the conditioned air and brings the same benefits as opening the windows when cool outside. As such, the strategy is often referred to as "free cooling." Water-side economization reduces the demand on the chillers that cool the conditioned air in many data centers, again by using outside air. Evaporative cooling techniques can reduce the energy demand even further. By using such techniques, Google has dropped its average trailing 12-month PUE to 1.10 (*6*).

Future improvements in cooling strategies will come from a shift in focus from air-cooling strategies to a focus on embedded liquid and evaporative cooling techniques, which take advantage of inherently higher heat transfer coefficients. Direct liquid cooling features microchannel cold plates mounted directly on the heat-producing chips. Reliability concerns related to the integration of liquids in the server chassis initially affected the implementation of this technology, but increases in chip energy density beyond the capabilities of air cooling, coupled with technology advances such as optimized microchannel designs (*7*) and detailed failure mode analysis and mitigation (*8*), have led to wider adoption of embedded liquid cooling in hyperscale data centers over the past few years.

> **"As the demand for data center capacity continues unabated, the demand on the power grid will continue to escalate."**

However, advances in integrated chip designs with three-dimensional architecture are creating energy densities beyond even that which can be controlled with direct liquid cooling. Thus, next-generation cooling research is investigating techniques such as flow and pool boiling (*9*) and even direct immersion of the chips in dielectric fluids with subsequent boiling at the chip interface (*10*). Thermosyphons, which feature gravity-fed liquid-vapor systems, are the focus of much attention (*11*), as they allow the high heat transfer possible with flow boiling while eliminating the reliability issues inherent with micropumps. In application, microevaporators are located directly at each chip, much like a cold plate; gravity-fed liquid feeds the evaporator, and the resulting vapor rises to a condenser located at the top of the server rack, where the loop begins again. Much two-phase flow research focuses on the use of environmentally friendly refrigerants such as HFC-245fa or HCFO-1233zd(E), adding the benefit that any leak will immediately vaporize, eliminating concerns around liquid leakage (*12*).

As the demand for data center capacity continues unabated, the demand on the power grid will continue to escalate. Thus, solutions for environmentally friendly and off-grid power production are of much interest. Some hyperscale data center operators are exploring sourcing their own sustainable power production using hydrogen fuel cells (*13*), and others are sourcing their energy from solar and wind farms. Future research trends will include a focus on advanced cooling techniques that feature energy recovery and reuse. Both liquid and two-phase cooling strategies produce a stream of heated liquid or vapor that can be used in various waste-heat recovery systems, including straightforward techniques such as hot water production and plant or district heating (*14*) and more complex systems such as absorption refrigeration or the organic Rankine cycle, which generates a source of electricity that can be fed back into the data center (*15*).

The current technical limitation is the low quality of the heat, and next-generation advances will require much attention to the integration of the cooling technology and the energy generation technique to meet the growing demands of our insatiable need for data. The past 5 years have shown incredible advancements in the technology used to cool data center equipment, but much work remains to be done to develop sustainable, environmentally friendly solutions to the energy demand required to power the cloud. ■

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PERSPECTIVE

Photon-engineered radiative cooling textiles

Personal thermal management offers a path to reduce climate control energy use

By **Po-Chun Hsu** *and* **Xiuqiang Li**

Take a few seconds to look around and list all the technologies that are indispensable for you. If your list does not include textiles, try to live a typical day without them. Textiles are arguably one of the earliest human inventions. Without textiles to cover the human body for warmth, our ancestors would not have been able to spread across the various climate zones of the Earth. Today, many textiles are made for social etiquette and aesthetic purposes, but the pressing threat of global warming has created demand for innovative textiles that help to better cool the person who wears them.

The rationale behind linking textiles and climate change is that wearing the cooler textiles for localized "personal thermal management" may reduce the demand for air conditioning. The impact of air conditioning is considerable, given that it is not only responsible for 10% of U.S. electricity consumption but that the refrigerants are also a source of high global-warming-potential gasses (*1*, *2*). Considering an indoor setting distinguishes the new generation of cooling textiles from textiles oriented for sports. On average, the metabolic heat rate of indoor light activities is 60 to 80 $\mathrm{W/m^2}$, balanced by the heat flux from the skin to the environment. This flux occurs through all viable heat transfer pathways: conduction, convection, radiation, and evaporation. Because one of the criteria of thermal comfort is the absence of sensible perspiration, evaporation only accounts for ~5 $\mathrm{W/m^2}$. Using the American Society of Heating, Refrigerating and Air-Conditioning

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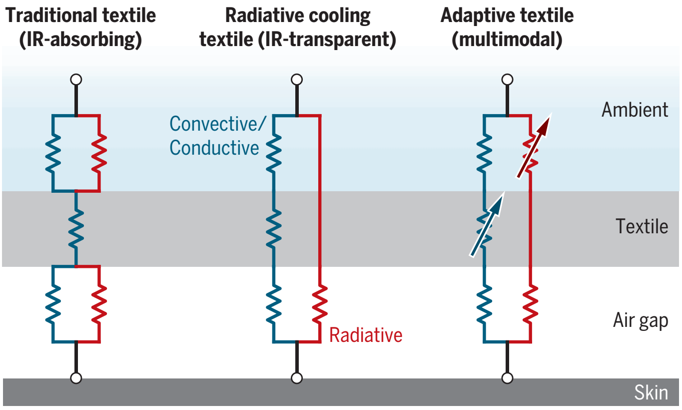
Engineers Standard 55 as the reference and assuming the clothing insulation is 1 clo (0.155 m^2K/W; clo is the industry unit for thermal insulation), then the heat transfer through textile conduction and natural convection contributes ~40 W/m^2, and radiation is responsible for ~25 W/m^2. This calculation demonstrates the substantial role of radiation in the human body heat balance. Unlike convective heat transfer, heat radiation is a surface property and does not require any media or moving part, making it a perfect tool for personal thermal management.

