David Etheridge. This

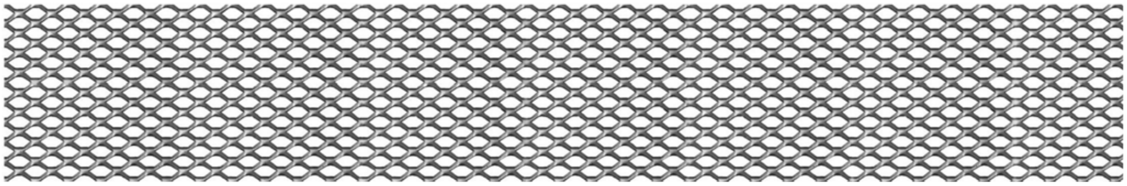

Figure 13. *An expanded metal structure examined for PCM thermal conductivity enhancement [12].*

Figure 14. *A metal foam that is used to enhance PCM performance.*

illustrates a basic application of heat pipes to enhance PCM thermal conductivity.

The operation of this system, perfected in conjunction with PCM and heat pipe suppliers and an installer, is comparatively straightforward. During the night, cool air is used to 'freeze' the PCM, and during the day, heat is extracted from the room air, which 'melts' the PCM. This cycle is repeated on a daily basis. The crucial process is the transfer of heat between the air and the PCM. Heat transfer coefficients need to be high, because the temperature differences between the air and the PCM are low, typically <6°C.

As highlighted above, the main problem is achieving sufficient heat transfer into (and out of) a PCM, because the material essentially behaves as a solid and conduction is, at least for a large part of the cycle, the principal transfer mechanism—in common with most sensible heat stores. Moreover, direct contact between the air and the PCM is undesirable, because of odours and perceived health hazards. The approach adopted was to use a heat pipe to provide an indirect but effective heat transfer path between the air and the PCM, with forced convection on the airside. This allows the PCM to be encased in a rigid sealed container.

Thus, a single module consists of a container of PCM into which one half of the heat pipe is embedded [14]. The other half of the pipe is exposed to the air. Both halves of the pipe are equipped with finned heat exchangers. The direction of heat flow changes from day to night, so the heat pipe is designed for reversible operation and is mounted horizontally.

Hydrated Glauber's salt was the basic material, with borax as an additive to obtain the required transition temperature range (nominally 21–23°C). The latent heat capacity is 198 kJ/kg and the density is 1480 kg/m^3. The PCM volume of the module was 7.8 l, which corresponds to a latent heat storage capacity of 0.64 kWh per module.

The modules are installed in a floor-standing unit that is suitable for installation in both new and existing buildings. Seven modules were used in each unit, giving a latent cooling capacity of 4.4 kWh, e.g. 500 W of cooling for 8 h. The unit also houses the fan. Figure 15 shows the installation at one of the two test sites. The fan is mounted centrally and pulls air across the heat pipes. At night, the air is drawn through a duct that is connected to a motorized window vent. During the day, the vent is closed and air is drawn directly from the room through the open flap (also motorized).

