HIGH EFFICIENCY TRIGENERATION SYSTEMS FOR BUILDINGS

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Abstract

This review focuses on recent polygeneration research in three areas: prime movers, cooling devices, and novel system integration options. The importance for polygeneration waste heat temperatures and amounts is addressed. Waste heat for eight prime movers used in micro CHP is characterized using a Q-T diagram. With regard to cooling technologies, the increasing demand for tight control of humidity and ventilation represents challenges as well as distinct opportunities for integrated energy systems. Polygeneration can provide efficient ways to accomplish better comfort, such as by separating sensible and latent cooling loads. The increasing legislation dealing with GWP of refrigerants for vapor compression systems also provides a driving force for thermally-activated cooling. Advances are being made both for vapor compression and thermally-activated cooling cycles, with much research in the areas of transcritical cycles**,** subcooling, adsorption cooling, desiccant dehumidification, and integrated systems. Many new adsorbent working pairs and desiccant dehumidification materials have regeneration temperatures low enough to utilize heat from reciprocating engine coolant or even a vapor compression condenser. This enables smaller installations (such as residences) to benefit from combined cooling, heating and power; and opens new possibilities for separating sensible and latent cooling to extend the operating range of sorption-based heat pumps and improve solar cooling efficiency.

Keywords

Pinch analysis, prime movers, trigeneration, polygeneration, waste heat, refrigerants, SSLC, hybrid cooling, desiccant dehumidification

Introduction

In 2006, buildings consumed about 40% [1] of all primary energy produced and used in the US (mostly fossil fuels, nuclear fuel, and hydroelectric power). Of this amount used in buildings, about 35% was for space heating, space cooling and ventilation, with another 10% for domestic hot water (DHW) heating. Thus, nearly 20% of all primary energy consumed in the US was to meet thermal loads relatively close to ambient temperatures. This represents a huge opportunity for savings, since most of the space heating and water heating was provided by directly burning fuel at over 1,000°C. By burning that fuel in distributed prime movers instead of in furnaces and boilers, net reductions in fuel consumption can be realized. Furthermore, once distributed prime movers are in place, reductions in fuel consumption for space cooling can also be realized by polygeneration systems.

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Prime Movers

In the context of trigeneration, it is important to consider the type and quality of waste heat available from each type of prime mover. An analysis of the cumulative heat transfer vs. temperature (Q-T analysis), a tool of pinch analysis [2], is indispensible for making these comparisons of waste heat available from various prime movers. To this end, the waste heat from existing and potential micro-scale prime movers are compared in this work.

From a system-perspective, the fuel energy that enters a prime mover exits in four ways: as electricity, exhaust/flue gas heat, coolant heat, and "other" losses (including convection and radiation from the surfaces of the device, cyclic heating of components, etc.) In the interest of a self-contained analysis, a reasonable estimate of the initial exhaust temperature can be obtained from an energy balance around the prime mover. A simple expression of this balance, shown in Equation 1, is possible by assuming constant specific heat of exhaust gases.

$$T_{exhaust} \cong T_{ambient} + \left(\frac{1}{1+AFR}\right)\left(HHV\right)\left(f_{exhaust}\right)\left(1-\eta_{elec}\right)\left(\frac{1}{c_{P,exhaust}}\right) \qquad 1)$$

Evaluation of this equation requires three empirical system-level values: the air-fuel ratio used by the device (AFR, mass basis), the electrical conversion efficiency (η_{elec}), and the fraction of waste heat rejected in the exhaust ($f_{exhaust}$), where waste heat is defined as fuel energy not converted to electricity. For consideration of the heat available in the coolant as well, knowledge of the fraction of waste heat rejected in the coolant (f_{clt}) and the coolant temperatures ($T_{clt,hi}$ and $T_{clt,lo}$) is also required. To create Figures 1 and 2, a $T_{ambient}$ of 25°C and a constant $c_{P,exhaust}$ of 1.2 kJ/kg-K were assumed, along with the values in Table 1 for each prime mover. Most devices are assumed to run on natural gas, which has a stoichiometric AFR of 17.2.

