Enabling Compact Thermal Systems through Insights on Microscale Coupled Heat and Mass Transfer Phenomena

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Abstract. Heat transfer in microscale geometries offers the advantage of high heat transfer coefficients and large surface area-to-volume ratios, and therefore, the potential to develop compact heat and mass transfer devices and systems. This paper provides an overview of a variety of applications ranging from tens of Watts to Megawatts of heat transfer rates that can benefit from these insights into coupled heat and mass transfer. Practical challenges and innovations in implementing microscale heat exchangers are briefly discussed. This is followed by examples that include wearable cooling systems, thermally driven heat pumps, cooling of aircraft carriers, carbon capture and methane gas cleaning using microscale hollow fibers, and the incorporation of microchannel heat exchangers into electrochemical storage systems and nuclear reactor cores.

1. Introduction

Many thermal processes across a wide swath of industrial, commercial and residential market segments require high heat transfer rates in small envelopes. In several applications, e.g., waste heat recovery, source temperatures are inherently low, compressing the temperature spectrum across which these energy conversion processes must occur. High heat transfer rates in small envelopes are best accomplished through high heat transfer coefficients, large surface areas, and judicious use of the available temperature difference. Phase-change heat transfer processes such as condensation and evaporation yield high heat transfer coefficients. These can further be enhanced through the use of microscale geometries. As the hydraulic diameter decreases, heat transfer coefficients increase. An associated benefit from the use of smaller flow passages is the high surface area-to-volume ratios they offer, further enhancing the heat transfer rates. Processes that involve single-phase liquids on the two sides of the heat transfer surface also have the potential for counterflow implementation, leading to the most optimal use of the available temperature difference, ultimately yielding high effectivenesses. The small diameter passages do present the issue of potentially higher pressure drops, which in phase-change processes, can adversely affect the saturation temperature, and also lead to higher pumping power. But such issues can be readily addressed by distributing the flow across multiple parallel channels, without an appreciable decrease in heat transfer coefficients. This paper provides examples of compact and efficient components and thermal systems that use these overarching design considerations to advantage.
2. Practical Design and Fabrication Considerations

2.1. Flow distribution

Many compact heat exchangers must supply single-phase or two-phase flows to multiple parallel channels of small hydraulic diameter. Invariably, such configurations are susceptible to flow maldistribution, which can adversely affect performance. In single-phase flow, maldistribution is often minimized by designing inlet and outlet headers to the channels with varying cross-section so that the pressure drop through the different channels is nominally equal, leading to an even distribution. In two-phase flow, the potential for maldistribution and flow instabilities can be more acute. In some cases, especially in evaporators and boilers, instabilities can lead to flow oscillations and flow reversal, leading to unsteady and inadequate performance. Inlet flow restrictors are sometimes used at each channel to minimize such possibilities. A recent study by Hoysall et al. [1] investigated maldistributions in two-phase flows entering multiple parallel channels of \( D_h = 0.4 \text{ mm} \), including high speed flow visualization followed by image analysis to compute void fractions and interfacial areas as the flow proceeded downstream. Two-phase flow can be maldistributed in two different ways, one being a maldistributed overall two-phase flow, the other being uneven distribution of the vapor and liquid fractions in different channels. It was seen that the liquid fraction would primarily flow through channels near the inlet port, while vapor would flow through the farthest channels. While such maldistribution would of course adversely affect heat transfer, when the objective of the heat exchanger is to accomplish mass transfer, as is the case in an absorber of an absorption heat pump, the flow of liquid and vapor in separate channels prevents mass transfer and can almost completely suppress absorption. To redistribute poorly distributed flows, they introduced periodic breaks in the microchannel walls, and also offset the downstream channel walls from the upstream walls. These channel breaks allowed the fluid to redistribute and gradually achieve an even distribution as the flow progressed (figure 1). Distribution of the two-phase mixture in the header itself before it enters the microchannel tubes was the focus of studies by Mahvi and Garimella [2-4]. They investigated two-phase flows of air-water mixtures and refrigerant R134a through rectangular, tapered and other headers, assigned flow regimes to the flows in the header, and developed models to predict flow distribution based on these regimes as well as the pressure drop through the entire circuit from the header inlet to the exit of the microchannel tubes. Such models are useful for the design of headers that minimize maldistribution. These models and passive flow distribution features go a long way in enabling the potential of microchannel heat exchangers to achieve high heat transfer rates.

