Punching above its weight?

Phase-change materials continue to represent an enormous opportunity to increase the energy savings delivered by low-energy HVAC systems. S**ean McGowan** reports on research that is unlocking this potential. Indeed, "High-performing low-cost thermal storage with phase-change material" won the AIRAH Awards 2012 gong for Excellence in HVAC and Refrigeration Research.

The Barbara Hardy Institute at the University of South Australia brings together a team of more than 250, including world-leading researchers, scientists, engineers and social scientists, to work on real-world issues of sustainability.

Formed in February 2011, the Institute champions its patron's vision for the "widespread adoption of sustainable principles and environmentally correct practices" by utilising multidisciplinary research approaches that challenge conventional thinking.

As a senior research fellow in the institute, Dr Frank Bruno, Affil.AIRAH, has acquired substantial funding over the years from both private and government organisations to lead research projects in the energy area. Challenging conventional thinking is his business, if not a defining characteristic.

With a Bachelor of Engineering in Mechanical Engineering, and a PhD in Mechanical Engineering, Bruno has worked on the development of high-density thermal storage materials (phase-change materials) and systems using these materials, as well as air conditioning, refrigeration, insulation and energy-efficient buildings.

"In the Barbara Hardy Institute, I am involved in research mainly related to thermal storage, and a little in air conditioning systems," he says.

Collaborating with a team of research staff, engineers and technicians, Bruno and postdoctoral fellows Dr Martin Belusko and Dr Steven Tay conducted a research project into the design of a phase-change material (PCM) storage system for low-energy cooling systems.

A novel approach was developed to design and optimise thermal storage systems using PCMs as the storage medium, allowing for the comparison of latent heat storage systems to sensible storage systems.

Along with developing a new type of high-performing PCM storage system, the research has also produced new, low-cost PCMs specifically for refrigeration applications.

"Thermal storage using PCMs represents an enormous opportunity to increase the energy savings delivered by low-energy systems using renewable sources of heating and cooling," Bruno says.

"Furthermore, thermal storage with PCMs can provide significant low-cost off-peak storage, particularly for cooling and refrigeration applications. Relative to sensible energy storage, PCMs can potentially store several times more energy per unit volume.

> The data revealed in this research shows that a PCM store can represent a realistic size for a commercial building, and compared to an equivalent ice slurry, would be at least 1.5 times smaller

"However, in practice, this is often not the case. PCM storage systems are also very expensive, and do not perform to their maximum potential."

The research program was undertaken to address these shortfalls.

Bruno says one reason that PCMs have not realised their potential is the lack of a suitable design method that engineers can follow.

Apart from thermal storage systems that use ice as their media, to date only a handful of PCM thermal storage systems have been used successfully in Australia for cold-storage or space-cooling applications.

"Thermal storage systems with PCMs have been predominantly designed and analysed by researchers through numerical modelling," he says. "However, no systematic attempt to determine and optimise the usefulness of PCMs in thermal storage has been conducted."

Compounding these issues is that questions have been posed about the cost, reliability and longevity of several of the available PCMs.

A NOVEL APPROACH

One of the outcomes of Bruno's research has been the design and optimisation of a PCM storage system based on heat exchanger design theory and the effectiveness-number of transfer units (-NTU) technique.

"A thermal storage system is like a heat exchanger," he says.

"There is competition between capacity (kW) and heat exchange effectiveness (when capacity is increased, efficiency will decrease). The effectiveness-NTU technique helps you to achieve the right capacity at maximum efficiency."

The effectiveness is described as the ratio of the actual heat discharged over the theoretical maximum heat that can be discharged. It is a function of the number of transfer units (NTU), which is based on the flow rate and surface area of the heat – transfer liquid.

The research paper describes the physical phase change as a "transient process" such that the "heat exchanger effectiveness is bounded between 0 and 1."

It says that the average effectiveness over the phase-change process can be determined by the average inlet and outlet temperatures over the phase-change process. The average effectiveness therefore is said to directly identify the performance of the thermal storage unit.

"During the phase-change process, heat is exchanged between the heat-transfer fluid and the phase-change interface within the PCM, at the phase-change temperature," the research paper says.

"This heat transfer is a function of the thermal resistance in the heat transfer fluid and in the PCM proportion which has already changed phase. Therefore, the outlet fluid temperature is determined by the thermal resistance in the system and limited by the phase-change temperature. Maximum heat transfer is achieved when the outlet temperature equates to the phase-change temperature."

The research goes on to say that thermal resistance also affects the discharge temperatures achieved from a PCM storage system. These are specified by the load's cooling requirements.

> Several prototypes have been built, tested and evaluated in-house, and a full-scale system is being designed that will hold 50,000kg of PCM

"Ideally, the discharge temperature should equate to the phase-change temperature of the PCM," the research says. "However, due to the thermal resistance, the discharge temperature will be above this temperature, and therefore a lower temperature PCM is required. As a result, charging this PCM is more energy intensive. Consequently, energy-efficiency storage is dependent on minimising the thermal resistance to heat transfer in the PCM storage system.

"To meet the temperature specifications in any thermal system, the effectiveness must be greater than that defined by the system. Therefore, the research says the effectiveness at 90 per cent of the phase change produces a design parameter suitable for sizing the storage capacity."

Previous research had involved investigations around the effectiveness of a tube-in-tank arrangement surrounded by PCM to determine these figures, as well as the energy storage effectiveness – the expected useful stored energy of at PCM storage system.

We are the champions

Dr Frank Bruno, Affil.AIRAH, Dr Martin Belusko, and Steven Tay earned the gong for Excellence in HVAC and Refrigeration Research at the AIRAH Awards 2012 for their work on "High-performing low-cost thermal storage with phase-change material".