Table 1: Parameters used in evaluating Equation 1 and Figure 2 for micro-scale devices

	AFR [kg_{air}/ kg_{fuel}]	φ [-]	HHV [kJ/kg]	η_{elec} [kW_{elec}/ kW_{fuel}]	$f_{exhaust}$ [kW_{exh}/ kW_{wh}]	f_{clt} [kW_{clt}/ kW_{wh}]	$T_{clt,hi}/T_{clt,lo}$ [°C]
SOFC	27	0.64	54,000	0.35	0.80	0.00	(no coolant)
SI-ICE	17.2	1.00	54,000	0.25	0.35	0.35	75 / 65
CI-ICE	30	0.57	54,000	0.28	0.35	0.35	85 / 75
MT	115	0.15	54,000	0.20	0.75	0.00	(no coolant)
SE/ORC	30	0.57	54,000	0.15	0.15	0.65	45 / 35
HT-PEMFC	(N/A)*	(N/A)*	141,900	0.30	0.00*	0.70	65 / 55
LT-PEMFC	(N/A)*	(N/A)*	141,900	0.30	0.00*	0.70	125 / 115

*it is assumed that PEMFC exhaust exits at operating temperature and is cooled by intake air

One use of the Q-T diagram is illustrated in Figures 1(a) and 1(b), which show the potential for using waste heat to either heat domestic hot water (DHW) or drive the generator of an absorption chiller (but not both simultaneously). Figure 1(a) shows the waste heat available for either of these loads from a spark ignition internal combustion engine (SI-ICE), and Figure 1(b) shows the waste heat available from a microturbine (MT). It can be readily seen that both of these prime movers can provide similar amounts of their fuel energy to DHW, but the MT is capable of providing much more heat for a higher temperature purpose such as driving an absorption chiller.

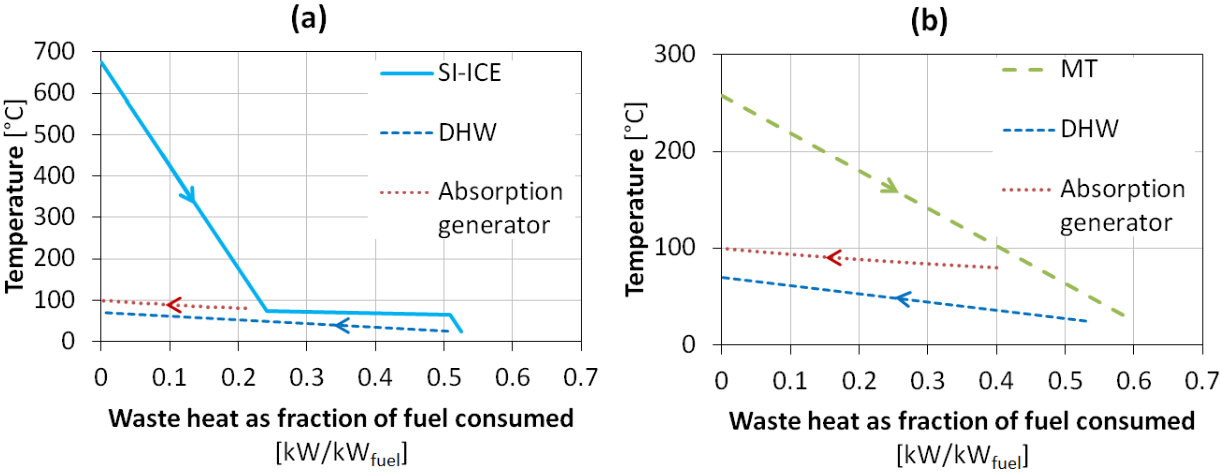

Figure 1: Q-T plots of waste heat available from (a) SI-ICE and (b) MT for *either* DHW *or* absorption chilling

Figure 1 shows Q-T diagrams with both available heat and heat loads, while Figure 2 shows the available waste heat for several prime movers of interest to polygeneration.

