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# Towards net zero: harnessing the “hidden” energy of latent heat

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This text accompanies the lecture slide deck as presented to the in-venue audience.

## Abstract

Aligned with the United Nation’s sustainable development goal 13, dealing with climate action, achieving net-zero systems is among the global challenges, demanding urgent, innovative solutions to reduce energy consumption and carbon footprint. One promising solution is harnessing latent heat – a somewhat hidden form of energy that is crucial during phase transitions, including the change from solid to liquid or liquid to gas. Key processes that involve latent heat include melting, boiling, condensation, and solidification. Thermal energy systems, being reliant on the transfer and storage of heat, are central to discussions on global energy demand. Heat, being a primary means of energy transfer, dictates many applications across several sectors, including industrial processes, transportation, and building climate control. Approximately 50% of global energy consumption is used for thermal purposes. Since the energy associated with phase change is stored and released at relatively fixed temperatures, utilising latent heat presents an opportunity to improve energy efficiency and thermal regulation effectiveness. Technologies using phase change processes have considerable potential to reduce energy consumption and provide low-carbon and even net-zero energy alternatives. This presentation delves into the concept of latent heat, emphasising its hidden power and transformative role in advancing a greener, sustainable future. A brief overview will be presented of some of my contributions towards flow-based phase change processes to enhance energy flow; followed by the impact of new heat transfer fluids and opportunities to further integrate complementary phase change energy storage mechanisms.

## 1. Introduction: From Hot Coffee to Hidden Power

Imagine you're holding a cup of hot coffee. You can feel the heat radiating from it. If you were to track its temperature with a thermometer, you'd see the number slowly decrease as it cools. This change in temperature is due to a loss of what's called **sensible heat**. It's the heat you can "sense" or measure with a temperature change. It's intuitive: add heat, the temperature goes up; remove heat, it goes down.

But what happens when you boil a pot of water? You heat it to 100°C, and then something curious occurs. As you pump more and more energy into the pot, the water begins to turn into steam, but the temperature of the remaining water *does not change*. It stays locked at 100°C until all the liquid is gone. Where is all that extra energy going?

This is the world of latent heat. The term "latent" comes from the Latin word meaning "to lie hidden." Latent heat is the hidden energy absorbed or released by a substance during a phase change—like melting from solid to liquid or boiling from liquid to gas—without changing its temperature. This energy is not lost; it is used to break the bonds holding the molecules together in their current state. When the process is reversed (like steam condensing back to water), this exact amount of energy is released.

This phenomenon is incredibly powerful. The amount of energy required to turn 1 gram of water into steam at is more than *seven times* the energy needed to heat that same gram of water from room temperature all the way up to its boiling point.

## 2. Relevance

Let us now consider what the relevance is latent heat.

### 2.1 The Modern Energy Challenge

Engineers have learned to harness this powerful, hidden energy in two fundamentally different ways: for passive thermal storage and for active heat transport. This engineering focus has never been more critical. Our global energy systems face an unprecedented challenge, squeezed between a surging demand for power and the urgent need to decarbonize in the face of global environmental change. This can be seen, for instance, by the recession of the polar ice caps and the increase in global $CO_2$ concentration.

The surge in power demand is acutely driven by the exponential growth of technologies like Artificial Intelligenceand the Internet of Things. Massive data centres, the backbone of this digital revolution, are incredibly power-hungry and generate vast amounts of waste heat. Other noteworthy sectors that are predicted to increase its share of electricity consumption are electrified transport, and space cooling. This creates a dual crisis: we need more clean energy supply while also managing thermal loads with radical new efficiency. In this landscape, mastering how we store, move, and utilize thermal energy is no longer a simple matter of optimization—it's essential for a sustainable future.

### 2.2 Harnessing Latent Heat

Faced with this challenge, leveraging the unique properties of latent heat provides powerful opportunities for innovation. This can be divided into two categories, according to the time scales at which they operate: Passive storage and active heat transport.

#### *Passive Thermal Storage: Phase Change Materials*

The most direct application is through materials chosen specifically for their phase-changing properties. These are called Phase Change Materials (PCMs). Think of them as thermal batteries. Instead of storing electrical energy, they store thermal energy as latent heat, typically during the solid-to-liquid transition.

The process is simple but elegant. Consider the charging (IE melting) and discharging (IE Solidifying processes: As a PCM melts from a solid to a liquid, it absorbs a massive amount of heat from its surroundings at a nearly constant temperature. When the surroundings cool, the PCM solidifies, releasing that same amount of stored heat back into the environment, again at a constant temperature.

This principle is behind many passive energy-saving technologies, such as smart Buildings where PCMs embedded in walls or floors absorb excess heat during the day and keeping the building cool, and release it at night, to drastically reducing operating costs.

#### *Active Heat Transport: Thermodynamic Cycles*

While PCMs are excellent for passively storing heat, the most impactful use of latent heat involves the liquid-to-gas transition (via vaporization) to actively transport energy. In these thermodynamic cycles, a working fluid acts as an efficient energy courier. It absorbs a massive amount of latent heat from an energy source, stores it, transports it, and then releases it precisely where it's needed. This fundamental principle is the engine behind many of our most critical technologies.

This includes power generation. The very same phase-change principle is the workhorse behind the vast majority of global electricity generation. In power plants, the Rankine cycle uses a working fluid (typically water) to convert heat into mechanical work. Water is boiled into high-pressure steam (picking up latent heat) and expands to spin a turbine, generating electricity.

After leaving the turbine, the low-pressure steam must be condensed back into a liquid releasing a significant amount of waste heat via a latent process. This isn't an optional by product; the Second Law of Thermodynamics dictates that this this fundamental energy transaction occurs.

Another critical technology is Heat Pumping in Refrigeration and Air Conditioning systems. In such systems, the goal is to move thermal energy from where it's not wanted to where it can be harmlessly released. A special working fluid, called a refrigerant, is used for this task. The refrigerant evaporates inside the unit (picking up heat via a latent process), carries energy in the fluid loop and condenses later (releasing that heat again via a latent process), effectively pumping warmth out of the space to cool it, or pumping warmth into a space to heat it.

Looping back to the challenge of data centres, these same principles are being miniaturized to cool high-heat-flux electronics. As chips for AI and high-performance computing become more powerful, they generate intense, concentrated heat that traditional fans cannot handle.

Advanced solutions like heat pipes and two-phase liquid cooling use a working fluid that evaporates directly on the processor's surface. This phase change absorbs far more heat than simple liquid flow, efficiently transporting it away to a heat sink. This technology is critical for preventing overheating and enabling the next generation of compact electronics.

## 3. Technical Foundation

Before proceeding to some of our recent and current research applications, it would be useful to first lay a technical foundation.

### 3.1 The Unseen Cost of Energy: Entropy

To truly appreciate the elegance of latent heat, we must introduce a fundamental concept from thermodynamics: entropy. Entropy is often described as a measure of disorder or randomness.

The Second Law of Thermodynamics states that in any energy transfer, the total entropy of a closed system will always increase. In simpler terms, energy naturally spreads out, and processes tend to move towards a state of greater disorder. Useful, concentrated energy (like electricity, or a hot flame) inevitably degrades into less useful, dispersed heat.

Think of building a sandcastle (a low-entropy, ordered state). It takes a lot of focused energy, but a single random, high-entropy event, such as a gust of wind or a wave, can easily flatten it, scattering the sand grains randomly. It is easy to go from order to disorder, but the reverse requires significant work.

In engineering, this "cost" of using energy is called entropy generation. Every time heat is transferred across a temperature difference, entropy is generated. The larger the temperature difference, the more entropy is created, and the more potential for useful work is irreversibly lost. This is a measure of inefficiency. Minimizing entropy generation is the key to maximizing energy efficiency.

