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Research Paper

PERFORMANCE ANALYSIS OF MICRO GAS TURBINE DRIVEN THROUGH COMPRESSION-ABSORPTION REFRIGERATION SYSTEMS

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The paper analyses configuration of combined refrigeration system consisting of a compression chiller and an absorption chiller that is driven by a micro turbine to generate cooling at low temperatures. The compression chiller is operated directly by the micro turbine at the low temperature stage and the waste heat from the micro turbine is used to drive the absorption chiller that operates at the high temperature stage and helps to the compression chiller performance. From the results obtained, it is concluded that the use of this configuration of integrated refrigeration system is more efficient and less energy consuming than the system without absorption chiller.

Keywords: Micro gas turbine, Combined refrigeration system, Absorption, Compression, Performance

INTRODUCTION

The accelerated need for new energy generation systems and distribution lines to cope with the increase in electricity demands in recent years is causing supply problems and high emissions of pollutants. Cooling demand is increasing dramatically, and peak demand for power in several countries now is in summer, not winter. Combined Heat and Power (CHP) is the simultaneous generation of heat and power in a single process. Combined heat and power applications will contribute significantly to reduction of CO_2 emissions due to their higher global efficiency in comparison to conventional power stations. The use of CHP systems in refrigeration application would bring several advantages such as enhancement in power since the system can be operated independent of the grid and saving energy. Another important benefit is the security of supply. Herold *et al.* (1991) have analysed Hybrid refrigeration cycles which combine a mechanical compressor and an absorption cycle in such

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way that they share a single evaporator. They have shown that the cycle have significant potential from a thermodynamic viewpoint. Ho *et al.* (2004) have presented a micro turbine co-generation system that provides electrical power and space cooling to a laboratory space. They studied the performance of the co-generation system under varying heat load in the cooling space and longer micro turbine operating period. Bruno *et al.* (2009) have studied the performance of gas micro turbines of different power capacities directly coupled to double effect water/LiBr absorption chillers. In these systems post-combustion natural gas have been used to increase the cooling capacity of the system. [4] Fernandez-Seara *et al.* (2006) analyzed an alternative refrigeration system that could reduce the electricity consumption in those applications. This system consists of a compression system at low temperature stage and an absorption system at high temperature stage. Also they studied the possibility of powering this system by means of a co-generation system. Cogeneration is synonyms with CHP. In hybrid refrigeration systems CHP can supply simultaneously the power to the compression system and the heat to the absorption system. Bruno *et al.* (2005) analysed various integrated configurations of several types of commercially available absorption cooling chillers and MGT cogeneration systems driven by bio-gas. MGTs are fuelled with biogas and their waste heat is used to drive absorption chillers and other thermal energy users. The chillers considered in this study include single- and double-effect water/LiBr and ammonia/ water chillers. The exhaust gas from the MGT can be used directly to drive the chiller or indirectly to produce hot water to drive the chiller. He conducted a case study for an existing sewage treatment plant. Chilled water is used to reduce humidity in the bio-gas pre-treatment process and cool the combustion air of the MGT. He identified the most interesting integrated configurations for tri-generation systems that use bio-gas and micro gas turbines. He analysed these configurations and compared them with conventional configurations using operational data from an existing sewage treatment plant. The best configurations are those that completely replace the existing system with a tri-generation plant that uses all the available biogas and additional natural gas to completely meet the heating demands of the sewage treatment plant. Garimella *et al.* (2011) has conceptualized and analyzed a novel cascaded absorption/vapour-compression cycle with a high temperature lift for a naval ship application. Also they compared the performance of this system with an equivalent two-stage vapour-compression cycle. In the present study, configuration of a refrigeration system that integrated with a micro turbine and an absorption chiller to generate cooling at low temperatures are analyzed. The electricity produced by the micro turbine used to drive the compression chiller and the heat recovered from the micro turbine is used in the absorption chiller. Overall efficiency of this configuration is compared to a system that is operating without any waste heat utilization and consisting of a micro turbine and a compression chiller. The main components of the proposed system are micro gas turbine, vapour-compression chiller and water/LiBr absorption chiller.