2.2. Fabrication issues

The geometries available to the designer of microchannel heat exchangers are not only governed by heat transfer and pressure drop considerations, but often, more so by fabrication constraints. Optima in microchannel heat exchanger geometries tend to favor the smaller hydraulic diameters. However, fabrication of such sub-mm heat exchangers with long channels presents challenges in terms of shape cross section, tolerances of dimensions, surface roughness, and straightness. One common method of fabricating such channels is to photochemically etch the passages on a sheet of metal, followed by diffusion bonding or brazing of an upper sheet to make the closed sets of passages. The etching process for rectangular channels, at \( D_h < 0.5 \text{ mm} \), usually results in shapes that are “half-stadium” shaped, i.e., with corners that are rounded, thereby not corresponding exactly to the desired shape. Diffusion bonding of these sheets is usually quite reliable in ensuring a leak-free bond. However, diffusion bonding can
be expensive and is also not suited for high volume production. Controlled atmosphere brazing is a less expensive alternative; however, considerable skill and iteration is required in ensuring leak tightness on the one hand, and preventing braze material from flowing into the channels and partially or fully blocking them on the other hand. The author has found that for stainless steel, channels with $D_h \approx 0.35$ mm are possible to achieve acceptable dimensional tolerances as well as ensure bonds that can withstand pressures of up to about 3500 kPa. Stamping and fluid forming (where the metal sheet is placed on the die, and fluid pressure is used to form the stamped sheet over the die) are other options to form such channels. While channels of $D_h \approx 0.35$ mm can be formed in this manner, the issue of residual stresses and the resulting potential for warping when these stamped sheets are brazed requires careful attention. One other fabrication issue for heat exchangers made of such channels is the configuration of the header. Large unsupported areas of the headers that bring the fluids to the channels can lead to bowing and failure when the operational pressures are high. Therefore, adequate supporting pegs, pins, vanes, etc., should be incorporated to decrease the unsupported span of these header regions. 3-D printing is another emerging technique that has gained acceptance for the fabrication of intricate shapes in materials such as plastic. It can also be used for metals, however, surface roughnesses are often not acceptably low, and possible channel lengths that can reliably be fabricated are limited. As this technology evolves, it is expected that 3-D printing will be a useful option not only for fabricating heat exchanger channels and heat exchangers, but perhaps entire thermal systems as monolithic blocks, which could significantly decrease parasitic plumbing losses, and require very little labor for assembly.

3. Heat and Mass Exchangers for Binary Fluid Phase-Change

In heat pump systems that employ binary fluids, e.g., ammonia-water, as the working fluid, the refrigerant ammonia must be desorbed from the solution in one component and subsequently absorbed back into the absorbent. The absorber is the lower pressure component in the system, whose pressure is closely tied to the evaporator pressure. A lower evaporator pressure is desired to achieve maximum cooling; however, at this same pressure, the solution concentration must be decreased to ensure that the absorber temperatures are high enough to be able to reject the heat of absorption to the ambient or the pertinent heat sink. At these low concentrations, sufficient refrigerant cannot be desorbed from the solution in the desorber. Therefore, the pressure drop in the absorber is at a high premium, and configurations that ensure counterflow solution-to-coupling fluid orientations and also adequate vapor space to minimize pressure drop are critical. A miniaturized geometry (figure 2) for absorbers that meets these requirements was conceptualized by Garimella [5] and experimentally demonstrated [6-8]. It was subsequently also demonstrated as a desorber and for system-wide application [9, 10]. In this configuration, vapor flows upward through a lattice of criss-cross microchannel tubes while dilute solution flows down by gravity, absorbing the vapor as it flows down, rejecting the heat of absorption to coupling fluid flowing through the tubes. The coupling fluid flows upward, in counterflow with the falling solution. Also, the vapor rising due to buoyancy, in counterflow with the falling solution yields favorable concentration and temperature profiles. The high surface area-to-volume ratio, tube-side microchannel heat transfer coefficients and the effective counterflow falling-film heat and mass transfer on the solution side all contribute to yielding a compact component as an absorber for a residential absorption system.