### 3.2 Latent Heat: The Efficiency Expert

This brings us back to PCMs and latent heat. How do they help in the fight against entropy? Refer to Figure 1.

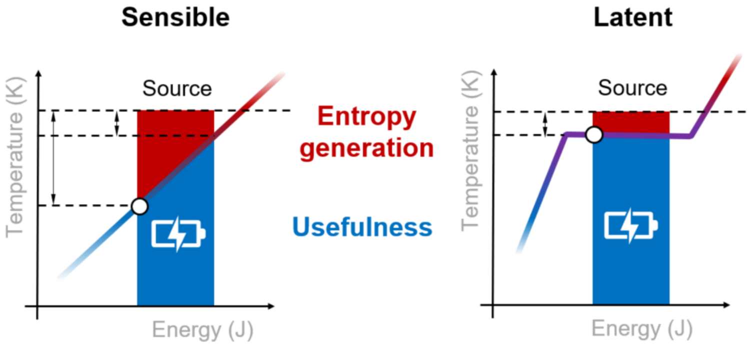

*Figure 1:Temperature dependence of sensible and latent energy storage methods.*

When you store energy as sensible heat, you must raise the temperature of a substance. For example, heating a tank of water from 20°C to 80°C. When you want to retrieve that energy, the water cools, and the temperature drops. The entire process involves constantly changing temperature gradients, which are a major source of entropy generation as can be seen on the left.

When you store energy as latent heat, the process is nearly isothermal since it happens at a constant temperature, as is shown on the right. A PCM absorbs massive amounts of heat at its melting point and releases it at the very same temperature when it solidifies. By operating with minimal temperature differences, PCMs dramatically reduce the entropy generated during thermal energy storage and release.

In essence, phase change processes allow us to "trap" and transport high-quality thermal energy and release it on demand with minimal thermodynamic degradation.

This is the pinnacle of thermal management: not just using energy, but using it *smartly* to minimize waste and inefficiency. From the simple act of water boiling in a pot, we can see a principle that allows us to build more efficient homes, create more reliable power grids, and develop smarter materials. Latent heat is nature's hidden gift for energy management, and by understanding and applying it, we can engineer a more sustainable and efficient world.

### 3.3 The Physics Behind the Change: A Molecular Perspective

Ever wondered what happens when a solid turn into a liquid, or a liquid into a vapour? Understanding these processes is crucial for designing thermal systems. Let's zoom in to the molecular level and break down the fundamental physics, thermal mechanisms, and fluid dynamics at play.

In a solid, molecules are tightly packed in a fixed structure. They are not completely still; they vibrate in place. The bonds between these molecules are strong, holding them in their rigid formation. In a liquid, molecules are still close together, but they have enough energy to break free from their fixed positions and move past one another. This is why liquids can flow and take the shape of their container. In the gas phase, molecules have a great deal of kinetic energy, enough to overcome intermolecular forces almost entirely. They are far apart from one another and move rapidly and randomly in straight lines until they collide with other molecules or the container walls.

Heat is the key driver of phase change. When you heat a solid, its temperature rises as the molecules vibrate more vigorously. However, once the solid reaches its melting point, any added energy, is entirely used to break the bonds holding the molecules in their fixed positions, allowing them to transition into the liquid phase.

Solidification is the mirror image. Likewise, between liquid and vapour, the energy level of the molecules is critical.  The way heat moves through a substance also plays a crucial role.

## 3.3 Thermal Mechanisms: The Role of Heat

Consider the cup of coffee again. Imagine we can measure the local temperature as we move away from the hot liquid. Inside the cup the temperature is high, across the cup wall the temperature reduces, and then steady falls as we move further away until the environment temperature is reached. These variations are affected by factors including the heat transfer mechanisms.

Firstly, consider Conduction: In a solid, heat is primarily transferred through vibrations that are passed from one molecule to the next. Conduction also occurs in fluids, but it is generally the weakest and slowest mode of heat transfer.

Next consider natural convection: Once a substance melts and becomes a liquid, natural convection often takes over. The liquid in contact with the heat source becomes warmer and less dense, causing it to rise. Cooler, denser liquid sinks to take its place, creating a circular flow. This bulk movement transfers heat far more effectively than conduction alone. This process occurs naturally during melting and solidification due to the temperature gradients.

Forced convection is much more powerful. The key difference from natural convection is that the fluid motion is caused by an external source, such as a pump, fan, or stirrer. By mechanically forcing the fluid to move, we can dramatically increase heat transfer rates, allowing for faster heating, cooling, melting, or solidification.

Finally, Boiling represents one of the most intense modes of heat transfer. It occurs when a surface is heated to a temperature above the boiling point, causing a phase change either via nucleate or convective boiling, or both.

Nucleate boiling is the most common regime. Bubbles of vapor form at specific nucleation sites on the hot surface. The rapid growth and departure of these bubbles cause intense mixing and turbulence at the surface, leading to extremely high heat transfer rates.

Convective boiling, also known as flow boiling, occurs within a fluid that is already moving, for instance, inside a pipe. It combines the effects of forced convection and nucleate boiling, leading to complex but highly effective heat transfer, which is critical in power plants and refrigeration systems.

## 3.4 Fluid Dynamics: All about motion

### *Natural convection*

The movement of the fluid, whether driven naturally or by external means, has a significant impact on phase change processes.

During solidification and melting without any external influence, the fluid dynamics are governed by natural convection as is seen in Figure 2.

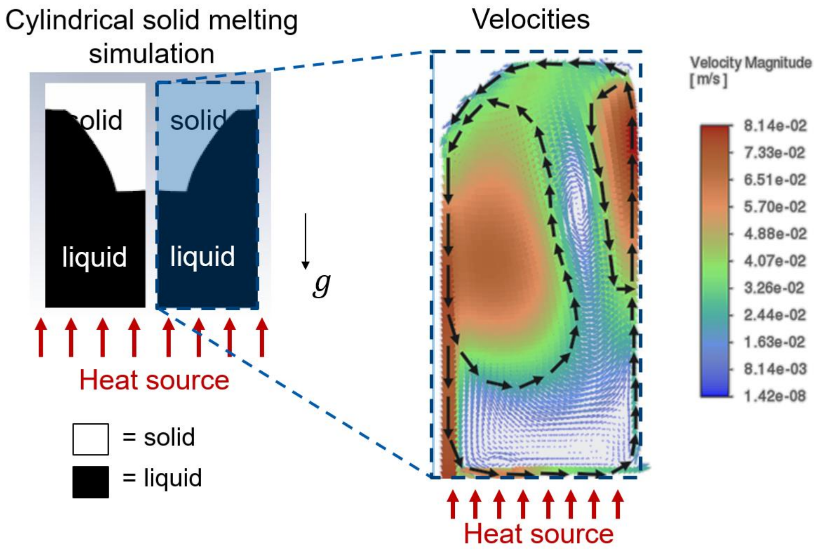

*Figure 2: Liquid-vapour interface during the melting of a cylindrical solid, and an associated velocity distribution in the liquid phase due to natural convection.*

The boundary between the liquid and solid, the **solidification or melting front**, moves through the material. Convection currents can cause this front to be uneven. In addition, the fluid motion affects the local temperatures at the phase front which influences how crystals form, or are dismantled.

### *Forced convection*

As mentioned, forced convective flow is driven by an external source, like a pump or fan, which allows for precise control. At lower speeds, this flow is smooth and orderly, called laminar flow. As the speed increases, the flow becomes chaotic and full of swirling eddies, a state called turbulence. While it sounds messy, this is highly effective, as the intense mixing it creates, dramatically boosts heat transfer.

### *Two-phase flows*

When boiling and condensation occurs, you often have a mixture of two phases moving together. This "two-phase flow" has its own unique dynamics. Let us first consider the flow patterns as represented by Figure 3.