DESCRIPTION OF THE MAIN SUBSYSTEMS

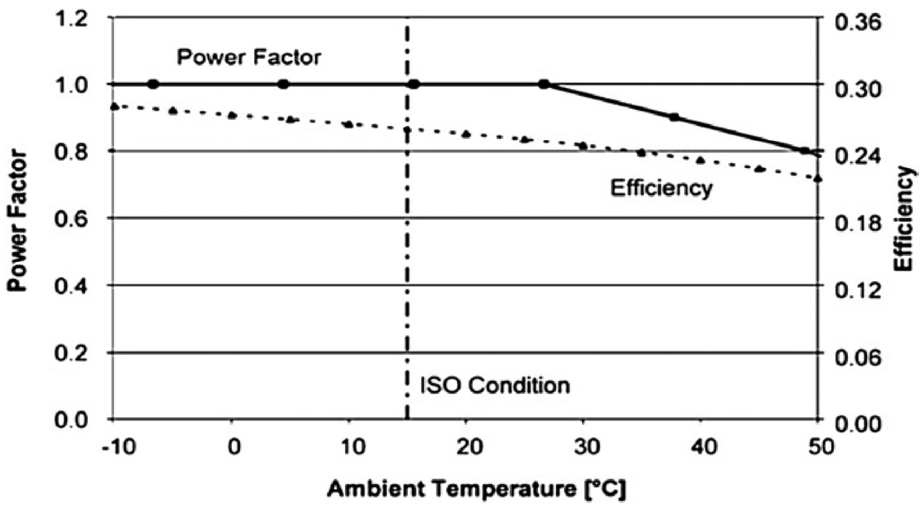
The main parts of proposed system are micro gas turbine, Vapour-compression chiller and water/LiBr absorption chiller.

Micro Gas Turbine

Micro turbines are small, compact high-speed turbo-generators of 28 to 200 KW, which consist of a centrifugal compressor, a radial turbine and a permanent magnet alternator rotor operating as a Brayton cycle. Their main features are that the high-speed generator is directly coupled to the turbine rotor and that they use power electronics instead of a gearbox and conventional generator to adapt the power produced to the grid power quality.

In a typical MGT re-generative system, the incoming atmospheric air is first filtered and used as a cooling medium for the alternator and electronic devices. The air leaving the alternator is later compressed and passed through the regenerator, where it is preheated with the hot gases leaving the turbine before it enters the combustion chamber. This reduces the amount of fuel used to reach the operating temperature. In the combustion chamber compressed fuel is burned with excess compressed air to produce hot gas at high temperature and pressure. This is then expanded through the turbine, which extracts energy and uses it to drive the compressor and the alternator. The turbine exhaust gas is fed through the regenerator and can then be fed to a boiler, a directly driven absorption chiller, a desiccant cooling system, or any other process that can benefit from high gases temperature. The main advantages that MGTs have over other technologies are the fuel flexibility, low emissions, quiet operation and low maintenance. The electrical efficiency of the current re-generative MGTs is in the range of 25-30% depending on the MGT size. However, the micro turbine efficiency depends on the ambient temperature. As the ambient temperature increases, the efficiency and the power of micro turbine both decrease (Figure 1). This is mainly because the air density at

Figure 1: Performance of Micro Turbine vs. Ambient Temperature



Source: Hwang (2004)

high air temperature is lower and, for the same inlet volume of air, a lower mass of fluid circulates the system. It should be noted that this performance dependence on the ambient temperature and might be changed through a different design approach.