The desorber of an absorption system also requires counterflow vapor-liquid and solution-coupling fluid flows. As the vapor is desorbed, it must interact with the incoming solution in counterflow so that the water fraction in the vapor is stripped to a large extent, providing relatively pure vapor that does not require excessive rectification. To achieve this, a countercurrent falling-film configuration that provides adequate space for the vapor to rise while in close contact with the falling film is needed. When considering microscale geometries, this requires careful design so that compactness of design can be
maintained without causing flooding and flow reversal. The author and co-workers [11-15] recently developed and experimentally demonstrated such a compact desorber (figure 3) based on diabatic distillation concepts coupled with the constraints of minimal exergy destruction, while also ensuring a countercurrent serpentine path for the vapor without flooding.

The heat exchanger designs described above, in which high heat and mass transfer coefficients are ensured in-tube as well as externally, can be used as building blocks for the development of a variety of thermal systems in various applications. Some representative applications that employ these concepts are described below.

4. Cooling and heating systems

Small capacity (e.g., 300 W to 10 kW) cooling systems can, in particular, benefit the most from the design of compact heat and mass exchangers, which facilitate portability and small system envelopes. Examples of vapor compression and absorption based heat pump systems are described below.

4.1. Wearable cooling systems

Wearable cooling systems are useful to ensure safety, comfort, and operational efficacy of military, fire-fighting, chemical response, and other hazardous duty personnel operating at elevated temperature environments. Rudimentary systems such as phase-change material pouches in vests are convenient, but allow severely limited mission duration. Electrically driven vapor-compression systems offer adequate cooling, but either they must be tethered to an electricity source, limiting mobility and range of operation, or if battery powered, suffer from very limited durations. Ernst and Garimella [16, 17] developed an engine-driven vapor-compression cooling system assembled in a backpack configuration, providing cooling to a vest worn by personnel (figure 4). An air compressor was modified to function as the refrigerant compressor, which was powered by a small-scale engine that in turn runs on fuel from a 2.0 l tank. A centrifugal clutch and reduction gear train system coupled the engine output to the refrigerant compressor and heat rejection fan. The 5.31 kg system (0.318×0.273×0.152 m³) provided a cooling rate of 300 W at a nominal ambient temperature of 43.3°C. It was operated in a controlled environment over a wide range of ambient temperatures (37.7–47.5°C), evaporator refrigerant temperatures (22.2–26.1°C), and engine speeds (10,500–13,300 rpm). A cooling rate of 300 W is sufficient for maintaining comfort at an activity level comparable to moderate exercise. The system uses ~0.316 kg/h of fuel to provide nominal cooling of 178 W for 5.7 h between refueling.

4.2. Miniaturized absorption cooling and heating systems

Absorption heat pumps provide cooling and heating using versatile thermal energy sources such as solar, natural gas combustion, waste heat, and others. They replace the compressor in the vapor compression system with a set of heat exchangers (e.g., desorber, absorber, solution heat exchanger.) While they have
the advantage of not requiring high grade electricity for operation and also being able to use natural and environmentally benign working fluids, the larger number of heat and mass exchangers and the added complexity compared to vapor compression systems has hindered the commercialization of such systems in small capacity residential and light commercial markets. However, Determan and Garimella [18] conceptualized, fabricated and successful experimental demonstrated a thermally activated microscale absorption heat pump for miniaturized or mobile applications. They used the several-fold enhancements in coupled heat and mass transfer possible in microscale passages to design compact components. More importantly, all heat and mass transfer components of an ammonia-water heat pump were integrated into one monolithic unit, to yield further reductions in size, parasitic pumping and heat losses/gains, minimize fluid inventory, and reduce material and assembly costs. Essentially, microscale passages, nominally \( D_h \approx 0.34 \) mm, were etched into stainless steel sheets 0.5 mm thick (figure 5). The etching pattern was designed to designate sets of microscale passages in different areas of the sheets for different functions, e.g., desorption, condensation, evaporation, absorption, and recuperative heat exchange. One sheet contained working fluid passages while an adjacent sheet contained the necessary coupling fluid flow passages. Thus, as the fluid streams flow through the passages in these sheets, the entire heat pumping action is completed using just a set of two 0.5 mm sheets. The required capacity is provided by assembling the necessary number of such sets of sheets, sandwiched between cover plates. The number of passages, and of sheets, as well as the size of these sheets, can be varied to meet a range of cooling requirements, thereby making the system modular. Cooling capacities of 100 W to tens of kW are possible through such minor changes in component geometry. These mass-producible miniaturized systems can be packaged as monolithic full-system packages or as discrete, distributed hydronically coupled components integrated into buildings. Their proof-of-concept unit delivered a nominal 300 W of cooling capacity in a packaged with overall dimensions of only 200×200×34 mm and a mass of 7 kg. Over a range of heat sink temperatures from 20 to 35°C, cooling duties of 136-300 W were achieved with 500-800 W of desorber heat input. Garimella et al. [19] subsequently scaled up the cooling capacity from the proof-of-concept system by a factor of 11.7 to demonstrate a 3.5 kW cooling standalone packaged unit with refined component designs (including counterflow desorption for better refrigerant purity) and the capability for semi-autonomous operation. The packaged unit also included a natural gas combustion module within the envelope to provide a complete gas-fired absorption unit. In addition, while the proof-of-concept unit used diffusion bonding to join the various sheets, in this later work, brazing techniques at such small dimensions were developed to enable low cost, high volume production of such systems. Subsequently, Staedter and Garimella [20] further demonstrated scalability by fabricating a packaged chiller with a cooling capacity of 7 kW using the same core technology.