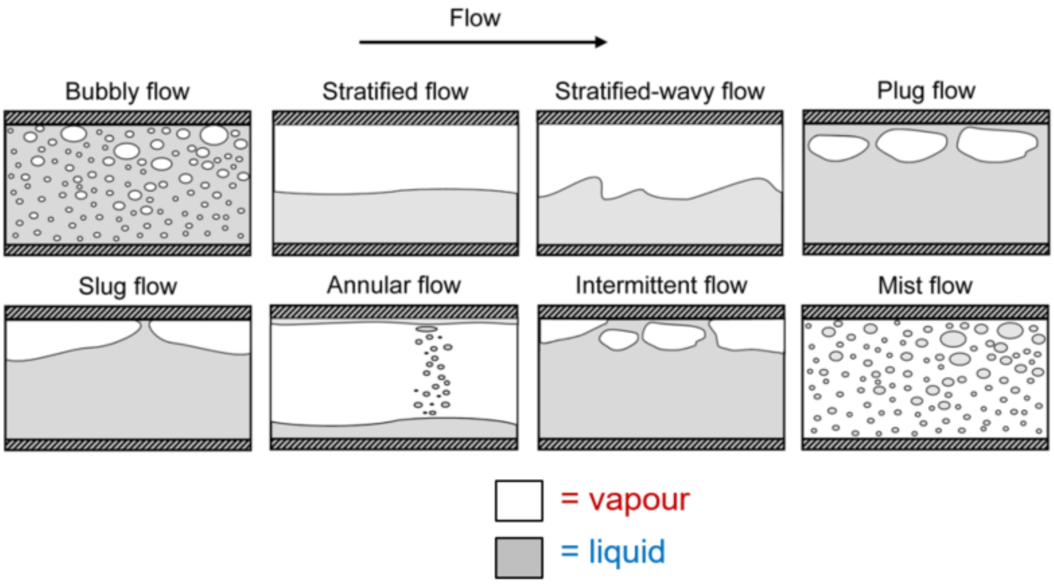

*Figure 3:Typical liquid-vapour flow patterns in a macro-scaled circular flow passage.*

In boiling flow, the interaction between the liquid and vapor creates distinct patterns. It might start as bubbly flow (small bubbles in liquid), transition to slug flow (large, bullet-shaped bubbles), and eventually become annular flow (a core of vapor with a thin film of liquid on the pipe walls). Each pattern has different heat transfer characteristics.

Another important aspect is surface tension. This is the cohesive force at the liquid-vapor interface that holds bubbles together. Surface tension governs the energy required to form a new bubble and dictates its shape and stability. It is a dominant force in small-scale systems and is critical for understanding nucleate boiling.

And lastly, before I move onto some of our research focus areas, we can consider the phase velocities.In a two-phase flow, the two phases rarely travel at the same speed. The lighter vapor phase is typically accelerated faster by pressure differences and buoyancy, moving at a higher velocity than the denser liquid phase. This difference is known as slip. Accounting for slip is essential for accurately predicting pressure drop and heat transfer in systems.

## 4. Some Recent and Current Focus Areas

The remaining discussion covering my recent and current research is divided into two thermal regimes, differentiated by their operational time scales. Active Heat Transport addresses instantaneous, high-flux thermal management, focusing on rapid phenomena like macro and miniature-scale flow boiling and condensation. Conversely, Passive Thermal Storage operates on longer time scales, hours or days, for energy banking, where we will examine solutions ranging from high-temperature solar thermal applications down to medium-temperature building thermal regulation solutions. Understanding this temporal distinction is crucial for optimizing the integrated energy system.

## 4.1 Macro Scale Flow Boiling

### *Concentrated Solar Power via Direct Steam Generation*

Our first focus is on macro-scale flow boiling in the renewable sector, a key area for achieving **net-zero carbon**.

Concentrated Solar Power uses large solar reflectors, such as the parabolic trough collectors shown here, to focus solar energy onto receiver tubes. Traditionally, this heats a synthetic oil to generate steam in a heat exchanger, providing reliable, dispatchable power. However, a promising alternative is Direct Steam Generation. Here, water flows straight through the receiver tubes, converted directly to high-pressure steam by the reflected solar radiation. This eliminates the intermediate heat transfer fluid and the costly heat exchanger, thereby increasing overall plant efficiency, reducing entropy generation, and lowering the levelized cost of energy.

Though promising, the complexity of managing solar transients requires specialized attention.

To understand the implication of phase change on system operation, consider the simplified component diagram, alongside the thermodynamic Temperature-Entropy diagram for the circulating water as shown in .

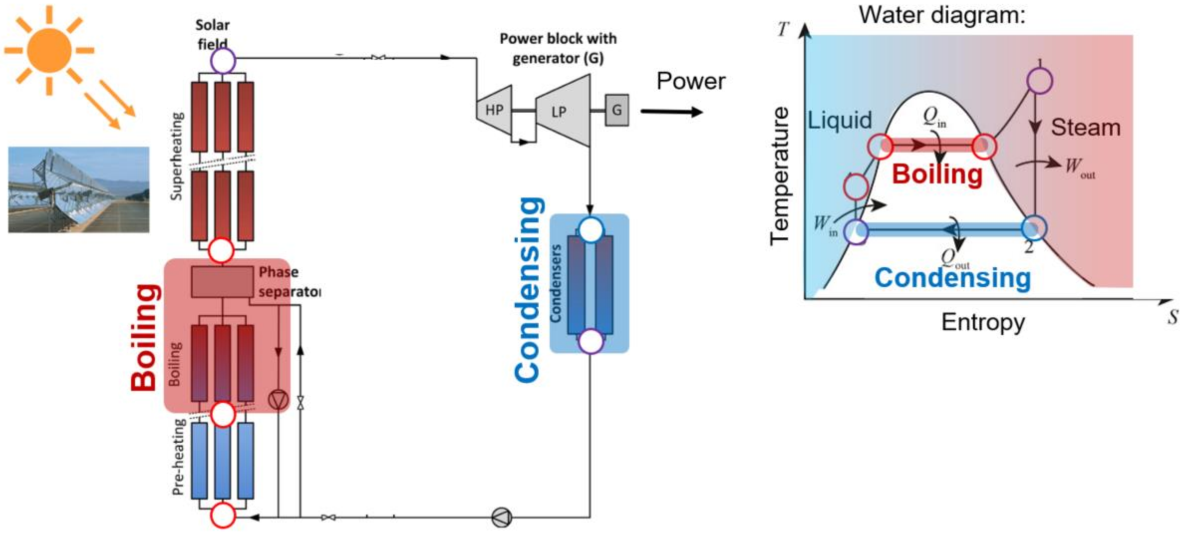

*Figure 4: A simplified direct steam generation concentrated solar power cycle and accompanying temperature- entropy diagram.*

On the entropy diagram, the liquid and vapor phases are indicated on the left and right sides of the vapor dome respectively, with boiling and condensation represented by two constant temperature lines.

As the cycle repeats, solar energy is utilized to pre-heat, evaporate, and superheat the water. The processes of interest are directional: steam production occurs during the increase of entropy from left to right at high temperature and pressure, while condensation occurs as entropy decreases from right to left at a lower temperature.

Since both boiling and condensation temperatures are governed by the system pressure and directly influenced by the local heat transfer mechanism, both flow boiling and condensation have attracted vigorous research interest.

A core theme in my research is the investigation of environmental transients, which for solar applications necessitates considering spatial and temporal variations in heat flux intensity both along and around the receiver tube.

In parabolic trough collectors, the flow is horizontal, meaning it's perpendicular to gravity. Although the tracking system keeps the focal point on the tube as the sun traverses the sky, the heat flux incidence is inherently non-uniform. Due to reflection from the parabolic mirror below, the bottom section of the tube always experiences a higher overall heat flux as is represented in *Figure 5*.

