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Waste heat and electrically driven hybrid cooling systems for a high ambient temperature, off-grid application

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ABSTRACT

Forward army bases at high ambient temperature off-grid locations require both power and cooling capacity to function properly. Due to the inefficient existing configuration to meet these demands, there are safety and stability issues as each liter of fuel consumed for electrical power must first pass through a complex, hostile network. In place of the conventional configuration composed of a Genset (electrical generator set) and an electrically powered VCS (vapor compression system), utilizing a smaller Genset with a waste heat driven $LiBr/H_2O$ (lithium bromide/water) AS (absorption system) provides a more efficient CHP (combined heat and power) configuration. With design criteria of ambient temperatures up to 51.7 °C, providing up to 3 kW of non-cooling electricity, and 5.3 kW of cooling, these two configurations were simulated in both steady-state and transient conditions. Additionally, the proposed AS's avoid crystallization and have air-cooled heat exchangers unlike conventional AS's which crystallize at high ambient temperatures and have bulky cooling towers. In the transient simulation for the hottest week, results showed a fuel savings of 34–37% with the CHP configuration.

1. Introduction

The advantages of CHP (combined heat and power) configurations over conventional ones are well known: reducing energy needs through efficient use of the resource [1–11], significant cost savings after payback [1,2,4,7,9,12], flexible application to micro, small, and large scale opportunities [1,4,5,8,13], reducing emissions and greenhouse gases [2,4,6,7,9,10], integration with renewable resources [2,5,13], and off-grid reliability and accessibility to energy, heating, and/or cooling [5,13]. Many of these advantages can become even more pronounced in specialized applications with unique circumstances. For military applications in the Middle East where temperatures rise to over 45 °C, air conditioning becomes a necessity. This presents a unique situation in which forward army bases are off-grid but require consistent cooling. The current solution uses ECU (environmental control units) consisting of VCS (vapor compression systems) in combination with diesel fueled generator sets (Genset) which require a steady supply of fuel in order for the bases to operate consistently. However, the inefficiency of this configuration results in a high fuel requirement which compromises both safety and stability when this fuel has to travel through a lengthy, complex, hostile network. In 2011, a report was published which indicated military costs of air conditioning as high as $20.2 billion per year when considering the aspects of infrastructure, transport, and safety as associated with the fuel requirement [14]. Even if this figure is exaggerated, it nonetheless highlights the need for energy conservation measures. Therefore, a CHP configuration utilizing a thermally activated cooling technology, thus recovering a significant amount of waste heat, provides the opportunity foremost for fuel savings which then compounds into reduced cost and increased safety and reliability.

$LiBr/H_2O$ (lithium bromide/water) absorption technology was chosen for this application because it tends to have the best COP (coefficient of performance) when compared with other thermally-activated cooling technologies [15–17]. It also does not have the toxicity issues of ammonia/water ASs (absorption systems). However, at higher ambient temperatures they suffer from crystallization, limiting their applications to less portable water-cooled heat exchangers with cooling towers. The occurrence of crystallization results in a degradation of performance and can even damage the system over time. This occurs in the concentrated liquid solution stream, after the expansion valve and before the absorber heat

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exchanger. Thus, there are great implications with developing anti-crystallization strategies for air-cooled absorber heat exchangers, as it would enable a release of portable AS's. Developing an effective anti-crystallization strategy was therefore one of the main objectives of this work. Much research has previously been carried out to find an ideal strategy such as using additives [18–22], different working fluids [19–22], and making system modifications [19,20,22–24]. Many of these ideas have been explored to determine their applicability for these circumstances in addition to novel designs.

The design requirements for this study were to provide 5.275 kW of cooling and 3 kW of electricity for non-cooling purposes in a high ambient temperature, off-grid location. To date, this task has been achieved by a 10 kW, oversized diesel engine supplying the electricity for a vapor compression system (VCS) and a non-cooling electrical load. The proposed CHP system consisted of a smaller, 5 kW engine appropriately sized for the non-cooling electrical load, with its waste heat powering an AS. For comparison, the proposed systems and the baseline system were modeled using EES (Engineering Equation Solver) for preliminary modeling and TRNSYS software for the full transient simulations [25,26].

The design point for the study was defined as an ambient temperature of 51.7 °C and 35.2 g kg^{-1} humidity ratio, with indoor conditions of 32 °C and 15.2 g kg^{-1} humidity ratio. The set point was specified more for proper function of electronics rather than for human comfort, however at the given ambient temperature, this will still be an improvement for any person. The supply air flow rate was specified as 0.280 kg s^{-1} with 0.024 kg s^{-1} of ventilation air. In transient simulations, the outdoor conditions were allowed to vary with a transient weather profile, while the cooling load and supply air flow rate varied with the ambient temperature and engine load.