One of the key advantages of absorption heat pumps is their versatility in heat sources. The microscale absorption technology described above was also used to develop packaged ammonia-water absorption chiller using diesel engine exhaust heat at forward operating bases in inhospitable ambient conditions. Fuel supply to such bases can be extremely expensive, and also lead to loss of life of personnel as they transport the fuel through dangerous and hostile territory. A 0.66 m × 0.61 m × 0.48 m \((L \times W \times H)\) chiller with autonomous control and the innovative configurations described above was designed [21] to provide 2.6 kW of cooling at an ambient temperature of 51.7 °C using the exhaust heat from the diesel engines that power these bases. The system delivered cooling duties of 2.5–1.8 kW at ambient temperatures as high as 40–52 °C with overall coefficients of performance (COPs) of 0.38–0.3
including accounting for power consumption for pumps, fans, and system controls.) The author and his research group have, since the fabrication of this latest system, also fabricated and demonstrated a 1.0 × 0.8 × 1.0 m system that delivers chilled water at 12°C with a cooling duty of 10.65 kW at an ambient temperature of 44°C, using a heat source at 165°C, yielding a COP as high as 0.63 even at these elevated ambient conditions.

4.3. Heat pump water heating systems

Domestic water heating systems typically use either electric resistance heating or natural gas combustion, with a maximum efficiency of ~95%. However, heat pumping could achieve significant improvements in system performance, and significantly decrease primary energy consumption for this essential function. Keinath and Garimella [22] demonstrated a compact ammonia–water absorption heat pump water heater (figure 6) using microchannel heat and mass exchangers. A direct natural gas-fired desorber, together with an integrated microchannel monolithic heat and mass exchanger that served as the hydronically coupled absorber, condenser and evaporator accomplish the heat pumping function. This prototype absorption heat pump water heater contains all auxiliary support systems to allow for connection to an off-the-shelf conventional residential water storage tank. The system delivered 2.58 kW of heat at a coefficient of performance (COP) of 1.6. Performance was experimentally demonstrated at the design condition of 32°C coupling water into the system and an ambient of 20°C, and over the range of expected water temperatures (10–60°C) and ambient conditions (10–32°C). Keinath and Garimella [23] compared different water heating technologies based on annual energy use and operating cost. Payback periods for the gas and electric heat pumps were computed with the electric and non-condensing gas storage units as a base case. Electric and gas heat pumps, at total initial costs of $2,400, yielded 3.6 and 3.1 year payback periods when compared with an electric storage unit, respectively. Daily total draw cases for a gas heat pump of 243, 303 and 379 L compared to a non-condensing gas storage unit as the base case showed payback periods of 4, 3.2 and 2.5 years, respectively. Thus, it can be seen that compact absorption heat pump water heaters offer significant energy use and operational cost savings compared to baseline water heating technologies with reasonable payback periods.