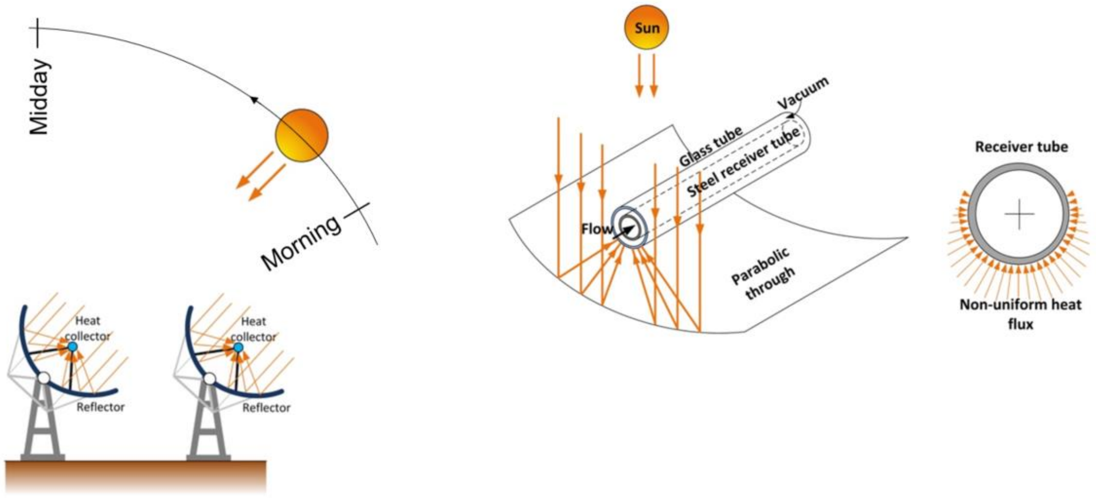

*Figure 5: Representation of a parabolic trough reflector and collector tube, and the associated maldistribution heat flux on the tube outer surface.*

Crucially, this maldistribution is time-dependent: the highest heat flux occurs on the sides of the tube during the morning and late afternoon, but the flux field becomes symmetrical around the vertical axis at solar noon. Because of the angle shift between the direction of gravity and the heat flux distribution, different combinations of boiling heat transfer mechanisms can be triggered.

Because field tests are difficult to repeat due to weather variations, our research centres around collecting experimental data under controlled laboratory scenarios. We use flow loops, like the one depicted in *Figure 6* to precisely regulate the thermodynamic state, fluid dynamics, and thermal boundary conditions.

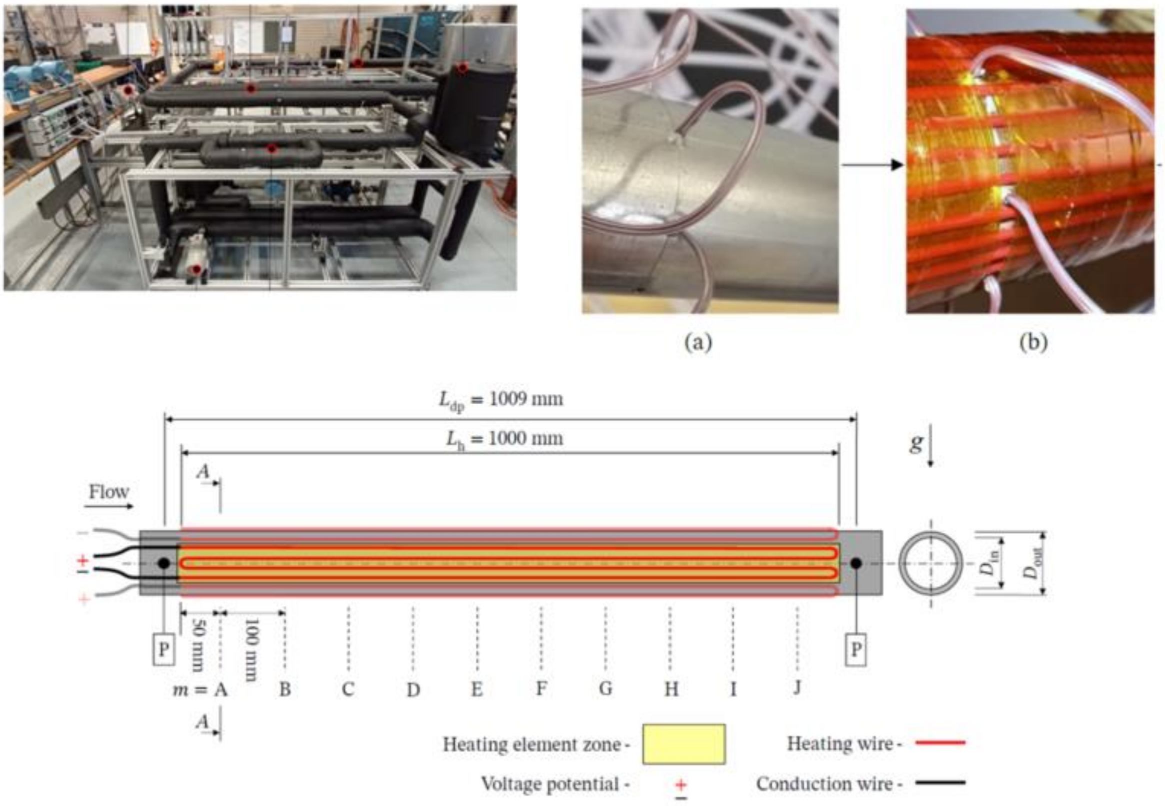

*Figure 6: Typical laboratory test facility and set-up to collect flow boiling data.*

Our interest lies in the phase change within the vapor dome, tracked by the vapor quality ($x$), which ranges from 0 for liquid, to 1 for vapor, as flow boiling progresses.

The photos on the right of *Figure 6* show a test section replicating the receiver tube. To simulate the non-uniform solar heat flux, we use multiple axial-running heating wires spaced circumferentially. These wires are individually energized, allowing us to reproduce a wide range of solar conditions. Crucially, in this case, the tube wall temperature is monitored by many embedded thermal probes.

Besides operational data, flow patterns are also observed and recorded using special sight glasses and high-speed video cameras.

The diagram shown *Figure 7*, is a flow pattern map, which documents the prevalence of each pattern, based on vapor quality on the horizontal axis, and flow rate on the vertical axis. At lower flow rates, stratified flow is typical, as gravity separates the liquid below the vapor. At higher flow rates, slug, intermittent, and annular flow are observed, depending on vapor content.

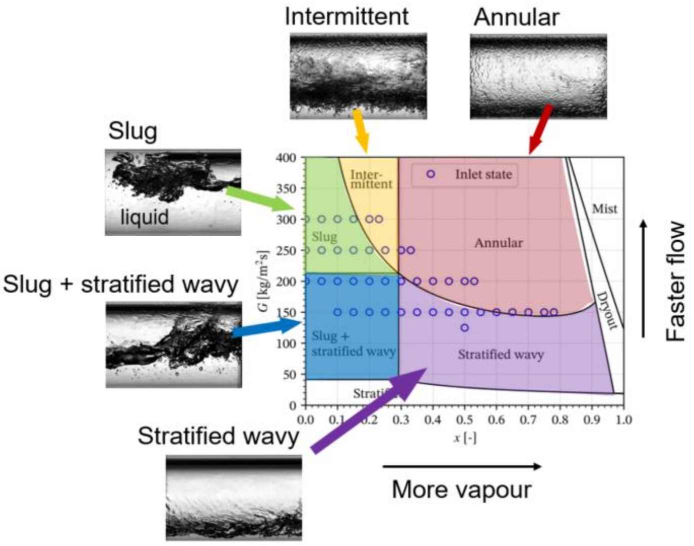

*Figure 7: Typical flow-pattern map (fluid and tube diameter dependent).*

The flow pattern is crucial because it influences the heat transfer mechanisms. Interestingly, we found that the heat flux distribution does not significantly alter the flow pattern, largely because hydrodynamics, gravity and surface tension exert a much more dominant influence.

