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Modelling and Simulation of Trigeneration Systems Integrated with Gas Engines

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ABSTRACT

In this paper integration of gas engines with combined cooling, heating and power (CCHP) systems was studied. The gas engine model, organic Rankine cycle model, Rankine cycle model and single effect absorption chiller model were developed in Aspen HYSYS V7.3. The series and parallel combination of Rankine and organic Rankine cycle integration with the gas engine showed an increase of 7% and 15% respectively in both the overall system efficiency and power generated. The trigeneration system provided cooling duty of 18.6kW, heating duty of 704kW to district heating system with 3.9MW of power generated and an overall trigeneration efficiency of 70%. The system also gave a 9% increase in the power generated when compared to the gas engine without waste heat recovery whilst bottoming with Rankine cycle, organic Rankine cycle and absorption refrigeration system.

Keyword: Modelling, Simulation, Trigeneration, Gas Engines, Waste Heat Recovery

INTRODUCTION

The availability of energy sources and global warming are major concerns for the sustainability of future energy production. The demand for energy has been on a steady increase despite the limited availability of fossil fuels [1]. For instance, the world energy consumption is expected to rise by about 40% between 2006 and 2030 [1] with an increase of 1.1% per year in residential energy usage [2], while a rapid increase in greenhouse gas (GHG) emission is anticipated and this creates a serious concern of environmental pollution [1, 3]. Therefore, with steady rise in residential consumption of energy, there is a need to give much attention in devising the most efficient, cost effective and least polluting energy conversion method [4-7] and promote technologies that reduces the depletion of the ozone layer, greenhouse gas emissions and use of fossil fuels [8]. With the Kyoto agreement, more emphasis is paid on reducing energy use from fossil fuels and evolving energy efficient systems such as combined cooling, heating and power (CCHP) [9].

Combined cooling, heating and power (CCHP) also known as trigeneration can simultaneously generate mechanical power (often converted to electricity), heating and cooling from one primary source [10, 11]. The types of trigeneration systems are determined by the prime movers, which constitute the main element of the power and heat production. The prime movers include steam turbines, internal combustion engines (ICE), gas turbines, micro turbines, Stirling engines or fuel cells. Among these prime movers, the CCHP system driven by fuel cells has achieved higher energy conversion efficiency because the efficiency of fuel cell is not subject to the limitation of Carnot efficiency [10, 12]. Gas engines as prime movers are a proven technology with an extensive range of size and the lowest capital cost of all CCHP systems [13] and also possess good operating reliability, high efficiency at part load performances offering flexibility in fuel types usage [14].

Of the fuel energy available for combustion, only 30% is converted into useful work with about 45% being converted into high and low temperature heat in the exhaust gas and the engine coolant system [15, 16]. Therefore, most of the energy is lost as waste heat. Integrating cooling and heating subsystems with conventional power plant can increase the efficiency of the plant to 80% [1]. In a trigeneration system, the waste heat from the power production can be utilized to drive the heating and cooling systems [7]. This waste heat can also be utilized through absorption refrigeration [17, 18] and bottoming cycles such as Rankine cycle (RC), organic Rankine cycle (ORC) and Kalina cycle (KC) to increase the overall efficiency by recovering waste heat from CCHP systems [19-21]. Waste heat recovery from CCHP systems offers an effective way of utilizing the energy of fuel efficiently, economically, reliably and with less harmful effects on the environment whilst improvement of the overall efficiency of the plant [5, 7, 22, 23].

The highlight of this paper is to examine the design of combined cooling, heating and power (CCHP) systems integrated with gas engines using Aspen HYSYS. The heat recovery of gas engines integrated with a combined cooling, heat and power system for potential benefits of additional power generation coupled with district heating was investigated. The waste heat recovered from the jacket water cooling and lube oil was exploited for absorption chilling. The heat integration of gas engines with a combination of Rankine cycle, organic Rankine cycle and absorption refrigeration evaluating the power generated and overall efficiency of the system whilst satisfying cooling and heating demands was presented.