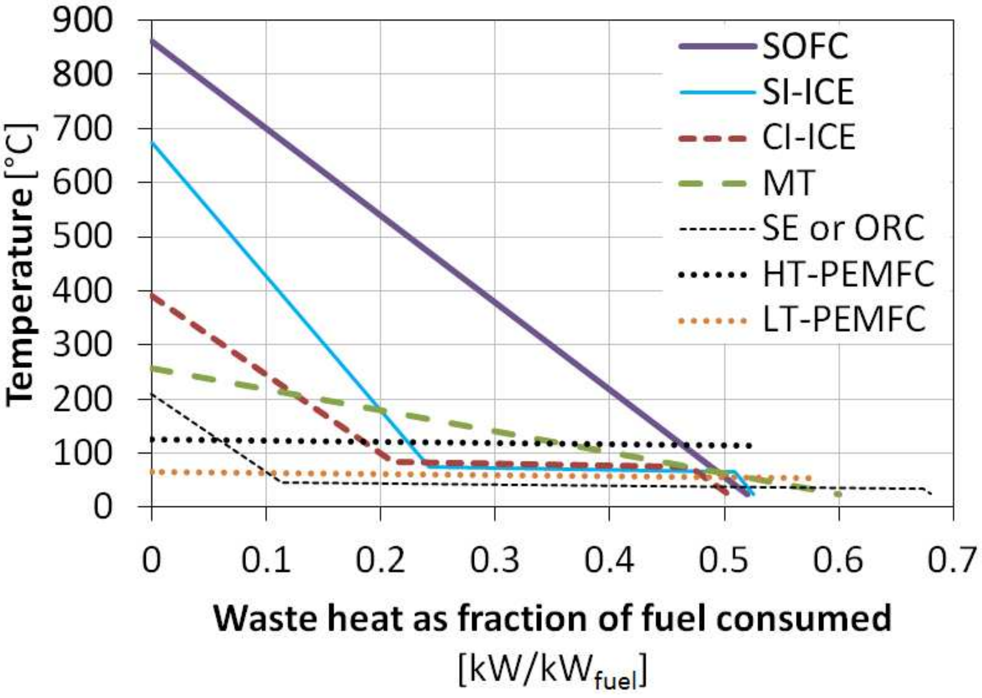

Figure 2: Q-T plot of waste heat available from various prime movers

Figure 2 has many uses for qualitative comparisons among prime movers and order-of-magnitude analyses. Detailed quantitative analysis would require using temperature-dependent specific heats, more precise manufacturer data for a particular prime mover, and consideration of part load performance. By visual inspection of Figure 2, one can determine the heat available at a certain temperature. When choosing a prime mover to drive a heat-activated device, the required regeneration temperature has a dramatic effect on the best choice of prime mover. For example, for making steam at 100°C, about 0.5 kW (per kW of fuel consumed) are available from a solid oxide fuel cell (SOFC), 0.4 kW from a MT, 0.2 kW from a compression ignition internal combustion engine (CI-ICE), 0.5 from a high temperature proton exchange membrane fuel cell (HT-PEMFC), and none from a low temperature PEMFC (LT-PEMFC). For heating domestic hot water (DHW) (from ~40°C to ~60°C), all of the prime movers shown have similar amounts of heat available (~0.48 to ~0.6 kW).

In addition, by dividing the x-axis of Figure 2 by the electrical efficiency of the prime mover, a graph of the heat as a fraction of electricity is obtained. Coupled with an analysis of the anticipated heat loads (as in Figure 1), this gives a more realistic estimate of the ratio of heat to electricity production than the single value of heat-to-electricity ratio provided by manufacturers.

If a typical heat-activated device is taken to have a nominal 100°C regeneration temperature, then clearly SOFC, HT-PEMFC and MT prime movers are the most generally suitable for polygeneration, providing a large fraction of their fuel energy as waste heat above that temperature. However, currently MT are not yet available below 25 kW, cost effective SOFCs and HT-PEMFCs are not yet widely available, and SI and CI reciprocating engines are the lowest cost and most common prime movers at residential and small commercial scales [3]. In order to be able to use more than 20-25% of the fuel energy from reciprocating engines for heat-activated cooling, it is necessary to reduce the regeneration temperature of heat-activated cooling devices. For a nominal regeneration temperature of 60°C, about 50% of the fuel energy consumed by a reciprocating engine could be used for regeneration. The opportunity also exists to raise the coolant temperatures of reciprocating engines without significantly affecting performance.

From Figure 2, the flue gases from SE and ORC prime movers are seen to not be ideal for driving a heat-activated device, since only a small portion of the fuel energy ends up in the flue gas of those devices. Development of a heat-activated device with low enough regeneration temperature to run off the coolant would enable these prime movers to be more useful for polygeneration. However, raising the coolant temperature of external combustion engines – Stirling engine (SE) and organic Rankine cycle (ORC) – directly adversely affects performance by raising the working fluid temperature on the cold side of the cycle and therefore decreasing the temperature difference that drives the cycle. Raising the coolant temperature thus decreases the mechanical efficiency while increasing the potential efficiency of the heat-activated device, presenting an optimization problem (similar to that encountered in solar thermal cooling).