4.4. Modular Thermal Hub (MTH) for integrated residential energy systems

The feasibility of implementing absorption systems at the small capacity range demonstrated above opens up the possibility of bringing about fundamental changes in supplying the various energy-intensive utilities to residential buildings. Such a thermally driven heat pump may be viewed as a Modular Thermal Hub (MTH), whereby with simple switching of coupling fluid loops, the core system can be used to function either as a chiller during the summer or a heat pump during the winter. Furthermore, the MTH could also serve the water heating function, as demonstrated above. Thus, if electricity were generated from a primary energy source onsite, e.g., using a micro turbine or a fuel cell, waste heat from that energy conversion could drive the MTH, and the conventional standalone AC system, the furnace for space heating, and the dedicated water heater could all be replaced by just one MTH (figure 8.) This method of delivery of essential energy functions to the house would enable the maximum use of primary energy through “near lossless” energy conversion, with a much smaller inventory of subsystems. Of course, temporal matching of electrical, space-conditioning and water heating loads with the available waste heat would be required, for which a combination of electrical and thermal storage could be employed.
4.5. Large-scale thermally driven cooling systems

Microscale phase-change can also benefit a much wider range of applications, even at Megawatt scales. Such microscale phase-change enabled systems were considered for application in waste heat driven cooling systems for aircraft carriers at the Megawatt scale by Garimella et al. [24]. A novel cascaded absorption/vapor-compression cycle with a high temperature lift for a naval ship application was conceptualized and analyzed. A single-effect LiBr/H₂O absorption cycle and a subcritical CO₂ vapor-compression cycle were coupled together to provide low-temperature refrigerant (−40°C) for high heat flux electronics applications, medium-temperature refrigerant (5°C) for space conditioning and other low heat flux applications, and as an auxiliary benefit, provide medium-temperature heat rejection (−48°C) for water heating applications. For a representative case with a 200 MW waste heat input from the aircraft carrier, it was shown that ~90 MW cooling at 5°C, and an additional 50 MW of cooling at −40°C is achieved, for a total cooling load of ~140 MW for the CO₂ compressor. Parametric analyses on the cascade cycle were conducted to estimate the performance of the system over a range of operating conditions. Very high COPs were shown over a wide range of operating conditions. When compared to an equivalent vapor-compression system, this system was found to avoid up to 31% electricity demand. The critical component linking the absorption and compression cycles is the water evaporator of the LiBr/H₂O cycle, which serves as the heat sink for the CO₂ condenser of the bottoming cycle. A shell-and-tube type heat exchanger was designed for this critical component. The condensation of CO₂ was accomplished in rectangular microchannel tube bundles that withstood the high pressure of CO₂, while water evaporated as a falling film over these rectangular tube bundles (figure 8). Both processes being phase change of fluids with excellent thermophysical properties yielded high heat transfer coefficients, and the isothermal processes on both sides led to thermodynamically optimal heat transfer. It can be shown that with a nominal tube bundle of 2.50×2.43×1.90 m, 40 MW can be transferred in this component across the absorption-compression cascade, with a temperature difference as little as 3 K.

5. Sorption-based separation processes

Insights into coupled heat and mass transfer processes can also be exploited to develop novel sorption based separation processes and systems. Two examples of relevant industrial processes are discussed below.

5.1. Carbon Capture using sorbent-loaded hollow fibers

With rising concerns about the impact of greenhouse gases on the environment, post-combustion capture of CO₂ from power plants is a topic that has received considerable attention. The fundamental issue in such systems is that relatively low-concentration CO₂ must be removed from large volumes of flue gas.
Techniques such as aqueous monoethanolamine (MEA) absorption, gas separation membranes, pressure-/vacuum-swing adsorption, temperature-swing adsorption, and chilled ammonia stripping are some options under consideration. The primary challenge in such techniques is that they require additional primary energy for capture and compression. In addition, there are concerns of emissions of working fluids, corrosion, materials compatibility, etc. Determan et al. [25] describe the challenges associated with these processes. Several of these systems require high-grade electrical energy input. Recognizing that absorption or adsorption systems require low-grade thermal energy, they investigated the use of sorbent-loaded hollow fibers operating in a rapid temperature-swing adsorption cycle for the capture of CO\textsubscript{2} from power plants (figure 9.) This approach is also ideally suited for heat recovery strategies that reduce the operating costs of capture facilities. They developed a detailed coupled heat- and mass-transfer model of the adsorption process in sorbent-loaded fibers, and investigated the effects of varying fiber geometry on the heat- and mass-transfer kinetics. It was demonstrated that rapid diffusion and adsorption in the fiber and the direct cooling of the fibers enables efficient capture of CO\textsubscript{2}, as well as substantial recovery of the sensible heat capacity of the beds, thereby reducing energy costs of the thermal-swing adsorption process. The fiber-level model was further extended to investigate rapid temperature swing adsorption carbon capture modules [26, 27]. The thermal wave heat recovery technique was employed to reduce the external thermal input and operational energy costs of the capture facility. Detailed heat and mass transport modeling of the sorbent-loaded fibers was conducted to address the rapid radial adsorption kinetics. It was shown that the local heating and cooling of the sorbent enabled by the coupling fluid in the bore of the fibers significantly reduces the time required for the adsorbing and desorbing phases. They found that a sorbent-loaded hollow fibers based capture facility can achieve significantly higher sorbent productivities (\textasciitilde1400\%) than that of other thermally driven capture technologies with moderate energy consumption (\textasciitilde5.9 MJ kg\textsuperscript{-1}). The very fast cycle times (\textasciitilde100 s) achievable with this adsorption process enable the high productivity that can substantially reduce the footprint of a plant-scale CO\textsubscript{2} capture facility. In addition, they showed that increasing the desorption temperature improves the overall performance of the module. A high coupling fluid pressure drop was found to substantially improve productivity, whereas a low coupling fluid pressure drop favored low energy intensity.