MODELLING AND SIMULATION METHOD

Scope of Simulation

The development of the trigeneration system model can be divided into three parts. The gas engine model configuration was developed in Aspen HYSYS V7.3 and validated as presented by Ekwonu [24]. The second stage was the development of the Rankine cycle (RC) model, organic Rankine cycle (ORC) model and a single effect absorption refrigeration model in Aspen HYSYS as reported by Ekwonu [24]. Finally, the gas engine model was then integrated with a combination of Rankine cycle and organic Rankine cycle models, and another combination of RC, ORC and absorption refrigeration system.

Gas engine with Rankine cycle and organic Rankine cycle

In the simulation, the operating conditions were fixed and two configurations were evaluated for benefits of utilizing the heat recovery from jacket cooling and lube oil, and exhaust gas. The gas engine model integrated with the Rankine cycle and organic Rankine cycle was developed because the heat recovery from jacket cooling and lube oil has a lower temperature, and the organic Rankine cycle has been found to perform better at using low temperature heat sources [25-27]. The two configurations investigated were:

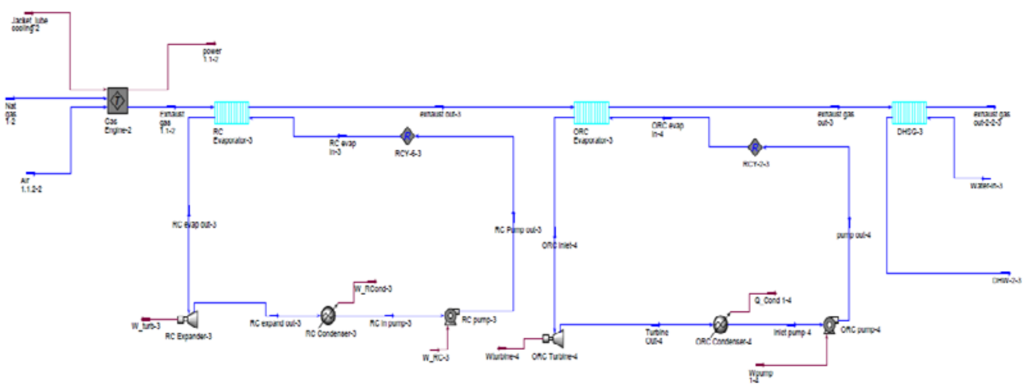

Fig.1: Aspen HYSYS model of the series system

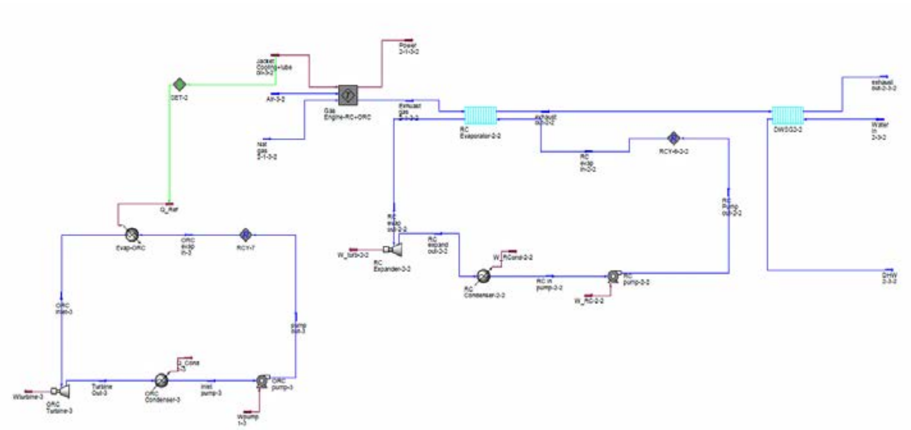

Fig. 2: Aspen HYSYS model of the parallel system

• The Rankine cycle connected in series with the organic Rankine cycle without the utilization of the jacket cooling and lube oil heat recovery. This configuration is named as the series system. In this configuration, the waste heat from the Rankine cycle was used as the heat source to the organic Rankine cycle. The waste heat from the organic Rankine cycle provided heat for the district heating system. The Aspen flowsheet of this configuration is shown in Fig.1.