Regardless of skin pigmentation, the human skin is a nearly perfect black body that emits thermal radiation through Planck's law. This radiation transmits through the air gap and is absorbed by the textile, which contains various types of resonating molecular vibrational modes. The textile then reemits to the ambience. Almost all clothing materials are highly absorbing in the spectral region of human body radiation. Although Kirchhoff's radiation law indicates that they are also good emitters, their infrared (IR) opacity inevitably results in the radiation shielding effect. Therefore, rather than engineering the existing clothing materials, the key to radiative cooling is to re-invent the material so that it is transparent in mid-IR, allowing the thermal radiation from the hot human skin to bypass the textile and directly reach the ambience (see the figure). By contrast, traditional IR-absorbing textiles emit from the cold outer surface with a much lower radiation power that is proportional to the fourth power of temperature, according to Stefan-Boltzmann's law. This design principle leads to polyethylene (PE) textiles because of its simple chemical bonds and very few resonance peaks in mid-IR. In 2015, Tong *et al.* numerically predicted that radiative cooling fabric could be achieved by controlling the PE fiber diameter and light-scattering mechanisms to obtain both IR transparency and visible light opacity for wearability (*3*). One year later, Hsu *et al.* experimentally demonstrated nanoporous PE (nanoPE) radiative cooling fabric (*4*). The nanoporous structure was designed to achieve multifunctionality such as visible opacity, breathability, and softness. Several efforts to enhance the wearability were also conducted, including sweat-wicking and wind permeability. Built on the intrinsic IR transmittance and nanoscale photonic engineering, this concept was further developed into large-scale woven and knitted textiles (*5*), outdoor cooling textiles (*6*), and visibly colored cooling textiles (*7*, *8*). Depending on the types, these radiative cooling textiles can have the cooling performance equivalent to more than a 2°C increase of indoor temperature setpoint. One should not underestimate this amount of setpoint increase because it applies to the entire building space, which has orders of magnitude more thermal inertia and heat loss to manage compared with the occupants. Estimates of energy savings suggests the potential for a 20% reduction of heating, ventilation, and air conditioning energy with this small setpoint increase (*9*).

Designing more comfortable textiles

Heat transport through traditional textiles occurs by conduction or convection (blue paths), but infrared (IR) radiation is blocked (red paths). Cooling textiles improve radiative heat transfer between the skin and the environment. Adaptive textiles control the heat balance without working fluids or continuous energy input.



GRAPHIC: N. CARY/SCIENCE

Looking ahead from the promise of energy saving, challenges and opportunities exist for the radiative cooling textiles. Thousands of years of evolution have made the expectation for clothing design to be complicated and often subjective in terms of what is considered necessary. Even for simple energy-efficient thermal comfort, psychological and environmental factors are in play that go beyond what might be ideal from a physical science perspective. The choices of IR-transparent polymers should be broadened to accommodate the various needs for wearability, such as moisture transport, skin touch comfort, scratch durability, and laundering. A general rule is to search for materials with a high content of crystalline aliphatic segments, followed by quantitative measurement of absolute extinction coefficient. Also, textiles should be adaptive. For example, the textile woven from carbon nanotube–coated bimorph yarns can respond to sweat and modulate the mid-IR emissivity (*10*), which is energy free and effective for the outdoors, but needs to increase the trigger sensitivity for the indoor scenario. A different strategy is to use active cooling by devices such as Peltier coolers that are either directly wearable or connected with recirculating water (*11*, *12*). These systems have superior cooling power, but the power consumption likely needs an energy storage or supply breakthrough to become part of daily clothing. A hybrid solution is variable passive thermoregulation, which uses energy to control the heat transfer coefficients rather than supply the thermal power. The tunable range is similar to the purely passive approach but can be actively changed according to user preference and potentially other signal inputs from the environment or the human body (*13*, *14*). Ultimately, the radiative thermal engineering can be combined with other textile heat-management mechanisms to accomplish multimodal control. A radiative cooling textile with coupled dynamic evaporative cooling can perform human body cooling even when the ambient temperature is higher than the skin.

Like many other renewable energy technologies, radiative cooling textile was initially a materials science and nanophotonics effort for niche applications for energy-efficient buildings by accomplishing the localized personal cooling, and it will eventually need to find the proper market position to be economically sustainable. In particular, these textiles will be joined by both traditional textile engineering and the booming wearable technologies. Our ancestors invented textiles as the "secondary skin" for thermal regulation. As textiles become an indispensable part of our lives, they hopefully will move closer to being as smart, versatile, and natural as our actual skin. ■

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