5.2. Methane gas cleaning using adsorbent-coated microchannels

The increasing availability and use of natural gas as an energy source with a lower carbon footprint than coal has increased the demand for scalable natural gas purification systems with small footprints. Industrial purification systems based on absorption, membrane separation, or adsorption techniques requires large capital costs or suffer from scalability issues. Among adsorption-based separation techniques, pressure-swing adsorption (PSA) has typically been preferred over temperature-swing adsorption (TSA) due to ease of operation and reliability. The low thermal conductivity of the adsorbent bed poses challenges for desorption and regeneration of the adsorbent, hindering the implementation of TSA processes thus far. However, the high heat and mass transfer coefficients possible with microchannels offer the potential for using the TSA process for gas purification.

Adsorbent-coated microchannels for pressure swing adsorption (PSA) for carbon dioxide removal were investigated by Pahinkar et al. [28]. Large adsorbent particle size and the correspondingly large mass transfer resistances, coupled with diffusion-based processes make the cycle times for conventional adsorbent-bed-based PSA long, yielding low gas removal capacities per adsorbent mass. However, adsorption capacity in microchannels during depressurization was much higher than those for a conventional bed-based PSA process under the same operating pressure limits, feed compositions, and
stage times. An activated carbon monolith was found to yield the highest operating gas removal capacity, thereby reducing cycle time and increasing throughput. Pahinkar et al. [29] then investigated the fluid mechanics and coupled heat and mass transfer processes within a microchannel monolith with a polymer-adsorbent matrix coating the inner walls of the microchannels (figure 10) during TSA-based gas separation. It was found that the operational difficulties in heating commonly used adsorbent beds for TSA, due to very low adsorbent thermal conductivity and void space within the bed, can be minimized by introducing the adsorbent as a thin layer coating the microchannel walls. The adsorption, desorption, cooling, and purge stage performances are enhanced by the sharp species and thermal waves in the microchannels. For selected operating conditions and geometries, the process yields similar or higher product purities and recoveries and at least an order of magnitude greater purification capacity when compared with PSA-based cycles. The energy requirement for the process was also found comparable with bed-based processes.