Overall, the novelty in this study was to show the benefits and savings that would result by replacing an existing, electrical and air-condition supply system with a CHP configuration for a particular application in a high ambient temperature, off-grid environment. In order to achieve this while using a LiBr/H_2O absorption system to supply the air-conditioning, appropriate strategies were devised to avoid the debilitating crystallization that would otherwise occur under these environmental conditions. Namely, these strategies were a novel design for a MIAE (membrane integrated absorber evaporator), and a cascaded absorption system configuration.

2. Baseline system

The VCS for this system was characterized as using R-134a as its refrigerant, with an evaporator delivering air at a temperature of 5 °C. This supply temperature was chosen as it could be considered typical for achieving adequate dehumidification for a conventional space, and these assumptions (along with those in Table 1) led to a COP (coefficient of performance) of 1.06 at the design condition. This equated to about 5.0 kW of electrical load for the desired cooling demand of 5.275 kW, and resulted in a total engine electrical load of 8 kW. If a higher COP was used, this would indicate that the baseline system engine was oversized for its purpose. The modeling of the baseline VCS was done in EES to find a COP curve fit for incorporation in the TRNSYS model. According to the EES model, the COP was as high as 3.2 at a temperature of 25 °C.

To include the engine model in the TRNSYS system, experimental data indicating the performance of a 3 kW diesel Genset as shown in Table 2 was provided for this study and used as a basis for both the 10 kW engine and 5 kW engine. The number of hours per given engine load in Table 2 was used to create one plausible load profile as shown in Fig. 1. For a better understanding of the baseline system, a schematic with its components is given in Fig. 2. It displays an engine supplying electricity for non-cooling electrical equipment up to 3 kW, and also powers the basic VCS, which is composed of condenser, evaporator, expansion valve, and pump, which cools the supply air as it is recirculated to the conditioned space.

Various assumptions were used for the creation of the engine model, including the experimental data on the 3 kW engine. Since the manufactured 3 kW Genset [27] was based upon a specific manufactured engine [28], many of the engine calculations were based upon its specifications. This included the fixed engine speed at 3600 RPM (rotations per minute), with a displacement of 320 cm^3/revolution for the single cylinder, air-cooled, 4-cycle engine. The engine volumetric efficiency was 85%. A constant air density of 1.075 kg m^{-3} was used below 35 °C. Additionally, the engine specs were assumed to be rated at an ambient temperature of 35 °C. A constant C_p (specific heat), for the engine exhaust was used in both the EES and TRNSYS models, specified as 1.2 kJ kg^{-1} K^{-1}. Density of the diesel fuel was 832 kg L^{-1}, with a LHV [lower heating value] of 43 MJ kg^{-1}. The resulting electrical efficiency of the engine was 20% at its rated capacity. De-rating specifications for this engine were not found and so were based on similar specs for another similar engine [29]. The engine power and mass flow rate de-rate by 0.5% for every 1 °C above 35 °C, which results in 87.5% of capacity at 60 °C. The input of rated exhaust flow rate for the TRNSYS engine component was scaled linearly with the rated engine capacity from the calculated exhaust flow rate. The flow rate of the engine exhaust was calculated for the 3 kW sized engine as the intake plus the fuel consumption. This resulted in an exhaust flow rate of 0.00908 kg s^{-1} for the 3 kW engine, which scaled linearly for the 10 kW engine, gave an exhaust flow rate of 0.03027 kg s^{-1}. This is in accordance with a 10.2 kW engine from the same manufacturer [30], which is a 2 cylinder, 4-cycle diesel engine, having a displacement of 570 cm^3, and a resulting exhaust flow rate ratio to the 3 kW engine of 1.05, verifying the linear approximation for scaling.

Table 1
Key modeling assumptions for VCSs (Supplemental VCS has better isentropic efficiency due to smaller pressure ratio. Lower condenser inlet temperature due to placement in the AS evaporator. 5 °C outlet of conventional VCS due to lower evaporator temperature for which VCSs are typically capable).

	Conventional VCS	Supplemental VCS for cascaded AS
Evaporator approach temperature [°C]	7	7
Condenser approach temperature [°C]	5	9
Superheat [°C]	10	10
Subcooling [°C]	5	5
Compressor isentropic efficiency	0.61	0.8
Compressor motor efficiency	0.85	0.85
Evaporator air inlet [°C]	38.9	38.9
Evaporator air outlet (T [°C], RH [%])	5, 100	19, 100
Condenser air/water inlet [°C]	51.7 (air)	22 (water)
ΔP in evaporator (refrigerant) [kPa]	50	50
ΔP in condenser (refrigerant) [kPa]	100	100

RH: relative humidity.

Table 2
Experimental fuel consumption and load profile for a 3 kW engine.

Load	Fuel cons [kg s^{-1}]	Mission profile [h]	Exhaust temp [°C]
0	0.000091	0.00	274
0.75	0.000157	4.60	329
1.5	0.000196	7.25	385
2.25	0.000246	7.25	413
3	0.000309	4.60	454