Microturbines have become much more readily available during the past decade. Despite generally lower electrical efficiency than reciprocating engines, MTs have a number of advantages, especially for polygeneration systems. Perhaps most importantly, they discharge waste heat in a single high temperature exhaust stream (as opposed to reciprocating engines, which discharge some heat in the high temperature exhaust and some through the medium temperature coolant).

Recent advances in low-cost but high-efficiency automotive-derived radial turbomachinery may allow MTs to be developed below 5 kW [5]. However, MTs are not currently available below ~25 kW, and for applications such as residential and small commercial, reciprocating internal combustion engines are the most common. Thus, to achieve high efficiency trigeneration at this small scale requires heat-activated equipment with regeneration temperature low enough to utilize coolant waste heat. This is an area in which significant advances are being made, for example with zeolite Z01 [6].

Perhaps the ideal fuel-fired prime mover for trigeneration systems, in terms of performance potential, is the SOFC, which can also run on hydrocarbon fuels. SOFCs combine the advantages of reciprocating engines and MTs by having high electrical efficiency (in fact higher than ICEs at micro scale) *and* discharging their waste heat in a single high-temperature exhaust stream (in fact higher than MTs). The exhaust temperature is so high, however, that direct use by heat-activated equipment may require exotic materials. The MT and SOFC both have significant opportunities for small-scale combined cycle power generation with a Stirling engine, ORC, or Kalina bottoming cycle. Due to the higher exhaust temperature, the SOFC may also be used in a combined cycle with a MT, and the MT exhaust would still be hot enough to additionally drive an absorption chiller [7]. As pointed out by [7], the main barrier to such a system is the currently high cost of SOFCs.

The exhaust gases from PEMFCs do not contain appreciable energy, although these devices do have the advantage of rejecting most of their waste heat in a single stream. In the case of LT-PEMFCs, the coolant temperature is too low for most uses besides DHW, while HT-PEMFCs operate at temperatures above the boiling point of water [4]. It is also important to note that an on-site fuel reformer for a PEMFC may provide some high-temperature heat.

Dramatic cost reductions with economies of scale can be expected for fuel cell, ORC and SE prime movers, although less so with reciprocating engines [8]. This is because reciprocating engine-based backup generators are already produced in very large numbers. The ~10-fold price differential between backup generators and micro combined heat and power (CHP) engines is due to the additional CHP requirement for emissions control, noise control, sophisticated power electronics, very long life engines, and heat recovery systems.

Heat-Activated Cooling Devices

The most significant barrier to more widespread adoption of heat-activated cooling is the higher first cost compared to vapor compression technologies. With this in mind, it is important to consider trends in vapor compression technology.

The past couple decades saw the phase-out of refrigerants with high ozone depletion potential (ODP), and now legislative restrictions are being imposed based on global warming potential (GWP). The establishment of a maximum allowable GWP is likely to effectively ban all of the most commonly used refrigerants. Low GWP refrigerants generally have lower performance and also require significant development by VCS manufacturers. This will reduce the traditional gap between VCS and heat-activated cooling systems, in terms of both performance and cost.

One environmentally benign working fluid for VCS is CO_2. CO_2 will conceivably never be banned, because it has ODP of zero, GWP of 1, and is non-toxic and non-flammable. However, the transcritical CO_2 cycle has inherently low performance, and much recent research has gone into improving it [9]. However, at the same time, manufacturers are developing more traditional organic refrigerants and refrigerant mixtures such as (R1234yf) which will be able to serve as drop-in replacements for the refrigerants widely used today (such as R134a). In order to maximize performance and compatibility with legacy equipment, these new organic fluids are being custom engineered to have slightly below the anticipated limits on GWP and flammability, and could conceivably be banned themselves in another decade or two as unpredictable future legislative restrictions are imposed. The political, engineering, and long-term equipment maintenance complexity of the VCS working fluids today provides a good selling point for polygeneration systems, which generally use environmentally benign refrigerants such as water and ammonia (or lack refrigerants altogether in the case of desiccant dehumidification systems).

