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Study of a novel hybrid refrigeration system for industrial waste heat recovery

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Abstract

The paper proposes a novel hybrid refrigeration system to convert industrial waste heat into refrigeration. The proposed system integrates Organic Rankine cycle, vapour compression cycle and liquid desiccant technology. The performance evaluation of the system recovering the waste heat from an industrial STACK has been conducted. The hybrid refrigeration system can potentially be used to convert industrial waste heat into refrigeration in the form of sensible cooling effect from vapour compression cycle and latent cooling effect from liquid desiccant unit. Results indicated under 200 kWth, the system can generate around 50 kW sensible cooling and 132 kW latent cooling effect, when the n-butane is the working fluid under 140 ^{o}C evaporating temperature. When the ORC condensation temperature is at 80 ^{o}C, the overall system COP ranges from 0.8 to 0.96.

Keywords: Hybrid heat-driven system, Organic Rankine cycle, Vapor compression cycle, Liquid dessicant cycle,

1. Introduction

Electricity, cooling and heating are three main energy forms required for residential, commercial and industrial applications. Polygeneration has received increasing attentions of many researchers [1]. The European Union

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considers polygeneration as a strategic technology with potential of reducing greenhouse emissions and overall energy costs [2].

Among the three main energy demands, refrigeration is the most expensive energy sources. In a conventional Vapour Compression Cycle (VCC), cooling coil has to be cooled down below the corresponding dew point temperature for the moisture removal, which requires large consumption of electricity. Heat activated cooling technologies such as absorption cooling [3, 4] and adsorption refrigeration technology [5, 6] have been extensively investigated since the 1970s due to the concerns of energy crisis. Alternatively, an Organic Rankine Cycle (ORC) based system can also be used to convert heat into refrigeration by integrating the ORC system with conventional VVC unit. The ORC-VVC system was first published by Prigmore et al. [7]. The mechanical power of the ORC unit was used to drive the refrigeration compressor of the VVC and an electrical generator for the objective to deliver 3 ton of residential cooling and 1 kW_e electricity [7]. An analysis of the effects on working fluids selections and parametric optimisation was conducted by Nasir and the results indicated the combined ORC-VCC system can achieve the overall COP at 0.219 for dry air under the outdoor temperature at 40 ^oC [8]. Theoretical analysis of the combined ORC-VCC refrigeration cycle indicated the system can be potentially used to recover the low grade heat as low as 60 ^oC and the refrigeration temperature can be as low as -10 ^oC [9]. Results indicated the COP of the system varies from 0.1 to 0.6, under the evaporator temperature from -10 ^oC to 10 ^oC [9]. A prototype system with 5 kW cooling capacity was built and tested by Wang et al. [10] for the objective to potentially recover engine exhaust heat or industrial waste heat. The experimental data indicated the overall system COP can be as high as 0.48 and the maximum cooling capacity of the system was 4.4 kW [10]. The thermodynamic and economic analysis of the ORC-VCC combined hybrid system shown under 53.5 kW_{th} heat input the polygeneration system can produce 1.4 kW_e electricity, 53.5 heating and 5 kW_{th} cooling with the payback period of 7 years [11]. As an air handling technology, liquid desiccant dehumidification using the moisture absorption characteristic of saline solution can effectively treat the latent heat under low grade thermal energy. The development of integrated system can potentially form a system achieving high overall energy efficiency. For example, Alelyani et al. [12] proposed a novel polygeneration system integrating a Rankine gas refrigeration cycle, evaporative cooling cycle, liquid desiccant technology and ejector to form a combined power and refrigeration system. The proposed concept adopted liquid desiccant for the latent cooling and the sensible cooling was provided by the cooling coil of the evaporative cooler [12]. The enhanced cycle showed overall exergy efficiency can be as high as 53% and the system can provide 354 kW_e electricity, 400 kW_{th} sensible cooling and 1199 kW_{th} latent cooling under thermal energy input rate of 2.4 MW_{th} of steam at 210 ^oC [12].

In this paper, a novel hybrid system has been proposed for the purpose of recovering low grade heat into useful energy such as refrigeration. The proposed system integrates Organic Rankine cycle, vapour compression cycle and liquid desiccant technology. The system can be potentially used to treat process air for the industry or building applications.