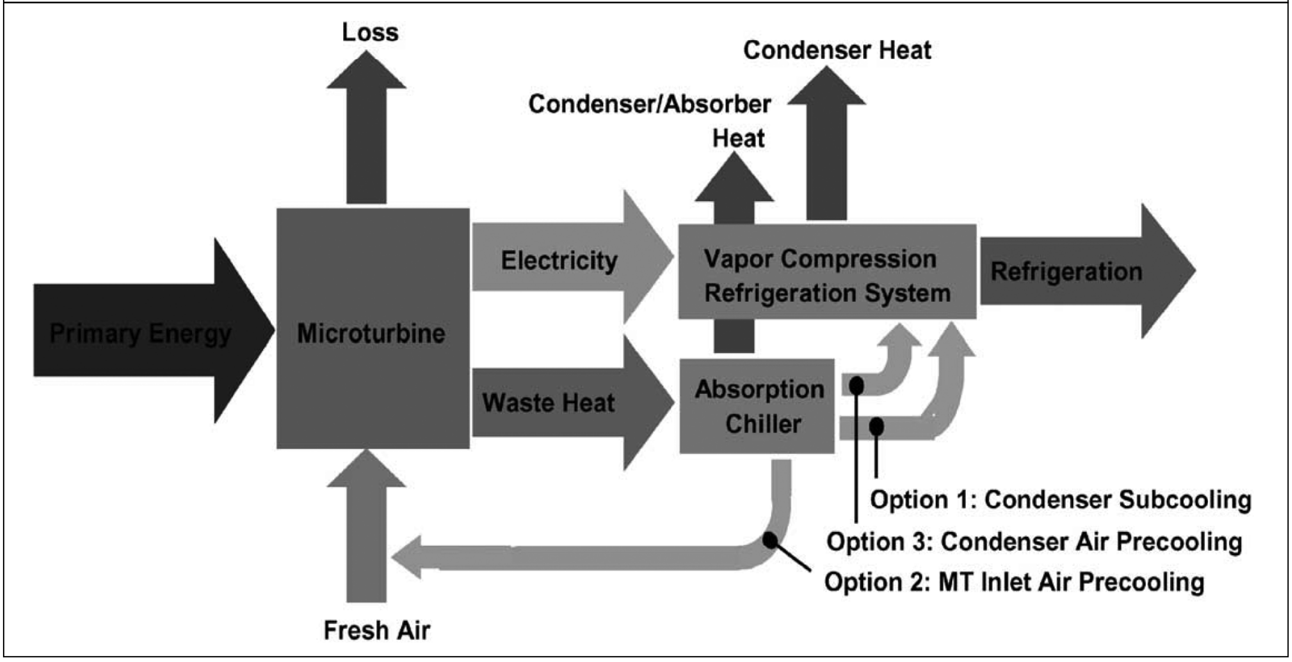
The power from the micro turbine is applied to the compression chiller compressor, the fans of the system and to the absorption chiller pump. To recover the waste heat from the micro gas turbine an exhaust gas heat exchanger produce hot water to drive the absorption chiller (Figure 2). It was assumed that 42% of the fuel energy from the micro turbine exhaust gas is delivered to the absorption chiller.

Absorption Chiller

Absorption chillers are thermally driven chillers that are well suited for the use of exhaust heat from prime movers such as micro turbines. There are various types of absorption cycles. They can be single effect, double effect or triple effect and can be powered by hot water, steam or combustion gases. Two preferred refrigerant and absorbent pairs in the absorption cycles are water/LiBr and Ammonia/water. Ammonia/water system requires higher generator inlet temperatures than water/LiBr system and higher pressures and hence higher pumping power.

It also requires a separation system to separate ammonia from water at the generator outlet but the water/LiBr chiller do not require any separation system. Though water/LiBr system has a limited range of operation, because of the crystallization, but the low cost and excellent performance of this working fluid combinations make it favourable for use. In the present study, single effect, hot water driven water/LiBr absorption chillers are considered. The model equations are formulated from mass and energy balances for each component of absorption cycle. The following

Figure 2: Energy Flow in Combined System



assumptions have been made during the present study:

- Refrigerant in the evaporator and condenser is pure water.
- Stream coming out from the condenser is saturated water, and the condenser pressure is the saturated pressure at condenser temperature.
- Saturated vapour leaves the evaporator and the evaporator pressure is the saturated pressure at evaporator temperature.
- The efficiency of the pump is 50%.
- Air cooled condenser and absorber are used. Condensing temperature and absorbent temperature are 10 °C higher than air temperature.
- The generator temperature is assumed as 90 °C at the ambient temperature of 30 °C.
- The evaporator temperature is assumed as 5 K at the ambient temperature of 30 °C.
- The power input to the condenser and absorber fan motor is 775 W for 1 cube metre per second air flow rate and the air flow rate through these components is 0.0537 metre cube per second for 1 KW heat transfer.
- The solution concentration at the outlet of the absorber is the equilibrium concentration to the absorber temperature.
- The solution concentration at the outlet of the generator is the equilibrium concentration to the generator temperature.