Other trends in building air conditioning are increasing demand for low energy consumption and high thermal comfort, including indoor humidity levels and ventilation rates. Traditionally, humidity is maintained by overcooling to the desired dewpoint and reheating, but this imposes an inherent performance penalty. Thus, there are opportunities for systems that provide excellent thermal comfort (with consideration of radiant heat transfer and humidity) with high performance. This presents opportunities of polygeneration with its high energy performance, but also challenges, since system complexity is already a barrier for polygeneration systems.

Another aspect of thermal comfort is proper ventilation. As buildings are built “tighter” (with less infiltration) to reduce heat loads, mechanical ventilation is becoming much more common. Traditionally, infiltration rates were so high that mechanical ventilation was not required. In that traditional context, adding a desiccant dehumidification system meant extra ductwork and fans. However, since mechanical ventilation may require some extra ductwork and fans anyway, the construction of tighter buildings lowers barriers to implementing desiccant dehumidification. The centralized availability of building exhaust air in the mechanical ventilation unit (which traditionally was lost throughout the building envelope) also allows for advanced configurations involving sensible heat exchange between supply and return air streams, evaporative cooling, and more [10], which are well-suited to desiccant wheels.

Desiccant materials for dehumidification and adsorption heat pumping are emerging which have very low regeneration temperatures. An example is the Z01 zeolite [6], with a nominal regeneration temperature of about 60°C.

System Integration

Separate sensible and latent cooling (SSLC) (or hybrid cooling)

Carnot COP (COP_{Ct}) can be defined based on external heat source/sink temperatures (e.g. ambient dry bulb and indoor dry bulb), or based on internal cycle temperatures (i.e. refrigerant-side entropic-average condenser and evaporator temperatures). If COP_{Ct} is defined based on internal cycle temperatures, today's VCS air conditioning systems deliver a significant fraction of the potential Carnot performance (f_{Ct}). For example, at an ambient temperature of 35°C, an air conditioner may have a condensation temperature of 40°C, and it may be cooling air to 9°C in the evaporator with refrigerant at 4°C to dehumidify and cool the space. Taking those refrigerant temperatures as estimates of the entropic-averages, a Carnot cycle operating between 40°C and 4°C has a COP of 7.7, while an actual device without reheat may deliver a COP of about 2.9 (f_{Ct} of 0.38). Adding reheat (as is typical) will lower the performance.

However, if the air conditioner were not required to provide dehumidification, supplying air at 20°C and allowing 5 K approach temperatures in the condenser and evaporator, the Carnot COP between internal temperatures (40°C and 15°C) increases from 7.7 to 11.5. The lower pressure ratio also allows a better compressor isentropic efficiency and reduces throttling losses, improving the f_{Ct} of an actual VCS and allowing a 70% reduction in compressor power with a COP of 5.0 (f_{Ct} of 0.43). In addition, no reheat is necessary with the supply air temperature already at a comfortable 20°C, further widening the performance gap.

Thus it is clear that cooling the air below the desired indoor dewpoint (to ~9°C) instead of below the desired dry bulb temperature (to ~20°C) represents a significant sacrifice in performance potential. However, in order to take advantage of this potential by not cooling the air to the desired dewpoint, the latent cooling must be handled separately.

While there are numerous possibilities for how to implement separate sensible and latent cooling (SSLC or hybrid cooling), many SSLC configurations represent opportunities for polygeneration, since dehumidification can readily be provided by waste heat-driven devices. SSLC can also be applicable to polygeneration without desiccant dehumidification, since a small VCS can be used to handle the latent load in order to allow a heat-activated device to operate at a higher evaporator temperature. This concept can be used to extend the operating range of a heat-activated cooling device such as a water/LiBr absorption chiller [11].

In addition, low regeneration temperature desiccants allow use of waste heat sources that have not been previously considered, such as condenser heat from a vapor compression system (VCS) [12]. Using condenser heat from a VCS to drive a desiccant or adsorption process for SSLC or subcooling is an interesting example of a polygeneration system with a VCS as prime mover.