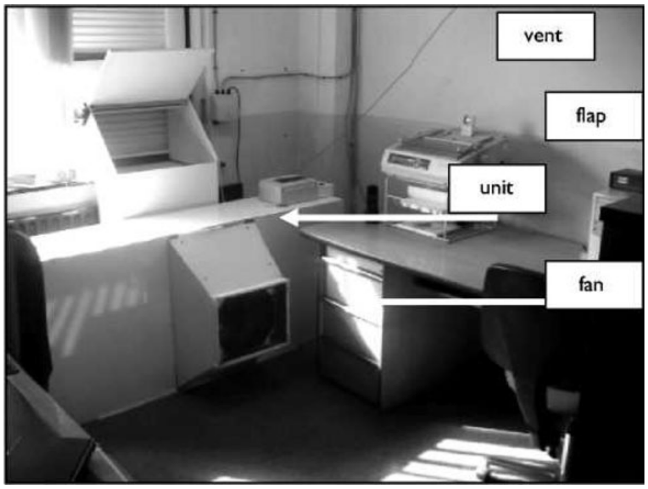

Figure 15. *The PCM room cooling unit installed at Nottingham University [14].*

In field trials, it was found that the system was capable of maintaining control over the room temperature and could respond quickly to changes in heat gains. In particular, the high thermal storage capacity of the PCM and the efficient heat transfer of the system allowed the room temperature to be controlled at a constant level in the same way as an air-conditioning system. This was recognized as being very impressive for what is basically a passive system. With forced nighttime cooling alone, the room temperature would have continued to rise resulting in a maximum temperature 2°C or 3°C higher. With only natural nighttime cooling of the room fabric, the rise would certainly have been even higher.

4.2.2 PCM control via the VCHP: combined heat and power units

As shown in Figure 4, the VCHP can be used to control the rate of heat removal from a thermal store. Huangfu *et al.* [15] at the Shanghai Jiao Tong University first proposed the VCHP in conjunction with a cogeneration unit to deliver heat to consumers,

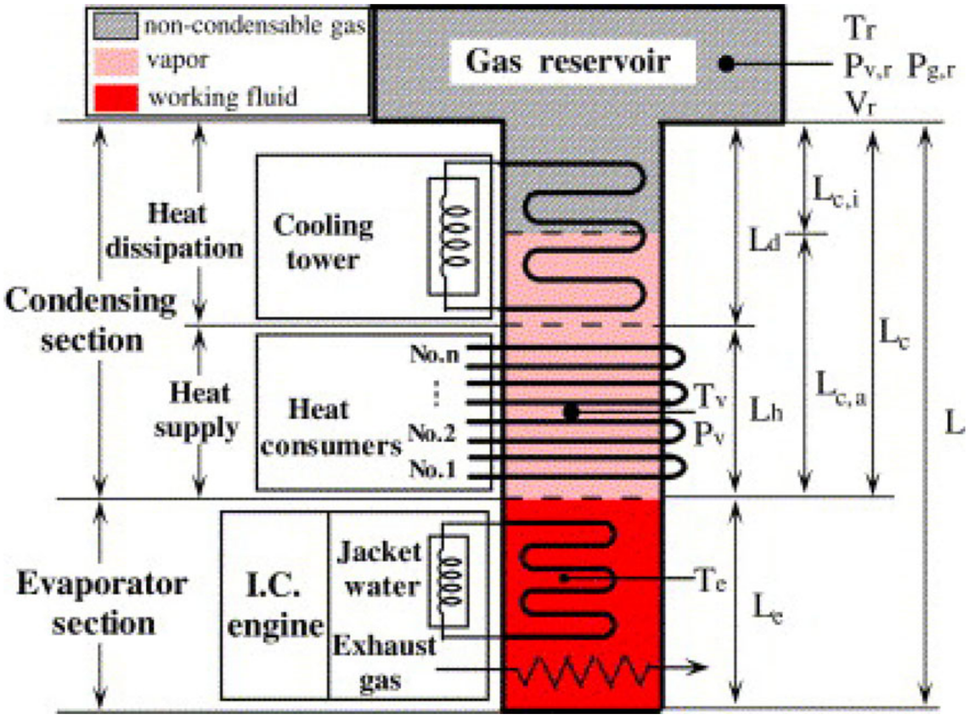

Figure 16. *The VCHP concept used to control heat output from a co-generation unit [15]. Reprinted from Huangfu* et al. *[15], with permission from Elsevier.*

using the heat generated by an internal combustion engine (Figure 16). The heat pipe evaporator is supplied by the engine heat, while the condenser has an adjustable volume, using the inert gas front position, to control the supply of heat to the users or the cooling tower. Even basic VCHPs are self-regulating to a degree, and as heat supply increases, the consumers can take more and the cooling tower can handle any surplus. If the engine is running at much reduced power, the heat output is essentially cut off by the growth in volume of the inert gas.