Compression Chiller

The compression chillers in this study is similar to conventional vapour-compression chillers and includes compressor, condenser, evaporator and expansion valve and using R22 as its working fluid. The model equations are similar to absorption cycle, formulated from mass and energy balances. The following assumptions based on Hwang (2004) are used in this model:

- Evaporation temperature was considered 10 K lower than the refrigerated air temperature.
- Condensing temperature was considered 10 K higher than air temperature.
- Degree of superheating at evaporator outlet is 5 K and the water exiting the condenser is 5 K sub cooled.
- Pressure drop at evaporator and condenser is 50 kPa.
- Compressor isentropic efficiency depends upon the pressure ratio.
- The same assumptions used for the fans of absorption chiller are applied in the evaporator and condenser fan motors.

ANALYSIS

The configuration of the integrated refrigeration system is analyzed to generate cooling at low temperatures and is compared for their energy efficiency to the base system. The base system is a system without absorption chiller and it consists of a compression chiller and a micro gas turbine. In the analyzed system the use of absorption chiller improves the overall system efficiency by reducing the electricity consumption in the compression chiller.

Performance of the Base System

The base system is used for reference and consists of a compression chiller and a micro gas turbine. In this case, the waste heat from micro gas turbine is released to the atmosphere.

Performance of the Configuration

In this configuration the absorption chiller operates at the high temperature stage and the compression chiller operates at the low temperature stage. A micro gas turbine supplies simultaneously the electricity to the system and the heat to the absorption chiller (Figure 3). If the power generated by micro turbine is equated to the power required by the system, the heat demand for the generator of absorption chiller is higher than the waste heat recovered from the micro turbine. Figure 4 shows the amounts of heat demand and the waste heat recovered at various refrigerated air temperatures. As refrigerated air temperature increases, the heat demand decreases by 50%, while the waste heat recovered decreases by 215%. It means that at higher refrigerated air temperatures, the heat demand is much higher than the waste heat recovered and extra heat is needed. There is a two stage compression chiller with an intercooler between two compressors of compression chiller in the configuration. Inter cooling between two stages of compression chiller reduces the work of compression per kilogram of vapour. The absorption chiller provides inter cooling. The compression chiller refrigerant and the water in evaporator of absorption chiller exchange heat in counter flow configuration. The higher amount of the heat recovered by micro turbine is used in the absorption chiller and the surplus cooling is employed to sub cool the liquid exiting the condenser of compression chiller, so the reduction in the work of compression increases. The cooling capacity of absorption