2. Description of the system

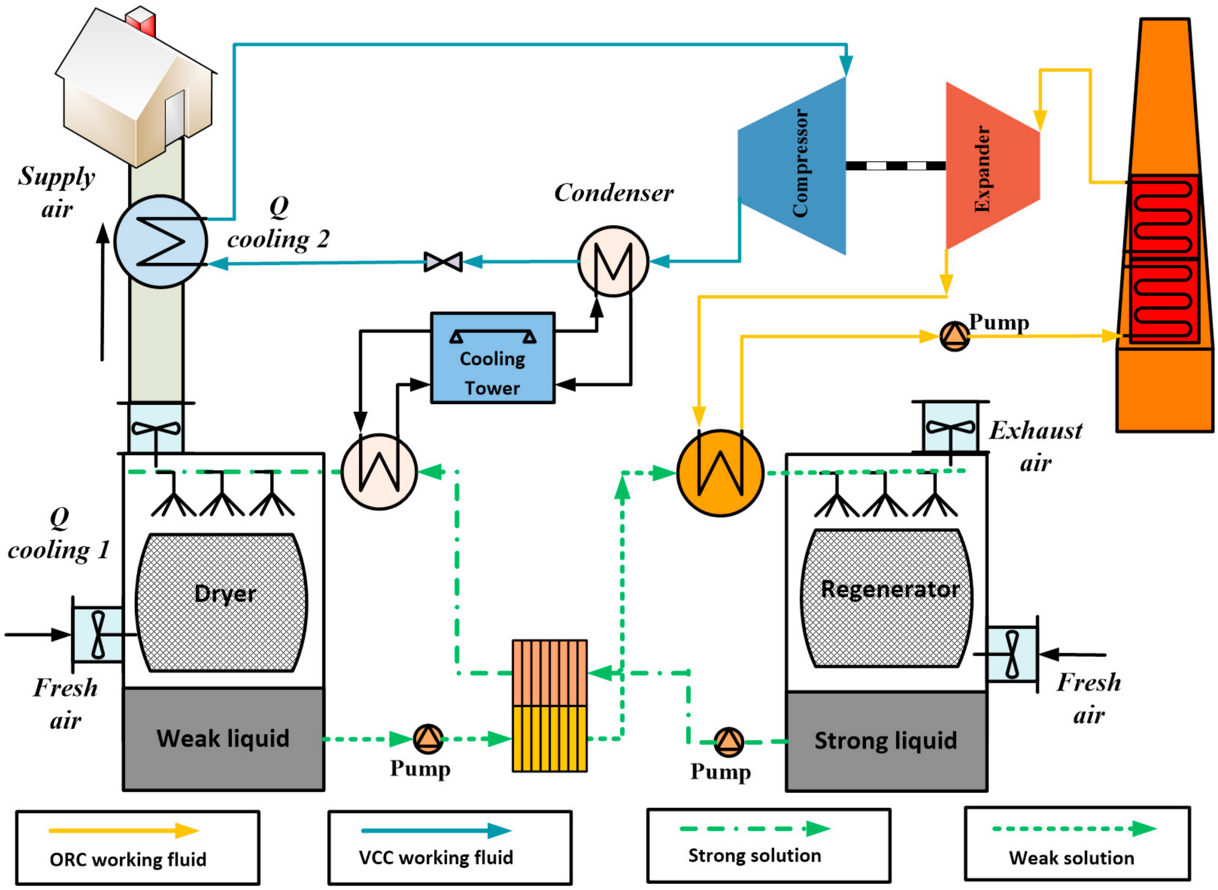

Fig. 1. Schematic diagram of the hybrid refrigeraiton system

Fig. 1 shows the schematic diagram of the proposed hybrid system consisting three subsystems: an Organic Rankine cycle (ORC), a Vapour Compression Cycle (VCC) and a liquid desiccant system. The evaporator of the ORC system is used to recover the heat from the stuck as illustrated in Fig. 1. The mechanical shaft power produced from the ORC system is used to drive the compressor of the VCC system. In a conventional ORC system, the condenser heat is normally dumped to the environment in order to achieve high temperature difference between the evaporating and condensing temperature. In this proposed hybrid system, the condensing heat from the ORC system is used to regenerate the weak liquid desiccant solution as illustrated in Fig. 1. The condenser heat of the VCC and the heat from the strong liquid desiccant solution are rejected to the environmental by a cooling tower. The conventional VCC refrigeration technology has to control the cooling coil temperature below the corresponding dew point temperature in order to remove the moisture. The proposed system can remove the moisture by the liquid desiccant system producing latent cooling effect and the cooling coil of VCC system is not required to be operated below the dew point temperature. The VCC system only needs to produce the sensible cooling effect.