In a project let by SES Ltd in the UK under the Technology Strategy Board funding programme, a derivative of the above is being constructed for a micro-combined-heat-and-power (mCHP) unit. In this unit, the pressure in the VCHP can be varied via an active feedback control method in response to domestic heating demand and a compact PCM thermal store encases the evaporator—supplied by the engine waste heat. Variations in inert gas pressure are used to regulate the domestic heating system heat exchange surface area (and, hence, capacity) smoothly and continuously, while the PCM thermal store is used to manage the availability of this heat over extended time horizons. Though the proposal is focused on domestic-scale mCHP applications, the concept is equally applicable to larger scale commercial combined heat and power plants. Northumbria's University's contribution is to develop a simulation model of the mCHP unit and VCHP and use the model to design a domestic-scale experimental pilot rig. The pilot rig will be constructed in Northumbria's Low Carbon Systems laboratory using an existing Stirling cycle mCHP module. The VCHP unit will be constructed by the collaborators to the sizing specification designed with the assistance of the simulation model. Northumbria will perform a series of experiments at thermal demands relevant to typical domestic heating loads—both winter (space heating and hot water) and summer (hot water only). The intention is to develop the research to a proof-of-concept stage only. A further application of the simulation model will be used to design system options for a range of house types with differing occupancies and heating demands. Results will be reported as a basis for possible prototyping and field demonstration [16].

Figure 17. *A porous honeycomb structure with circumferential heat pipes for isothermalization [17]. Reprinted from Reay and Harvey [17]. The role of heat pipes in intensified unit operations, pp. 147–153, 2013 with permission from Elsevier.*

4.2.3 Isothermalization: learning from space technology

The isothermalization of satellite structures was illustrated in Section 2. In Figure 17, a honeycomb structure (that could of course equally be a foam) forming part of a satellite has four circumferential heat pipes embedded within it in order to minimize temperature excursions and any deformation that could result.

This is analogous to what might happen in a chemical reaction—an example would be metal hydride heat storage systems, where control of hydrogen charging which is an exothermic reaction needing rapid and ideally uniform removal of heat can benefit from heat pipes [17].

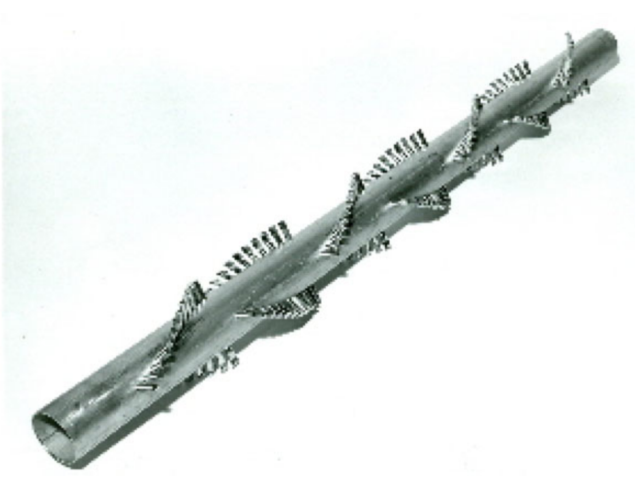

Figure 18. *A heat pipe-based encapsulated PCM mixer/heat transfer device.*

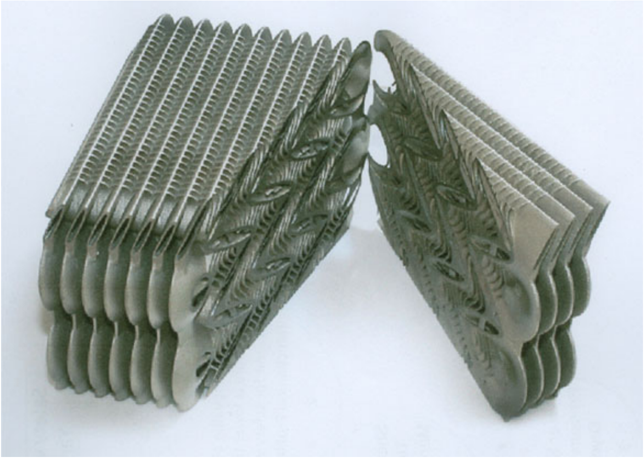

Figure 19. *A compact heat exchanger from Within Lab produced by AM [18] was kindly supplied by Within Laboratories.*