Figure 3: Schematic Diagram of Configuration

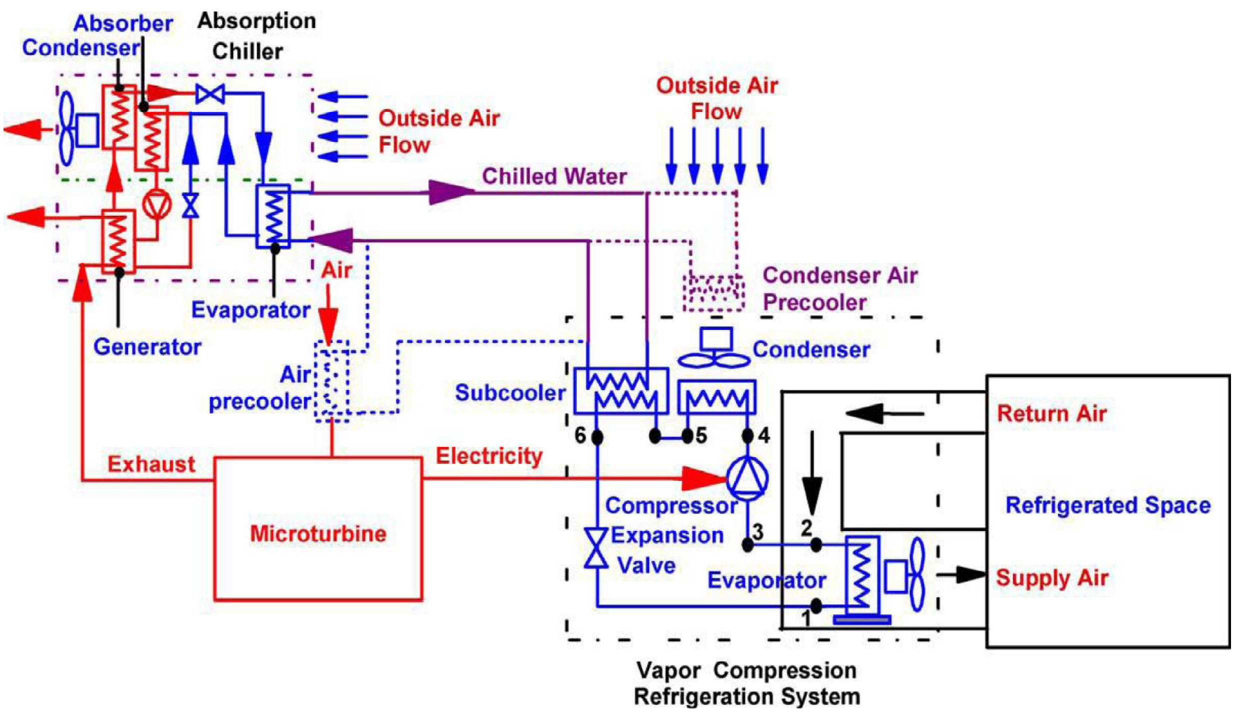
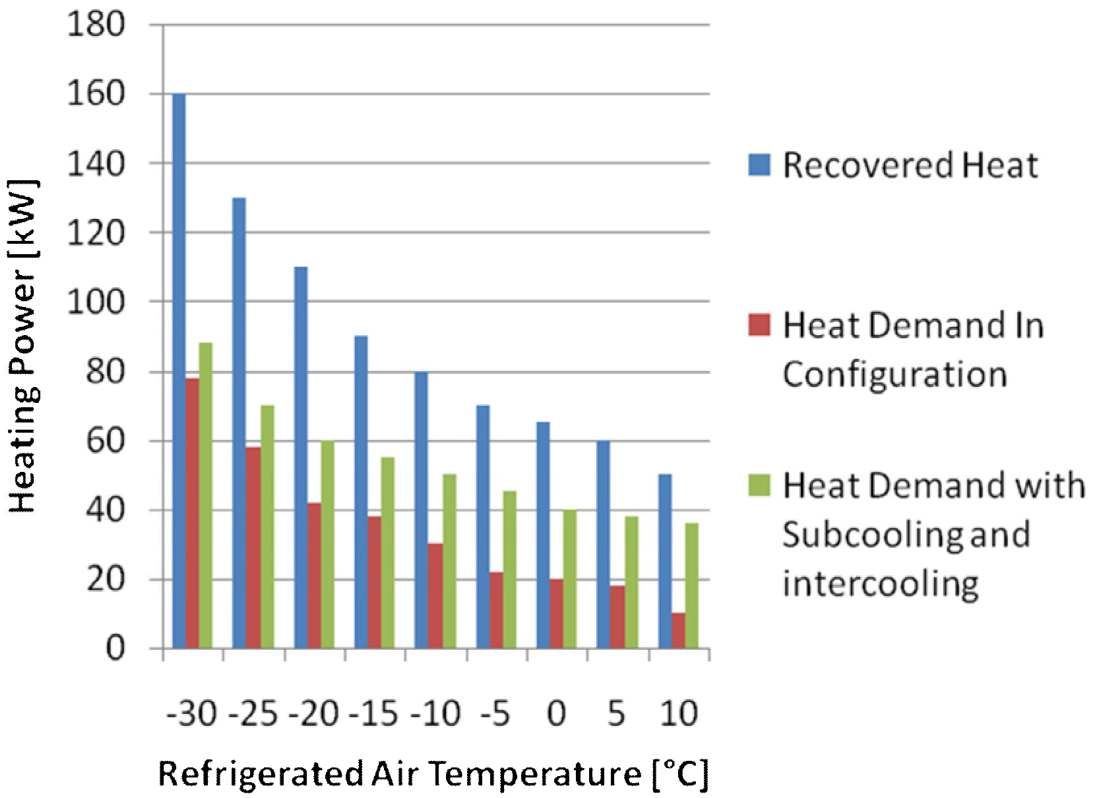