3. Evaluation methods

The heat from the STACK can be calculated by Eq. (1), where $\dot{m}_{exhaust\_air}$ is the mass flowrate and $C_{p\ \ exhaust\_air}$ is the heat capacity of the exhaust air. The parameters used in the calculation are listed in Table 1.

$$\dot{Q}_{heat} = \dot{m}_{exhaust\_air} \times C_{p\ \ exhaust\_air} \times (T_{STACK\_bottom} - T_{STACK\_top}) \tag{1}$$

The thermodynamic simulation model of the system were coded in Engineering Equation Solver [13]. The ORC model has been previously described in ref [14]. The condensation temperature of the ORC system is set at 90 ^{o}C. Therefore the condenser heat of the ORC can be used as the heat source for the liquid desiccant system to regenerate the weak liquid solution. The mechanical power of the ORC expander shaft is assumed to be fully used by the compressor of the VCC system [15]. In order to simplify the calculation process, the COP of the VCC system is set at 3.67 and the COP of the liquid desiccant unit is set at 70% as stated in ref [16] and ref [12] respectively.

$$COP_{\_overall} = (\dot{Q}_{ref\_sen} + \dot{Q}_{ref\_lat}) \div \dot{Q}_{heat} \tag{2}$$

Table 1 Parameters of exhaust air from and the operational conditions the STACK

Definition	Symbol	Value
Exhaust gas temperature bottom of STACK	T_{STACK_bottom}	200 ^{o}C
Exhaust gas temperature top of STACK	T_{STACK_top}	110 ^{o}C
Exhaust gas volume flow rate	$\dot{V}_{exhaust\_air}$	Averagely 9,800 m3/h
Density of exhaust air at 200 ^{o}C	$\rho_{exhaust\_air}$	0.748 kg/m^3 [17]
Heat capacity of exhaust air	$C_{p\ \ exhaust\_air}$	1.097 kJ/(kg·K) [17]

4. Results and discussion

The proposed hybrid refrigeration system can provide two cooling effects. The liquid desiccant system can be used to generate latent cooling and the VCC unit can provide the sensible cooling. The industrial case study indicated there is around 200 kWth available from the STACK. Four working fluids have been selected to evaluate the performance of the ORC based hybrid refrigeration system under different evaporating temperature. The sensible cooling generated from VCC system and the latent cooling from the liquid desiccant unit under ORC condensation temperature at 90 ^{o}C has been plotted in Fig. 2 and Fig. 3, respectively. Results indicated the system using n-butane as the ORC working fluid could produce the highest latent cooling effect under the same operational conditions as shown in Fig. 3. When the sensible cooling effect is considered more important than the latent cooling effect, the working fluid toluene should be considered as indicated in Fig. 2. When the evaporating temperature is above 140 ^{o}C, among the four working fluids the n-butane shows the best performance. The results indicated the hybrid refrigeration system can generate around 50 kW sensible cooling and 132 kW latent cooling effect, when the n-butane is the working fluid under 140 ^{o}C evaporating temperature.