4.2.4 Fluidized or encapsulated PCMs

Increasingly, PCMs are being encapsulated in polymers and other materials, to increase mobility and enhance heat transfer. They can be pumped or fluidized in order to improve convective heat transfer. A concept that can mix the PCM capsules as well as transfer heat into or out of them is the heat pipe mixer illustrated in Figure 18. Originally developed for the food industry, where the cooling or heating of viscous foodstuffs is often required, the unit could effectively 'stir' the capsules inside the tube, at the same time taking heat effectively to an outer fluid stream (or conversely adding heat to the PCMs).

5 CAN ADDITIVE MANUFACTURING ASSIST IN OPTIMIZING NEW CONCEPTS?

Additive manufacturing (AM) (alternatively known as 3D printing or rapid prototyping) is an assembly method that permits components in polymer and metals to be fabricated in forms not possible with conventional casting or machining processes. The heat exchanger shown in Figure 19, for example, would be impossible to cast and AM has in this instance allowed a compact metallic exchanger with enhanced internal and external surfaces to be produced.

More recently, Thermacore, a heat pipe manufacturer, in conjunction with Liverpool and Northumbria Universities in the UK, have successfully fabricated heat pipes in aluminium using AM (Figure 20).

Destined for spacecraft use, these lightweight units are unique in that the wall and the wick—the capillary structure necessary to carry liquid from the condenser to the evaporator—were built up from the end cap together—effectively fully integrating the two and minimizing thermal resistance. One could therefore build heat pipes into the storage container in such a way that the enhancement structure (such as a foam) and the thermal control system—the heat pipes—have ideal thermal contact and are optimized for the desired storage cycle characteristics. Items such as metal storage radiators, as well as structures for charging with PCMs, could be assembled in such a way.

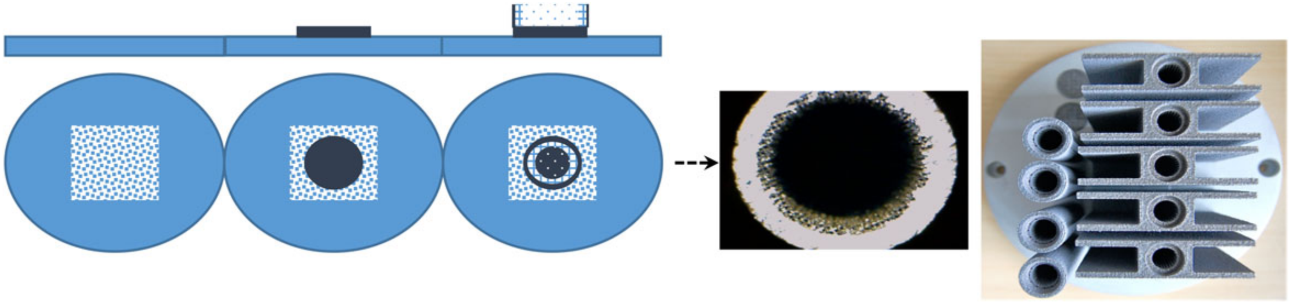

Figure 20. *The fabrication procedure and outcome of heat pipe manufacture using AM [19]. Reprinted from Ameli* et al. *[19], with permission from Elsevier.*

5.1 The next step: a 3D printed PCM

Research at Heriot-Watt University, Edinburgh [20], is examining the use of metallic PCMs to improve the performance of Fischer–Tropsch (F–T) chemical reactors—these being used for converting gas to hydrocarbon-based liquids. Compact F–T reactors are like highly compact heat exchangers. One could contemplate more effective F–T reactors assembled using AM, but incorporating at the same time a metallic PCM in optimum locations that would have been modelled previously in order to give ideal reaction kinetics.

6 CONCLUSIONS

TES is increasingly important across a range of sectors—from industry to transport and the home. The main characteristics of the heat pipe and thermosyphon—mainly associated with their high effective thermal conductivities—can benefit thermal store performance in a way not always possible with other enhancement methods.