A subcritical VCS cycle rejects heat through the condenser, which can be divided into three internal regions: refrigerant de-superheating, condensing, and subcooling. The refrigerant condensing process takes place at a constant temperature generally 5-10°C above the temperature of the heat sink. The de-superheating region occurs over a range of refrigerant temperature, and the amount of heat it contains (and over what temperature range) depends primarily on refrigerant properties, compressor isentropic efficiency, and operating temperatures. Generally, however, the de-superheating region may contain 10-35% of the heat rejected through the condenser and may start at 20-45°C above the condensing temperature. As shown in Figure 3, a divided condenser can allow the superheat and some of the condensing heat to be combined in a high air-side temperature stream useful for desiccant regeneration. Figure 3 shows two alternative air streams to use as the regeneration air streams. For a constant pinch temperature, using building exhaust air allows more of the condenser heat to go towards regeneration – if outdoor air is used, either the regeneration air outlet temperature must be lower (as shown) or the amount of condenser heat captured by the regeneration air stream must be lower (not shown). The rest of the condensing heat and subcooling is rejected directly to ambient in the second portion of the split condenser to maintain conventional high-side pressure (for transcritical cycles, the concept of a divided gas cooler is similar).

If the resulting desiccant dehumidification is sufficient to handle the latent load of the building, then the VCS evaporator temperature can be substantially increased, reducing compressor work and improving overall system performance [13]. However, as pointed out by [14], the resulting higher evaporator temperature causes less superheat to be available in the condenser (not reflected in Figure 3), and higher air flow rates must be used, resulting in more fan power. Still, COP improvements of 36% for R410a with a divided condenser and 61% for CO_2 with a divided gas cooler were found in experimental results [14].

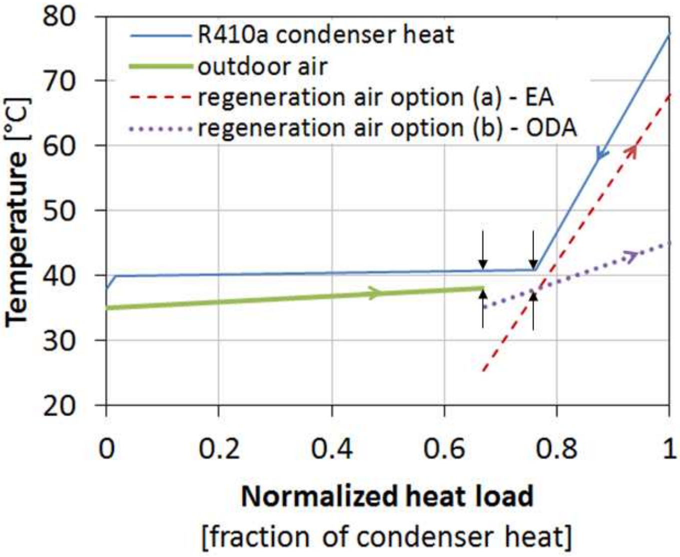

Figure 3: Q-T plot of waste heat available from split VCS condenser, and two options for recovering it. Black arrows indicate pinch temperatures in each heat exchanger

Besides providing an opportunity for heat-activated dehumidification, SSLC may also help enable air-cooled heat-activated cooling systems by reducing the required temperature lift. For example, during periods when the ambient temperature is too high to operate a conventional water-LiBr absorption system, a small VCS (operating at low evaporator temperature, but sized only for latent load) could provide the required latent cooling to the space, allowing the absorption evaporator temperature to increase to prevent solution crystallization [11].

The use of SSLC can also be applied to solar cooling. As detailed in [15], a concentrated photovoltaic/thermal (CPVT), or hybrid solar collector, can be used to drive a SSLC, or hybrid cooling system. A concentrated solar collector focuses radiation on a photovoltaic (PV) module while liquid coolant actively cools the PV module, effectively creating a solar combined heat and power solar prime mover. The thermal output drives a desiccant dehumidification wheel, which allows the electrical output to drive a VCS with high evaporator temperature and therefore high COP. Based on simulation results, the hybrid solar, hybrid cooling system is found to provide better thermal comfort and more than twice the solar COP than a solar-driven absorption chiller.

Another possibility for handling latent loads separately may be made possible by membrane separation technologies. Recent research is investigating membranes for use in air dehumidification [16]. There is also the possibility of coupling membrane dehumidification with evaporative cooling [17].