Shown in *Figure 8* are examples of the heat transfer results obtained after intense data processing. This data, specific to Organic Rankine Cycles, reflects operation at lower temperatures than traditional cycles.

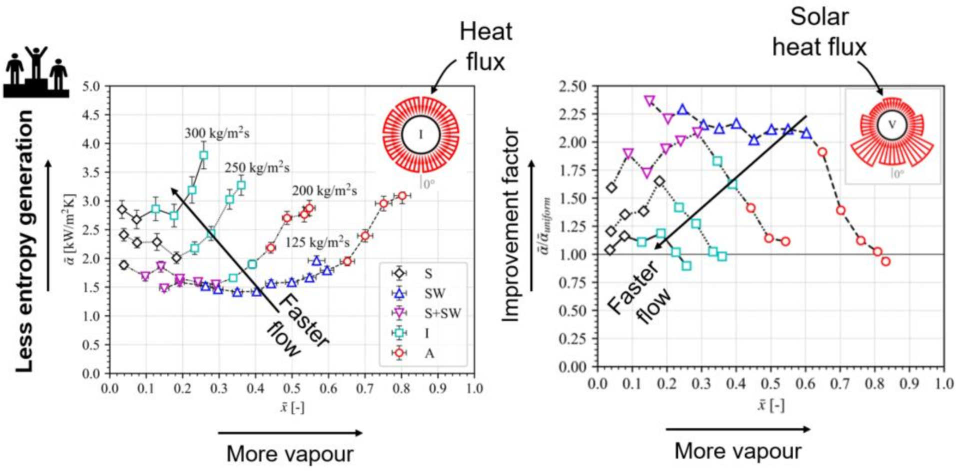

*Figure 8: Example result showing the influence of the heat flux distribution and the vapour quality (flowrate, fluid type, heat flux intensity and tube diameter dependent).*

The two graphs compare the flow boiling mechanism's ability to absorb energy under distinct heat flux distributions. The vertical axis represents the heat transfer capability. On the left, a classical uniform heating profile is shown, while the right displays a typical solar noon-time profile. Both the vapor quality and the flow rate significantly influence these results due to the governing flow patterns.

The most notable discovery, however, is the influence of heat flux distribution on the boiling mechanism itself. We found that the entropy generation associated with direct steam generation applications is significantly lower than in traditional heat exchangers.

Next, in *Figure 9* we can examine further examples of the impact of solar time on entropy generation. The angular shift between gravity and the applied heat flux introduces competing mechanics: buoyancy, convective boiling, and nucleate boiling together produce complex outcomes.

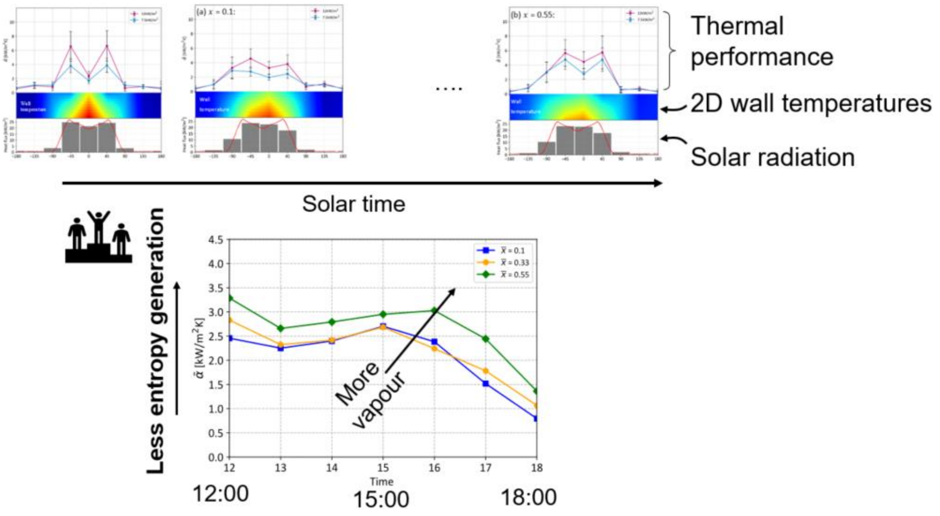

*Figure 9: Example result showing the influence of the solar time and the vapour quality (flowrate, fluid type, heat flux intensity and tube diameter dependent).*

Firstly, the conjugate heat transfer within the receiver tube—illustrated by the two-dimensional temperature profiles—significantly alters the actual heat flux distribution on the inner wetted wall. Secondly, the local circumferential heat transfer ability is strongly affected, often scaling directly with the local effective heat flux. Remarkably, our work demonstrated that while the lowest entropy generation (and thus the most efficient operation) occurs precisely at solar noon, the Direct Steam Generation approach can sustain this high efficiency over a broad window, specifically from approximately 8 a.m. to 4 p.m. This extended period of highly efficient operation underscores the practical advantage of direct steam generation.

### *Manipulating the flow patterns*

It is clear that the flow pattern is a key driver for potential efficiency improvements, raising the question of whether we can manipulate the liquid-vapor distribution. Our ongoing efforts focus on this theme: intending to encourage typical stratified flows to behave more like annular flows without significant increases in capital or operating costs. This can be achieved by introducing a simplistic spiral insert that hugs the inner tube wall as represented in *Figure 10*.

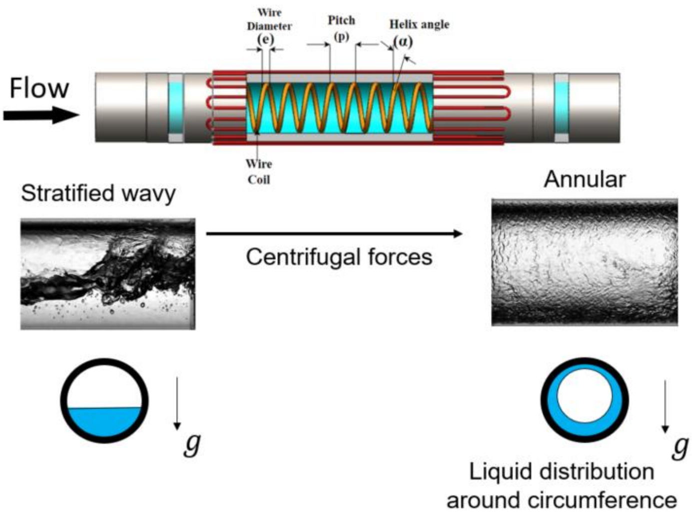

*Figure 10: Spiral inserts to enhance flow pattern towards annular flow.*

This superimposes a centrifugal-induced swirl motion onto the axial velocity components. This motion more evenly distributes the liquid, causing a general thinning of the liquid layer, and ultimately producing a more robust boiling mechanism. Initial results are promising, and we plan to publish these findings soon to report on the influence of among others, the geometric parameters of the inserts.

### 4.2 Macro scale condensation

Other opportunities for reduced entropy generation also exist, notably during condensation. Of the various condenser designs, air-cooled condensers are critical for arid climates, as they use little to no water. However, their drawback is lower efficiency compared to water-cooled systems.

To enhance heat rejection, techniques such as using downward-inclined tubes can be implemented. Low-pressure vapor enters the larger passages at the top, rejects heat to the surroundings as it flows downward, and is finally collected as liquid in the smaller flow passages at the bottom. Similar to flow boiling, the resulting flow condensation is complex, and requires careful investigation. The graph displayed in *Figure 11* illustrates the heat transfer ability of a condensing flow across various angular inclinations, with 0° representing horizontal flow.