Figure 4: Histogram of the Recovered Heat Rate from the Micro Turbine and the Demand of Generator in Cofiguration (at Ambient Temperature of 30 °C)



chiller was utilized to sub cool the liquid exiting the condenser of compression chiller and provides lower vapour quality refrigerant to the evaporator, which provides a lower refrigerant mass flow rate for the same cooling capacity. Therefore, the consumption of refrigerant in compressor will reduce.

Performance Improvement of Refrigeration System with Absorption Chiller

The performance of the configuration is analyzed in two respects: (i) refrigeration cycle efficiency enhancement and (ii) reduction in overall system energy. First, the enhancement of the refrigeration cycle efficiency is analyzed for three options. It should be noted that only the results for the air cooled absorption system case are presented here since similar performance enhancement was observed for the water-cooled absorption system case.

Refrigeration System with Condenser Sub Cooler

In the sub cooler cycle using an absorption chiller, the sub cooler cools the refrigerant exiting the condenser and provides lower vapour quality refrigerant to the evaporator, which provides a larger cooling capacity for the same refrigerant mass flow rate of the original vapour compression system. The performance of the configuration with sub cooler using R22 as its refrigerant was modelled using EES. The following assumptions were used for the model:

Evaporator

- Refrigeration capacity is 100 kW. Refrigerant mass flow rate is adjusted for each case.
- Evaporation temperature is 10 K lower than the refrigerated air temperature.
- Superheat of vapour is 5 K exiting the evaporator.
- Pressure drop is 50 kPa.

Condenser

- Condensing temperature is 10 K higher than the inlet air temperature.
- Degree of sub cooling at condenser outlet is 5 K.
- Pressure drop is 50 kPa.

Compressor

- Isentropic and volumetric efficiencies change depending upon the Pressure Ratio (PR).

Sub Cooler

- H_2O/LiBr absorption chillers provide the additional sub cooling.
- Absorption chiller works only for an ambient temperature between 7.2 and 40.6 °C.
- The sub cooled liquid refrigerant and chilled water exchange heat in counter flow configuration. The approach temperature is 2 K.
- The approach temperature limits the degree of sub cooling.
- The sub cooler does not affect the pressures of the evaporator and condenser.
- When the air-cooled absorption chiller is used, the evaporating temperature of the absorption chiller is controlled dynamically according to the ambient temperature when the water-cooled absorption chiller is used; the evaporating temperature is maintained at 38 °C of the ambient temperature.

Motor

- Air flow rate through the evaporator is 0.0537 m^3/s for 1 kW refrigeration capacity.
- Power input to the evaporator and condenser fan motor is 775 W for 1 m^3/s airflow rate.
- Evaporator motor is located in the cold air stream and works as thermal load.