Simultaneous heating and cooling

A simultaneous heating and cooling system integration example is the Energy Concepts Co. Thermosorber^{TM}. This ammonia/water absorption machine with generator-absorber heat exchange (GAX) is designed to simultaneously provide chilled water for air conditioning (or industrial uses) and hot water at up to 71°C. A recently commissioned steam-fired project in a pulp mill simultaneously provides 528 kW of chilled water at 2°C with a cooling COP_{th} of about 0.5, and hot water at 55°C with a heating COP_{th} of about 1.5 [18].

In theory, all heat pumping devices have the capability to simultaneously provide heating and cooling. However, the device efficiency will usually suffer when the heat exchanger normally in communication with ambient temperature is instead put in communication with a less ideal temperature source/sink. The Thermosorber^{TM} leverages high-glide absorber designs developed for GAX cycles to achieve an absorber temperature glide of over 40°C [19]. Then, by exploiting the large temperature glide of the absorber solution, matching the heat capacity flow rate of the water to it, and using the water to cool the condenser and absorber in series, it was possible to achieve a fairly hot water supply temperature while maintaining a cooling COP_{th} and heating COP_{th} typical of single-utility (heating- or cooling-only) ammonia/water GAX machines.

Integrated or packaged polygeneration systems

In the interest of making polygeneration systems more compact and improving system performance, researchers at Shanghai Jiao Tong University have developed a “thermal management controller” [20]. This design used heat pipes to optimally regulate temperatures and distribute heat among heating, cooling, and heat rejection circuits for ICE-based polygeneration. Such systems are an important step towards packaged polygeneration systems.

Refrigerant subcooling

Another possibility for polygeneration is utilizing an absorption chiller to subcool refrigerant in a VCS refrigeration system [21]. A prime mover can supply electricity to run the VCS, with waste heat powering a chiller that subcools the refrigerant out of the VCS condenser. Refrigerant properties impose a fundamental limit to how much subcooling can be provided at given operating conditions, but given the inherently low COP of VCS refrigeration applications, each unit of subcooling provided by the absorption chiller can offset significant electricity consumption.

Conclusions

A Q-T analysis of prime mover waste heat reveals the promise of MTs, SOFCs and HT-PEMFCs for polygeneration, and highlights the incentive to develop lower regeneration temperature heat-activated devices for improved polygeneration system efficiency with other prime movers. Some trends in vapor compression cooling, such as regulations on refrigerant GWP, tighter buildings and greater demand for high thermal comfort, represent opportunities and challenges for polygeneration. Separating sensible and latent loads is a big opportunity for polygeneration in at least two ways: (1) waste-heat driven desiccant dehumidification can be used to enhance the COP of VCSs, and (2) VCSs can be used for dehumidification duty to raise the evaporating temperature (and therefore operating range and performance) of heat-activated cooling devices. Simultaneous heating and cooling is another trend which can be exploited by polygeneration systems, especially with cycles having a large temperature glide, such as GAX absorption chillers. Finally, refrigerant subcooling is an opportunity for polygeneration in large commercial and industrial facilities with large refrigeration loads.

Nomenclature

AFR:	air-fuel ratio $[kg_{air}/kg_{fuel}]$
CI-ICE:	compression ignition internal combustion engine
COP:	coefficient of performance
EA:	exhaust air
f_{Ct}:	fraction of Carnot performance (e.g. COP_{actual}/COP_{Ct})
HCFR:	heat capacity flow rate [kW/K]
$HCFR_{pp}$:	heat capacity flow rate per unit power produced $[kW_{exh}/K^{-1}kW_{elec}{}^{-1}]$ or $[K^{-1}]$
HRSG:	heat recovery steam generator
HT-PEMFC:	high temperature proton exchange membrane fuel cell
ICE:	(reciprocating) internal combustion engine
LT-PEMFC:	low temperature proton exchange membrane fuel cell
MT:	microturbine
ODA:	outdoor air
ORC:	organic Rankine cycle
PEMFC:	proton exchange membrane fuel cell
SE:	Stirling engine
SI-ICE:	spark ignition internal combustion engine
SOFC:	solid oxide fuel cell
T:	temperature [°C] or [K]
VCS:	vapor compression system
φ:	Equivalence ratio $[AFR_{stoich}/AFR_{actual}]$

Subscripts:

clt	coolant

clt,hi	coolant high temperature (e.g. engine coolant supply)
clt,lo	coolant low temperature (e.g. engine coolant return)
Ct	Carnot
elec:	electrical
exh:	exhaust
wh:	waste heat

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