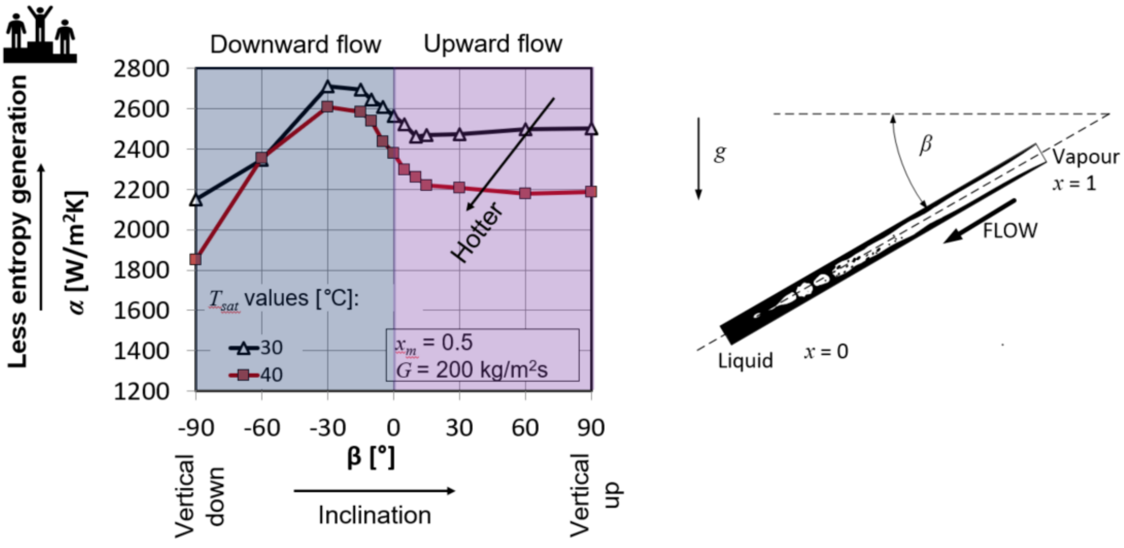

*Figure 11: Example result showing the influence of the solar time and the vapour quality (flowrate, fluid type, heat flux intensity and tube diameter dependent).*

We found that, in addition to previously mentioned parameters like flow rate, vapor quality, and condensation temperature, the inclination exerts a significant influence. While upward flow shows a relatively weak dependence, substantial efficiency enhancements, consistent across multiple condensing temperatures, were achieved at downward inclinations of between 20° to 30°.

This outcome reflects the complex interplay between phase velocities, gravity effects, and liquid layer thickness. Up to this point, I have not discussed the pressure drop penalty that often accompanies heat transfer improvement. Encouragingly, for some of the earlier-mentioned flow boiling scenario enhancements, this penalty can be negligible. However, when the vapor distribution is severely influenced, as with downward inclination condensation, flow friction adds a new dimension, presenting intriguing trade-offs that must be thoroughly analysed.

### 4.3 Miniature scale flow boiling

Flow scale plays a crucial role. Moving to the opposite extreme, when we consider microchannel passages, the competing flow and energy transfer physics behave distinctly differently. Understanding this behaviour is vital for several applications, particularly on the energy demand side of the economy.

The snapshot shown in *Figure 12* is from a high-speed flow visualisation indicating an example of bubble dynamics during flow boiling in a horizontal microchannel. This microscale approach coupled with latent heat is one of the most promising techniques to reduce entropy generation in the rapidly expanding data centre economy.

*Figure 12: Snapshot of a high-speed flow visualisation video during flow boiling in a microchannel.*

Note that the relative size of the bubbles to the channel is now critical. Bubble confinement results in different flow patterns that can become highly unstable. As before, all prior mentioned parameters, including channel orientation, must be rigorously investigated. Our core intent remains mapping and characterizing energy absorption abilities as is represented in *Figure 13*.

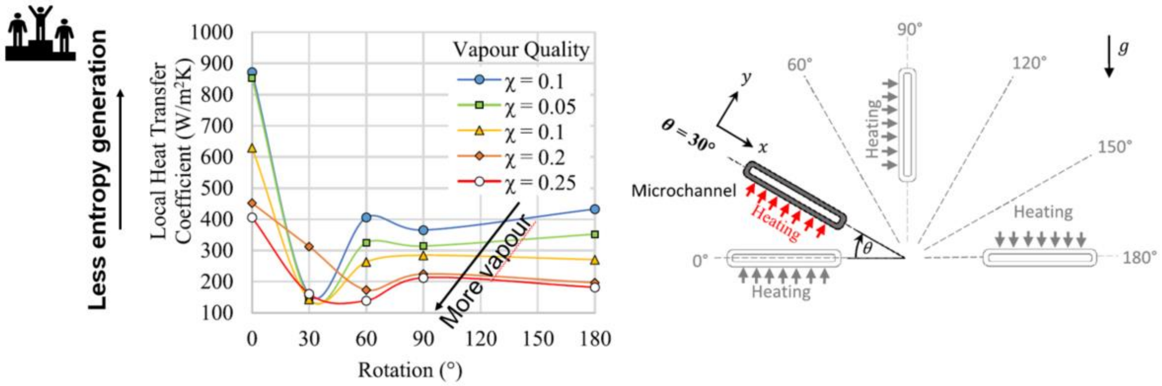

*Figure 13: Flow boiling heat transfer ability results with a microchannel at different azimuth angles.*

One of the most intriguing themes is the emergence of new heat transfer fluids with tailored surface tension behaviour. This parameter significantly affects bubble size and growth rates at the molecular level. Novel self-rewetting fluids have the distinct ability to draw liquid toward hot spots, allowing for continual surface quenching and resulting in more robust and stabilized flow boiling. This contrasts sharply with typical fluids like water, which are prone to surface dry-out and a severe breakdown in heat transfer.

The two snapshot sets of video recordings shown in *Figure 14* emphasize this, showing surface temperature and flow patterns for vertical downward flow, the most challenging orientation.

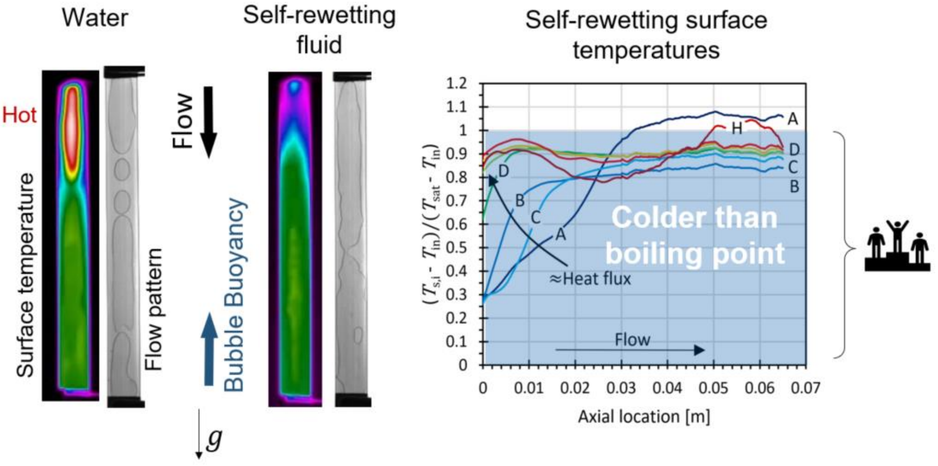

*Figure 14: Performance of self-rewetting fluids during flow boiling at downward flow inclinations in a microchannel.*

While water on the left, resulted in dry-out and hot spots, the self-rewetting fluid on the right, maintained more stable flow and consistent cooling. This mechanism is so effective that, under nearly all operating scenarios, the heat source surface was cooled to below the boiling temperature of the fluid. This is an intriguing discovery that warrants a dedicated discussion beyond this discussion.