Further enhancements in separation effectiveness were sought [30-32] by passing the feed gas through microchannels, followed by sequential flow of desorbing hot liquid, cooling liquid, and purge gas through the same microchannels. This configuration (figure 11) enables both the coupling fluid and the working fluid functions in the same channel, thereby reducing the pertinent thermal resistances as well as the size of the system, although the fluids have to flow through the microchannels in sequential fashion. The transient displacement of gas and liquid phases in these microchannels was investigated by Moore et al. [33]. A fluid dynamics model for bulk fluid displacement in 200 μm channels was developed and validated with the data from an air-water flow visualization study performed on glass microchannel test sections of 200 μm diameter using high speed videos. Interface velocities, void fractions and film thicknesses were determined using image analysis and used to validate the models. It was found that during the displacement of gas by liquid, a single liquid slug cleanly displaces the gas in the channel with little interaction at the liquid-gas interface. For the displacement of liquid by gas, dry-wall, thin-film, ring-film, intermittent, and rivulet flows were observed. Pahinkar and Garimella [31, 32] experimentally and computationally investigated gas separation in the adsorbent-coated microchannels. Experiments on porous-layer-open-tubular (PLOT) columns containing zeolite 5A using a ternary mixture of helium (He), nitrogen (N₂) and carbon dioxide (CO₂) showed sequential breakthrough of N₂ and CO₂ and gradual saturation of adsorption sites with trace water. The heat and mass transfer model results for a pressure drop range of 5–55 kPa and channel lengths from 1 to 4 m were found to be in reasonable agreement with the data. Adsorption experiments on custom-made adsorbent-coated
microchannels with known adsorbent mass and layer thickness yielded better agreement than the data on PLOT columns. With the optimum microchannel geometry and adsorbent and heat transfer fluid (HTF) materials, up to two orders of magnitude greater purified gas throughput is possible compared to bed-based designs. They developed a comprehensive performance map of the process to determine ranges of product purity, CH₄ recovery and process capacity, and energy requirements. System footprint was also shown to decrease by 82% compared with a TSA process using separate microchannels for the flow of working and coupling fluids. Staged purification was shown to increase product purity. Finally, the energy requirement for the process was found to be lower than that for MEA absorption systems.

6. Electric and hybrid vehicle battery cooling
In the fast emerging market of electric and hybrid vehicles, lithium-ion batteries offer high specific energy and energy density compared to other rechargeable cell chemistries. However, these batteries present challenges related to thermal management [34], especially due to the poor thermal conductivity of the materials involved. Conventional thermal management systems remove heat from the exterior surface of the battery, causing undesirable temperature increase and internal thermal gradients. Bandhauer and Garimella [35] proposed the use of internal cooling to reduce these negative effects, thereby improving safety and durability. Essentially, microchannels carrying an appropriate mass of refrigerant are integrated with the current collectors (figure 12). As the heat is released during charge and discharge processes, the refrigerant evaporates and rises to the top, where it enters an array of finned air cooled passages that condense the refrigerant, thus passively closing the cooling loop. By conducting phase-change pressure drop and heat transfer experiments on such a cooling system over a range of net heat inputs and saturation temperatures, they characterized the circulation flow rate and heat removal capabilities. These were used by Bandhauer and Garimella [36] to determine the performance improvement in large lithium-ion battery packs intended for electric and hybrid electric vehicles based on their measurements of reversible and irreversible electrochemical heat generation rates on a C/LiFePO₄ lithium-ion battery designed for high-rate applications. A fully coupled 2-D electrochemical-thermal model that utilizes temperature dependent experimental data was developed and used to predict air and liquid surface cooling using a dynamic power profile for two different cell designs (8 Ah and 20Ah). While liquid cooling was found to reduce peak temperature significantly, it had the adverse effect of imposing a temperature difference across the cell, which causes current and depth of discharge to vary locally, adversely impacting cell life. Neither air nor liquid cooling allowed the pack size to be reduced beyond factors of 2 or 4, respectively. In 3-D simulations, it was found that large temperature differences with this cooling method lead to significant non-uniform cycling, in turn causing premature aging. The innovative internal cooling system with passive microchannel liquid-vapor phase change, however, substantially reduced the thermal resistance from the heat source to the cooling fluid, enabling the highest charge and discharge energy extraction density despite the cell-level volume increase [37]. Such a system also allows control of the phase change temperature, which can be optimized to balance capacity fade and energy extraction at elevated temperatures, yielding systems much smaller than the most compact external cooling system.

7. Microchannel heat exchangers for nuclear reactors
One of the primary emphases for nuclear power plants is safety, and small modular reactors provide enhanced safety due, in part, to the smaller pressure vessels and reactor containment structures. However, the power densities in such reactors have been necessarily low, compared to the conventional
larger light water reactors. The Integral Inherently Safe Light Water Reactor (I2S-LWR) is a large (2850 MWth) pressurized water reactor that addresses this drawback by including primary-to-secondary coolant heat exchangers in the downcomer of the reactor pressure vessel. This integral configuration eliminates the possibility of large line-break accidents, reduces primary coolant inventory, and does not require large external steam generators. This is only possible by using a microchannel heat exchanger (MCHX) configuration (figure 13), which can be accommodated in the limited available volume while delivering high heat duties. Kromer et al. [38] designed, modeled, and optimized the liquid-liquid MCHX for this application, and validated its performance experimentally on a test section representative of the I2S-LWR MCHX design.