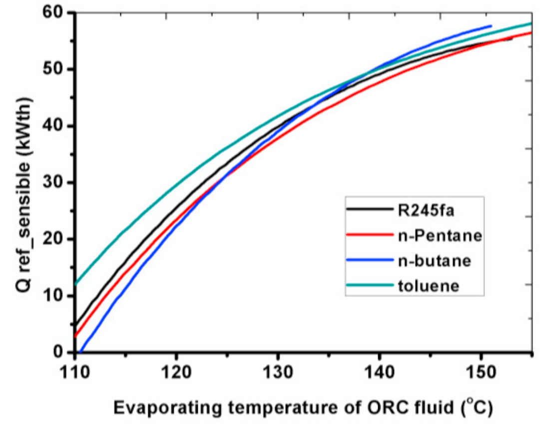

Fig. 2 Relationship between evaporating temperature and sensible cooling

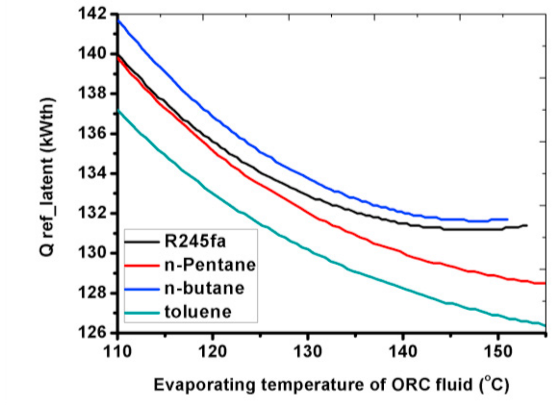

Fig. 3 Relationship between evaporating temperature and latent cooling

The overall system COP using four different ORC working fluids have been studied and the results are plotted in Fig. 4. Under the evaporating temperature from 110 to 155 °C, the overall COP varies from 0.7 to 0.95. The increase of ORC evaporating temperature can improve the system overall COP as shown in Fig. 4. Because the high ORC evaporating temperature is desirable in order to achieve high system performance, n butane has been selected as the working fluid, who can obtain the highest overall system COP among the four working fluids. Further analysis has been conducted to illustrate the effect of ORC condensation temperature on the overall system COP. The results have been illustrated in Fig. 5. Some of the data have not been included, when no effective cooling effect cooling effect can be produced from the VCC system. When the ORC condensation temperature is at 80 °C, the overall system COP ranges from 0.8 to 0.96 as the black line illustrated in Fig. 5.

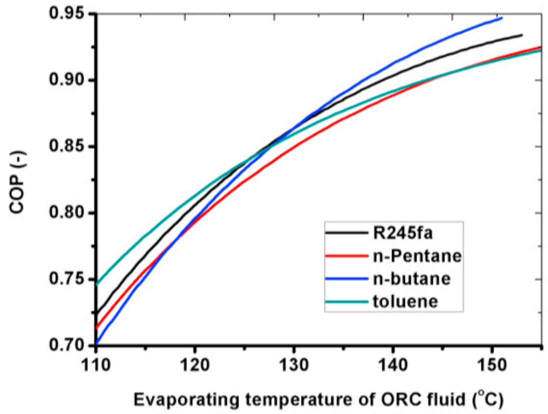

Fig. 4 Relationship between evaporating temperature and overall system COP

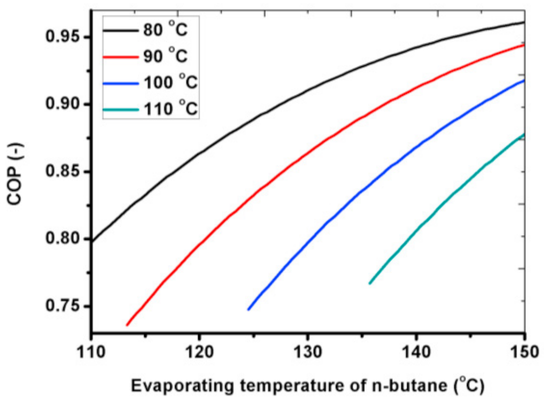

Fig. 5 Effect of ORC condensation temperature on overall system COP

5. Conclusions

A novel hybrid refrigeration system has been proposed in this study to recover industrial waste heat into useful energy. The integrated system consists of an Organic Rankine cycle, a vapour compression cycle and a liquid desiccant unit. The concept is to use the condensation heat from the ORC to drive the liquid desiccant unit for latent cooling production and convert the ORC mechanical power to sensible cooling effect by the VCC unit. Results indicate the system can potentially convert 200 kW thermal heat source to 50 kW sensible cooling and 132 kW latent cooling effect under the optimal conditions. The evaluation of the overall system COP shows the COP ranges from 0.8 to 0.96, when the ORC condensation temperature is controlled at 80 ^{o}C and the n-butane is selected as the working fluid.

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