## 4.4 Solid-Liquid Latent Thermal Storage

I've focused primarily on the short time-scale latent heat effects. However, to achieve a net-zero future, we are also required to consider the longer time scale applications of latent heat, specifically energy storage. This brings us to a complementary concept: **net zero energy**, where the goal is maximizing energy utilization. – All energy, not just those that we are used to.

### *High Temperature Storage in Direct Steam Generation*

Let us reconsider the direct steam generation plant shown in *Figure 15*, now including energy storage modules installed parallel to the solar collector fields. During the day, excess thermal energy is stored. At night, the storage modules replace the solar field to sustain steam production.

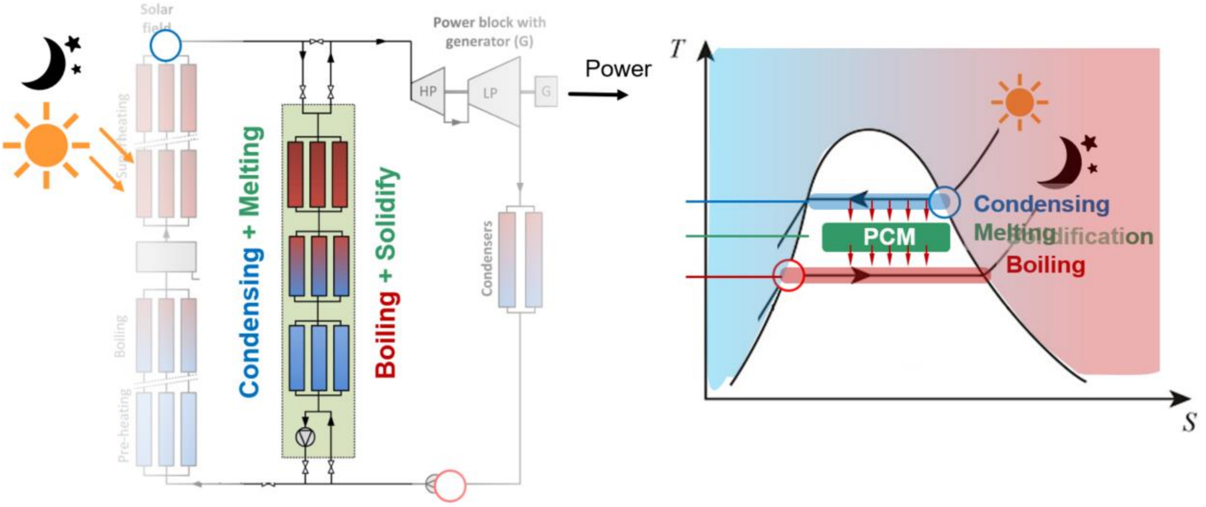

*Figure 15: Direct steam generation plant with latent PCM thermal storage integration.*

Due to the constant temperature nature of flow boiling, using latent phase change materials (PCMs), which melt and solidify at a consistent temperature, is highly appealing from an entropy perspective. To enable heat transfer, the power cycle must switch between two high-pressure operating modes. During daytime storage, the steam temperature must remain above the PCM's melting temperature. Conversely, when discharging at night, the steam temperature must drop below the solidification temperature, as illustrated on the entropy diagram.

The simultaneous coupling of two different phase-change processes, boiling and condensation with melting and solidification, causes a complex thermal-fluid problem. This demands consideration across multiple length scales: from single tube interactions to full system integration.

Our research uses experimental and numerical methods to address the geometric design and its impact on the PCM side of the energy module; alongside empirical modelling for system-level thermodynamic integration.

Examples of this mid-scale consideration are shown in *Figure 16*. Our goal is to characterize the energy charge (i.e. melting) and discharge (i.e. solidification) operational modes.

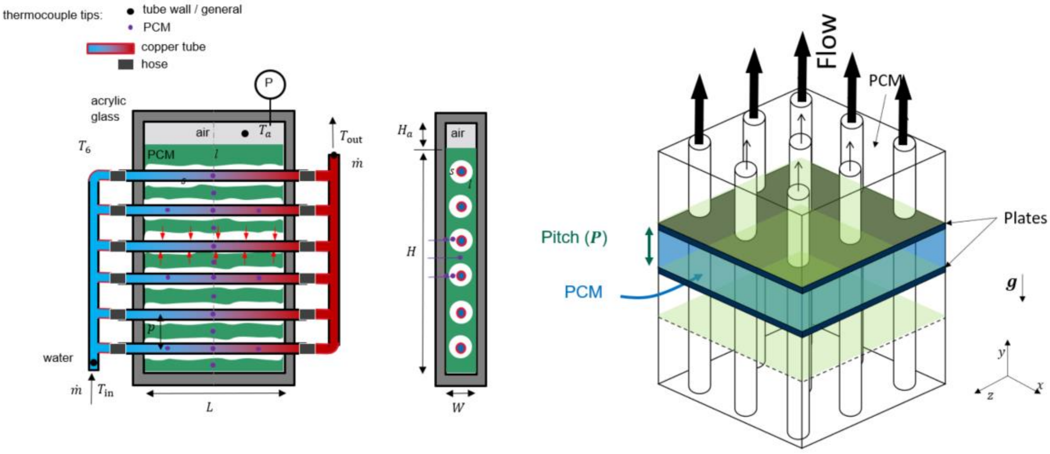

*Figure 16: Mid-scale considerations for solid-liquid based PCM thermal storage.*

A key distinction of PCM systems is the reliance on conduction heat transfer and natural convection, which were previously the weakest heat transfer mechanisms. Solidification poses the most significant challenge.

This is due to the stationary solid phase and the inherently low thermal conductivity of most phase change materials. As energy is discharged, the heat must migrate through the thickening solidified phase, which severely increases thermal resistance and rapidly degrades the energy delivery rate. Therefore, employing thermal conductive fins (as shown on the right *Figure 16*) and carefully optimizing tube spacing, are vital design considerations in our ongoing research.

### *Medium Temperature Storage in Buildings*

While power generation can utilize PCMs with high melting temperatures, numerous other applications across different temperature ranges can also benefit from volumetrically compact PCM energy storage, particularly in space cooling, which is the fourth-highest global electricity consumer as mentioned earlier. Providing space cooling and ventilation is an ethical and often legal requirement, which regrettably translates into heavy reliance on energy-hungry cooling plants.

However, the South African climate offers a unique opportunity for semi-passive and passive thermal regulation in buildings to offset high energy costs. The 24-hour summer temperature closely aligns with human thermal comfort of between 22 and 25 °C as is represented in *Figure 17*.