Common misconceptions about PCM thermal storage systems

They can always store a lot of energy.

"PCM thermal storage can only store a lot of energy when it has good heat transfer," says Bruno. "Also, a PCM thermal storage system is better than a sensible storage system [like water] only when the charging and discharging temperatures are close to each other."

They save energy.

"This depends on the design of the system," Bruno says. "Generally, storage does not save energy – it stores energy for later use. However, storage could help the system to save energy by operating at times when the system is more efficient. For example, a refrigeration system operates with higher efficiency during the night time compared to the day time. Also, thermal storage could store heating or cooling from a renewable energy source, which could off-set energy produced from a non-renewable energy source."

They are expensive.

"This depends on how the system is developed," says Bruno. "Also, the current price of some PCMs is about $6–7 per kilogram, but they could potentially be made cheaper."

All PCMs are the same.

"This is not true," Bruno says. "It depends on the formulation, which affects the storage capacity, stability and life of the PCM. A lot of commercially available PCMs we have tested do not match their specifications – they perform worse!"

Found to offer the best performance and minimum cost, this type of system was then used in a parametric study of the energy storage effectiveness, based on the average effectiveness of the phase-change process.

The impact of the heat transfer surface area was investigated by varying the length of the copper tube used, as well as the tube's diameter, number and mass flow rate.

This system was based on a night-time cooling system using cooling towers as a heat sink for a typical multi-storey commercial building incorporating a chilled beam system covering a total floor area of 8000m².

With a design load of 120W/m² or 960kW, and based on a night-time operational period of nine hours, a total potential storage capacity of 8640kWh was calculated, requiring 127.5m³ of PCM volume based on the latent energy of the PCM17.

PCM17 is a commercially available hydrated salt material with a melting point within the temperature range being considered. The heat-transfer fluid (HTF) used was an aqueous salt-based liquid with very low viscosity at low temperatures, which reduces pumping power.

"In a chilled beam system, the temperature of the heat source requires an inlet temperature of 18°C, and delivers an outlet temperature of 21°C,: according to Bruno et al's research. "The heat sink is the night-time wet bulb temperature, which is expected to be 15–16°C. Therefore, the allowable temperature change in the HTF ranged from 1 to 2°C. Consequently, based on a fixed-mass flow rate for temperature differences of 1°C, 1.5°C and 2°C, the mass flow rates of the HTF to achieve the design load are 230kg/s, 153kg/s and 115kg/s respectively."

This study was carried out based on the ε-NTU technique, such that when the length and diameter of the tube was varied, the maximum PCM diameter is changed so that the total PCM volume is constant.

Different tube diameters were analysed based on typical copper tubes used in air conditioning systems. Using the ε-NTU technique, the length of the tube was varied for each tube diameter. In order to minimise pump losses that correspond with lengthening the tube, the total length of tube was split into equal lengths and the total number fixed to 100.

The study found that when the tube diameter was small (6.4mm), the pumping losses were significant. However, it was discovered that while pumping losses became negligible at larger tube diameters, energy-storage effectiveness decreased.

"Therefore, the highest storage effectiveness is achieved with the smallest possible diameter with the minimum pressure drop."

As high-pressure drops were observed when all tube diameters less than 12.7mm were used, this diameter was found to be the most suitable due to its high energy-storage effectiveness and negligible pressure loss.

APPLYING EFFECTIVENESS

The research says that energy-storage effectiveness can be used to directly determine the amount of PCM needed in a PCM storage system.

"The calculated useful stored energy can be directly compared to the sensible energy stored within the heat-transfer fluid. At low-temperature differences of 1°C, the energy-storage effectiveness co-efficiency is less than 70 per cent; however, the overall storage effectiveness of a PCM system is at least 18 times greater than the sensible energy density that can be achieved using the heat-transfer fluid as the storage medium. With increasing flow rates, the ratio of the latent-to-sensible energy that can be stored consistently increases, showing that the PCM systems can dramatically reduce the required storage volume in a low-energy cooling application."

By determining this, the amount of PCM can be increased to achieve a fixed, useful energy usage.

Bruno says one of the failures of PCM storage systems reaching their potential is that the critical value of effectiveness is not well known or understood by those working on these them.

"Often with thermal storage, people look at the theoretical capacity," Bruno says. "The real capacity relates to how efficient the heat exchange is, and this is defined by effectiveness."

The data revealed in this research shows that a PCM store can represent a realistic size for a commercial building, and compared to an equivalent ice slurry, would be at least 1.5 times smaller.

"In an off-peak air conditioning application for a building, modelling has shown that this type of PCM storage system can store 18 times more useful energy than sensible storage systems per unit volume," says Bruno.

These research outcomes have led an Australian company to begin commercialising the technology.

Several prototypes have been built, tested and evaluated in-house, and a full-scale system is being designed that will hold 50,000kg of PCM. This system is expected to be installed in a refrigeration application by the end of next month.

Along with commercialising the PCM storage system, the research has also shown how PCMs can be used effectively without the addition of additives typically used to stabilise and prolong their life.

This is expected to lead to the development of new, low-cost PCMs for this and other heating and cooling applications.

Would you like to know more?

The research on designing a PCM storage system using the effectiveness number of transfer units method has been published in 17 peer-reviewed papers in leading journals and conference proceedings around the world.

It also formed Australia's contribution to the International Energy Agency (IEA) Task 4224 program, which is aiming to develop compact thermal energy storage. Task participants collaborating with the University of South Australia are from Austria, Belgium, Canada, France, Germany, Italy, Netherlands, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the US.

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