• The integration of the organic Rankine cycle with the recovered heat from the jacket cooling and lube oil whilst the integration of the Rankine cycle with the gas engine exhaust. This configuration was named the parallel system. In this configuration, waste heat from the Rankine cycle was used as heat source for the district heating system. The 'Set-2' operator in the Aspen HYSYS flowsheet (Fig. 2) converts the negative value of the heat flow of the jacket water cooling and lube oil to a positive evaporator duty. This is necessary as the jacket cooling is designed by Aspen HYSYS as a cold energy stream and the 'Set-2' converts the negative value to positive to make it a hot energy stream.

In both configurations, the waste heat from the system was further used for district heating based on the district heating system reported in the Guidelines for District heating Substations (Tab. 1) [28].

Tab. 1: Rating and design data for district heating system [28]

District heating system	Rating data	Design data
High temperature system	100°C; 1.6Mpa differential pressure 0.6-0.15MPa	120°C; 1.6MPa
Low temperature system	Max. 85°C;0.6MPa differential pressure 0.35-0.3MPa	90°C; 0.6MPa

According to the guidelines, most district heating systems use high temperature. Hence, the high temperature district heating system was incorporated in the series and parallel models respectively.

Trigeneration with Gas engine

The gas engine was integrated with the series system (series combination of RC and ORC) and the absorption refrigeration system using the jacket water cooling of the engine.

The absorption refrigeration system model in Aspen HYSYS was developed using the input values of ammonia-water absorption refrigeration (Tab. 2). The sour Peng-Robinson (sour PR) equation of state was used in the Aspen HYSYS simulation.

Tab. 2: Input values for the absorption refrigeration system [30]

Parameter	Values
Evaporator Temperature	10°C
Condenser Temperature	30°C
Absorber Temperature	30°C
Generator Temperature	70°C

RESULTS AND DISCUSSION

Integration of gas engine with combination of Rankine Cycle and Organic Rankine Cycle

A combination of the Rankine cycle and organic Rankine cycle was investigated. The two configurations- series and parallel; using same input values as the individual bottoming cycle integration with gas engine model was evaluated. The generated power in the series configuration (3841kW) was less than that generated in the parallel configuration (4142kW). This could be as a result of the utilization of jacket cooling and lube oil and waste heat from the exhaust gas in the parallel system while in the series system; only the waste heat of the exhaust gas was utilized. The overall efficiency was 47% for the parallel compared with 44% for the series system. The parallel system offered potential power generation via the utilization of the waste heat of the exhaust gas and jacket cooling and lube oil thereby improving the overall efficiency of the system.

Tab. 3: Comparison between the series and parallel combinations of Rankine cycle and organic Rankine cycle

Parameter	Series	Parallel
RC power, kW	204	378
ORC power, kW	46	172
Overall power, kW	3841	4142
RC efficiency, %	20.5	20.5
ORC efficiency, %	14.6	14.6
Overall efficiency, %	44.0	47.0

Integration of gas engine with absorption refrigeration systems

Absorption refrigeration utilizes low grade waste heat between 60-120°C [29]. The jacket water cooling of the gas engine at 82°C was integrated with a single effect ammonia-water cycle. The absorption refrigeration system gave a COP of 0.528. The efficiency of the trigeneration system was 70%, with a total of 3913kW of power generated from the combined RC and ORC. The absorption refrigeration provided a cooling duty of 18.6kW whilst an evaporator duty of 15.0kW (Tab. 4). An increase of 9% in the power generated when compared with the gas engine alone was observed. This was due to the effective recovery and utilization of the waste heat from the jacket water cooling of the gas engine.

Tab. 4: Trigeneration system characteristics of gas engine

Parameter	Values
Evaporator duty, kW	15.0
Condenser duty, kW	18.6
Total Power, kW	3913
COP	0.528
Trigeneration efficiency, %	70

CONCLUSION

The paper presented the investigation the integration of gas engines with bottoming cycles (RC and ORC) and ammonia-water absorption refrigeration system. A combination of the Rankine cycle and organic Rankine cycle was integrated with the gas engine model. The system performance of the combination of the Rankine cycle and organic Rankine cycle was investigated, with two different configurations of both cycles. The results showed that parallel system, which utilized heat recovery from jacket water cooling and lube oil, offer higher performance than the series system, wherein the heat recovered from jacket water cooling and lube oil was not utilized. The trigeneration system with the gas engine offered potential additional power generation whilst providing cooling and district heating with an efficiency of 70% and a 9% increase in the power generated without consuming additional fuel.

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