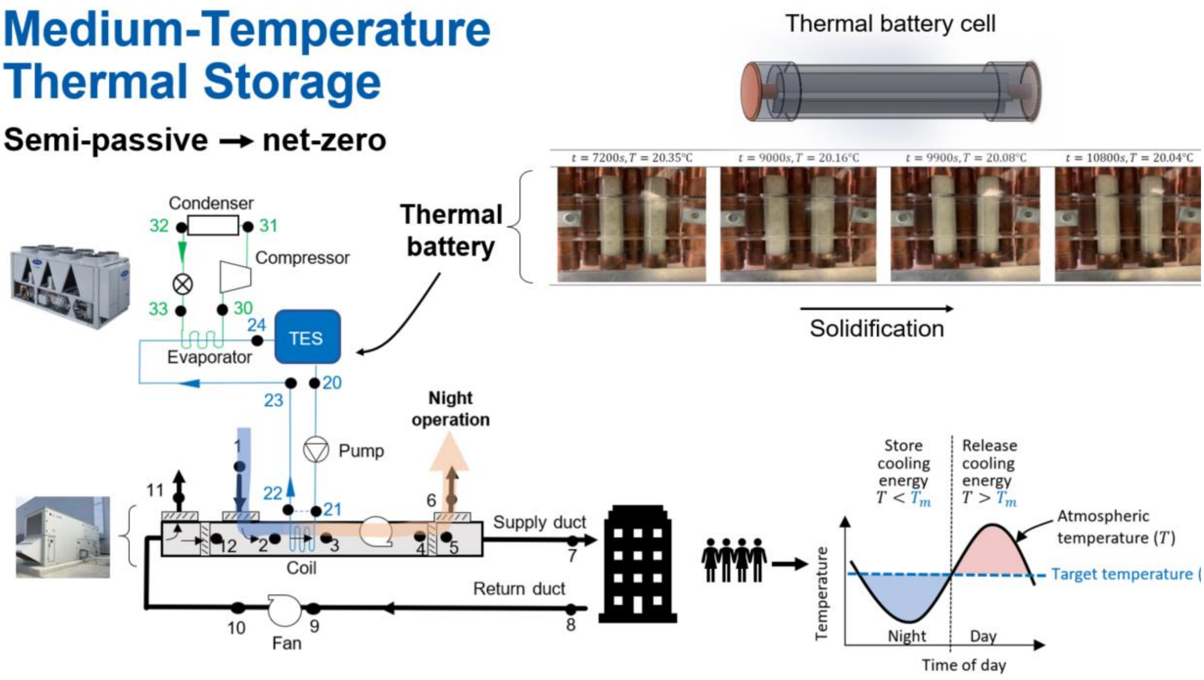

*Figure 17: PCM energy storage integration for semi-passive thermal regulation in buildings.*

By integrating thermal storage modules, as diagrammed, daytime heat is absorbed when outdoor temperatures are high. This stored energy is released 12 hours later when cooler ambient night temperatures make heat removal more viable at a significantly lower entropy generation rate.

Consequently, our recent and current work focuses on the development of thermal PCM cells, acting like thermal batteries, that can integrate into existing heat exchanger equipment (as shown in the top diagram in *Figure 17*). Critical aspects include careful internal design to ensure that efficient solidification occurs nightly, to enable the cells to absorb heat again the following day.

Such a solution differs from PV panel power generation:  The available roof area of most commercial buildings cannot provide sufficient PV power to also support space cooling. However, when we interact with the cold atmosphere at night, as is discussed here, vastly more energy is to our disposal.  This greatly contributes towards the establishment of hybrid net-zero installations.

When considering fully passive systems, which rely on natural ventilation without mechanical air movement, PCM thermal energy storage still remains a viable solution.

One of our ongoing projects, represented in *Figure 18*, investigates this. PCM tubes containing easily obtainable, low-cost natural plant-based substances, such as coconut oil, absorb heat from the occupied space during the day, causing the material to melt. This provides localized cooling and thermal relief to occupants below, as demonstrated by the simulation results on the left.

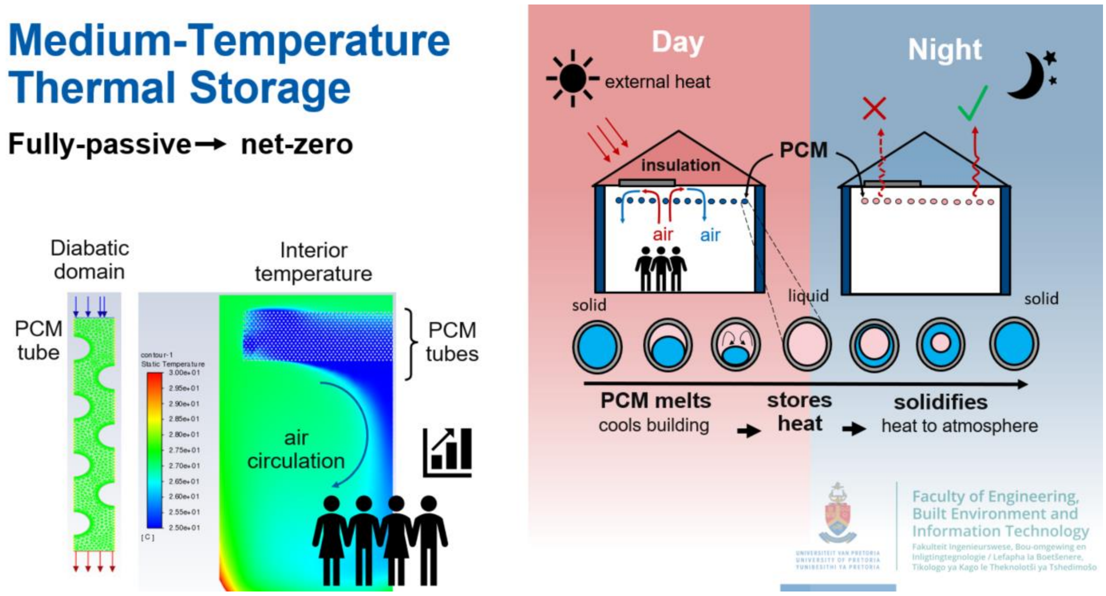

*Figure 18: Fully passive thermal energy storage scheme.*

Night operation, however, involves trade-offs: if excessive thermal insulation is used in the building envelope, the necessary night-time heat rejection can be hindered, as is represented on the far right. This presents one of many key optimization opportunities currently under investigation, and several more applications deserve representation, but for the sake of brevity are excluded from this discussion.

## 5. Summary and Closure

In summary, we tackled the challenge of net-zero (energy and carbon) across two distinct time scales. Firstly, via Active Heat Transport we optimize direct steam generation concentrated solar power by studying non-uniform transients and manipulating fluid flow patterns to improve efficiency. This work also extends to high-flux cooling via microchannels and the use of self-rewetting fluids. Secondly, via Passive Thermal Storage robust phase change material systems are developed for long-duration energy banking. This allows for both 24/7 operation of solar power plants, and the thermal regulation in buildings to reduce cooling energy consumption.

Finally, to conclude this brief journey, let us reflect on the Earth's global circulation patterns as represented in *Figure 19*. Nature has already accomplished all the principles discussed here.

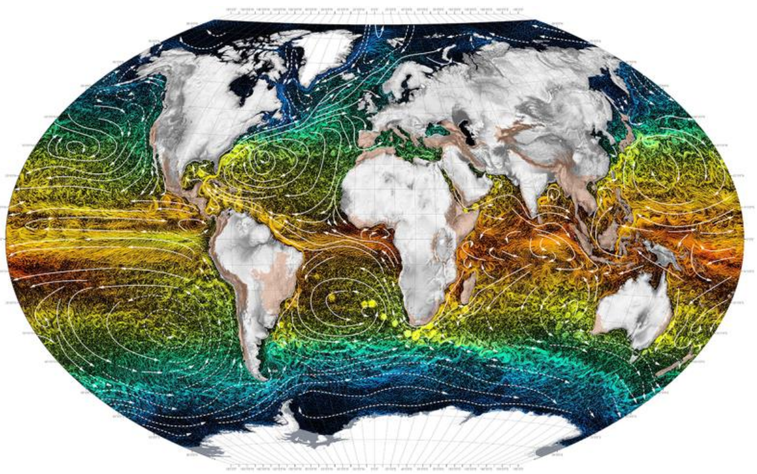

*Figure 19: Fully passive thermal energy storage scheme. (Image credit: Prof Richard J. Weller [http://atlas-for-the-end-of-the-world.com](http://atlas-for-the-end-of-the-world.com) )*

The planet’s thermal state is mostly governed by phase change: water evaporates and condenses when it rains: natural convection governs the powers of both atmospheric weather systems, as well as the ocean currents; and crucially, the dynamic melting and freezing of polar ice maintains the narrow thermal environment essential for life. May nature’s supreme examples humble us, and inspire us towards continued observation of the world around us.

## Acknowledgement and Thanks

As mentioned by poet John Donne in the 16th century: “"No man is an island, entire of itself; every man is a piece of the continent, a part of the main.” We can only operate with the support from others.

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