New manufacturing methods, in particular AM, may ultimately allow some storage materials to be constructed within optimized heat transfer surfaces in a manner not currently possible.

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REFERENCES

[1] Reay DA, Kew PA, McGlen RJ. *Heat Pipes: Theory, Deign and Applications*, 6th edn. Butterworh Heinemann, 2014.

[2] Weng Y-C, Cho H-P, Chang C-C, *et al.* Heat pipe with PCM for electronic cooling. *Appl Energy* 2011;**88**:1825–33.

[3] Zhang M, Lai Y, Zhang J *et al.* Numerical study on cooling characteristics of two-phase closed thermosyphon embankment in permafrost regions. *Cold Reg Sci Technol* 2011;**65**:203–10.

[4] Mashiko K, Okiai R, Mochizuki M, *et al.* Development of an Artificial Permafrost Storage Using Heat Pipes, Paper No. 89-HT-15, ASME/AIChE National Heat Transfer Conference. Philadelphia, PA, 1989.

[5] Dincer I, Rosen MA. Thermal Energy Storage—Systems and Applications. 2nd edn. , 2010.

[6] Zalba B, Marin JM, Cabeza LF, *et al.* Review on thermal energy storage with phase change materials, heat transfer analysis and applications. *Appl Therm Eng* 2003;**23**:251–83.

[7] Azad E, Bahar F, Moztarzadeh F. Solar water heater using gravity-assisted heat pipe. *Heat Recov Syst CHP* 1987;**7**:343–50.

[8] Polasek F. Heat pipe research and development in East European countries. *Heat Recov Syst CHP* 1989;**9**:3–18.

[9] Vasiliev LL. Heat pipe research and development in the USSR. *Heat Recov Syst CHP* 1989;**9**:313–33.

[10] Caruso A, Grakovich LP, Pasquetti R, *et al.* Heat pipe heat storage performance. *Heat Recov Syst CHP* 1989;**9**:407–10.

[11] http://www.lsbu.ac.uk/case-studies/lsbu-research-helps-london-underground-passengers-keep-their-cool (6 March 2015, date last accessed).

[12] Mustaffar A, Harvey A, Reay DA. Melting of phase change material assisted by expanded metal mesh. Submitted to SET2014. *Appl Therm Eng* (Special issue) 2015.

[13] Lee Y, Wu C-Z. Solidification heat transfer characteristics in presence of two-phase closed thermosyphons in latent heat energy storage systems. In: *Proceedings of the 6th International Heat Pipe Conference.* 25–29 May, Grenoble, 1987.

[14] Turnpenny JR, Etheridge DW, Reay DA. Novel ventilation cooling system for reducing air conditioning in buildings. Part 1: testing and theoretical modeling. *Appl Therm Eng* 2000;**20**:1019–37.

[15] Huangfu Y, Wu JY, Wang RZ, *et al.* Development of an experimental prototype of an integrated thermal management controller for internal-combustion-engine-based cogeneration systems. *Appl Energy* 2007;**84**:1356–73.

[16] Novel Variable Conductance Heat Pipe Coupled with a Stirling Engine. Grant EP/L505912/1. http://www.epsrc.ac.uk/research/ourportfolio/vop/ (6 July 2014, date last accessed).

[17] Reay DA, Harvey AP. The role of heat pipes in intensified unit operations. *Appl Therm Eng* 2013;**57**:147–53.

[18] Additive manufacturing company. http://withinlab.com/case-studies/index11.php (6 July 2014, date last accessed).

[19] Ameli M, Agnew B, Leung PS , *et al.* A novel method for manufacturing sintered aluminium heat pipes (SAHP). *Appl Therm Eng* 2013;**52**:498–504.

[20] Odunsi A. Temperature stabilization in Fischer–Tropsch reactors using phase change materials. In: *Presentation at the 22nd Process Intensification Network Meeting*. Newcastle University, 21 May 2014. www.pinetwork.org (1 July 2014, date last accessed).