8. Passive low-grade heat driven heat pumps
The absorption heat pump systems described above, while being thermally driven, still need an electrically driven pump to pump solution from the low to the high pressure side of the cycle. In remote locations and in areas in the developing world where electricity infrastructure is not well established, this could present a challenge that decreases the likelihood of implementation. Also, in such areas, it is typically difficult to repair or replace a faulty pump. The diffusion absorption refrigeration (DAR) cycle offers a potentially fully thermally activated cooling technology, in which the solution is recirculated around the cycle by a thermally driven bubble pump across varying partial pressures in different parts of the system. The passive operation makes it a useful system in remote areas for purposes such as storage vaccines, medicines and other critical survival items. Rattner and Garimella [39, 40] developed a DAR system using low grade heat applied to a distributed heated bubble-pump generator (BPG), and an enhanced absorber. The system achieved cooling at temperature ranges suitable for refrigeration ($T_{\text{evap}} = 6 \rightarrow 3^\circ C, \text{COP} \sim 0.06$) and air-conditioning ($12 \rightarrow 8^\circ C, \text{COP} \sim 0.14$) at design conditions ($T_{\text{amb}} = 24 ^\circ C$) with low source temperatures (110–130 °C) and passive air cooling.

9. Conclusions and outlook
A variety of thermal systems in diverse application areas and across a wide range of capacities enabled by heat and mass transfer innovations at the microscale were discussed above. A general framework such as the one developed by Little and Garimella [41] can be used to identify additional similar opportunities for thermal energy recovery and upgrade. They also suggested the typical thermodynamic cycles (Rankine, Maloney-Robertson, Ejector, Sorption, Vapor-Compression, etc) that were most appropriate for the temperature ranges under consideration, with end uses ranging from power production to cooling and heating, heat transformers to upgrade low-grade heat to higher temperatures, and others. It was shown that simple screening of these cycles can be conducted for such assessments, not only based on cycle COP, but also on overall system footprint using overall heat transfer conductances for heat exchangers. Four case studies for waste heat recovery for data centers, vehicles, and process plants were conducted, illustrating the utility and limitations of such solutions.

The case of waste heat recovery in data centers, in particular, holds significant potential for energy savings, as demonstrated by Little and Garimella [42], who conceptualized a novel approach of integrated power, cooling, and waste heat recovery and upgrade systems that considerably lower the energy footprint of data centers. On-site power generation equipment supplied primary electricity needs of the data center. The microturbine-derived waste heat was recovered to run an absorption chiller that supplied the entire cooling load of the data center, essentially providing the requisite cooling without
any additional expenditure of primary energy. In addition, the remaining waste heat rejected by the data center was boosted to a higher temperature with a heat transformer, with the upgraded thermal stream serving as an additional output of the data center with negligible additional electrical power input. Such upgraded heat can be used for district heating applications in neighboring residential or commercial buildings, or as process heat for commercial end uses such as laundries, hospitals, and restaurants, depending on the location of the data center. With such a system, it was shown that the primary energy usage of the data center as a whole can be reduced by up to 23% while still addressing the high-flux cooling loads, in addition to providing a new income stream through the sales of upgraded thermal energy.

The increased implementation of such thermal systems in a variety of applications will lead to decreased primary source inputs and sustainable energy utilization. In fact, Rattner and Garimella [43] noted that two-thirds of input energy for electricity generation in the USA is lost as heat during conversion processes. On the end use side, they found that 12.5% of primary fuel and 20.3% of electricity are employed for space heating, water heating, and refrigeration, but low-grade heat could suffice to drive these functions. Thus, they quantified the quantity and temperature bands in which waste heat was available in each county of each state of the USA, and matched these heat sources with appropriate end uses. They found that the available waste heat can satisfy all US space and water heating needs. Furthermore, high temperature exhaust from power plants can satisfy 27% of residential air conditioning with thermally activated refrigeration, or all industrial refrigeration and process heating from 100 to 150°C. Also, they found that engine coolant and exhaust could satisfy all air conditioning and 68% of electrical demands in vehicles. Overall, they found that primary energy requirements of the US could be reduced by 12% through the implementation of such thermal systems, with appropriate temporal and spatial matching of the heat sources and thermal needs, in part facilitated by thermal storage.

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