Refrigeration System with Sub Cooler and Micro Turbine Intake Air Pre Cooler

Since the utilization of the sub cooling capacity from the sub cooler is limited, the surplus cooling capacity by the sub cooler can be employed to pre-cool the intake air entering the micro turbine. The surplus cooling capacity and the amount of the cooling capacity used to pre cool the micro turbine intake air are compared to the sub cooling capacity available from the sub cooler. If this surplus cooling is utilized to pre cool the intake air entering the micro turbine, the micro turbine efficiency can be improved. For example, the micro turbine efficiency improvement is 13% if all the surplus cooling capacity is used at 40.6 °C. However, heat transfer limits the utilization of the surplus cooling in most cases because the intake air temperature cannot be lower than the sub cooler temperature. To account for this heat transfer limitation, the ambient air temperature was assumed to be higher than that of the sub cooler temperature by 2 K. The cooling capacity used to pre cool the intake air increases as the ambient temperature increases but its utilization is clearly limited especially at low ambient temperature. This heat transfer limitation results in the limitation of the micro turbine efficiency improvement. Moreover, it means that the current waste heat recovery is large enough and more waste heat recovery can not contribute to the further enhancement.

Refrigeration System with Condenser Air Pre Cooler

In the pre cooler cycle using an absorption chiller, the pre cooler cools the air entering the condenser and supplies the air at reduced temperature. The lower air temperature entering the condenser results in a lower pressure ratio and reduced compressor power consumption. The same assumptions used for the evaporator, condenser and compressor of the cycle with sub cooler were applied in the model. The following assumptions for the pre cooler were used in addition to the previous assumptions:

Pre Cooler

- Airflow rate is the same as that of the conventional cycle to increase the air temperature by 5 K across the condenser.
- LiBr absorption chiller provides the pre cooling.
- Absorption chiller works only for ambient temperature between 7.2 and 40.6 °C.
- Pre cooler does not affect the evaporation pressure.
- Refrigerant and air heat exchange occurs in cross counter flow configuration. The approach temperature is 2 K.
- The same assumption for the evaporating temperature of the absorption chiller used for the sub cooler cycle is used.

The Effect of Ambient Temperature

The effect of ambient temperature on system performance was also investigated over the range 10-40 °C. In absorption chillers, if the solution concentration is too high or the solution temperature is reduced too low, crystallization may occur and interrupt system operation. As the ambient temperature decreases, the generator temperature must be decreased to avoid of crystallizing. At low ambient temperatures, overall efficiency can be increased by decreasing temperature of the absorption chiller evaporator. Also at ambient temperatures higher than 30 °C, by generator temperature of 90 °C, the generator couldn't disrobe lithium Bromide from water due to the high concentration of the entering solution to the generator. By increasing the ambient temperature, the temperature of generator and evaporator in absorption chiller has been changed to solve this obstacle and also to have optimum efficiency. These changes of operating temperatures of

Table 1: Temperature of Generator and Evaporator of Absorption Chiller vs. Ambient Temperature

Ambient Temperature in °C	10	15	20	25	30	35	40
Evaporating Temperature in °C	2	2	2	2	5	8	14
Generating Temperature in °C	65	75	80	85	90	95	100

generator and evaporator in this study are presented in Table 1.

CONCLUSION

- Micro turbines have emerged as one of new on-site power generation technologies to provide a reliable power supply against the increasingly susceptible electric grid.
- The overall energy efficiency of the system using micro turbines as its power supply can be improved, if the waste heat from micro turbines is recovered by an absorption chiller.
- The results show that the use of absorption chillers to assist the compression chillers to generate low temperatures (lower than 0 °C), can reduce energy consumption.
- A refrigeration system with condenser evaporator heat exchanger and auxiliary boiler, with condenser evaporator heat exchanger and a conventional compression chiller that works under integrated system condition with intercooler between two compressors, and with intercooler and sub cooler can reduce energy consumption by as much as 133%, compared to the system without any waste heat utilization from the micro turbine.
- The integrated system with this configuration can operate at high temperatures as much as 40 °C, while with increasing the ambient temperature, the temperature of absorption chillers evaporator and generator increase.
- To operate this system at ambient temperatures lower than 30 °C, the temperature of absorption chiller generator must be decreased to prevent crystallization.
- The energy consumption of a refrigeration system with condenser evaporator, heat exchanger and auxiliary boiler has high efficiency to generate cooling at low temperature but the energy consumption of this system at low ambient temperatures and at high refrigerated air temperatures, is higher than the system without absorption chiller.

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