

Thermodynamic Evaluation and Comparison of Efficiency Performance for a Thermally Driven Combined HP-ORC System using Conventional Expansion Valve or Two-Phase Ejector in the CO₂ VCC HP Cycle

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Abstract:- Conventional domestic heating systems consume significant amount of energy generated mostly from fossil fuel. Most of these heating systems reject considerable amount of heat energy to the atmosphere to meet the second law of thermodynamics concept. Combined heat and power cycles designed to convert the wasted heat into useful energy modes. Recently, thermodynamics coupling of heat pump (HP) and ORC cycles for heating application are proposed and investigated. However, many synthetic working fluids used in these thermodynamic cycles have been band or predicted to be phased out due to environment concerns. Natural working fluid such as CO₂ used in the vapor compression heat pump cycle is proposed to replace synthetic refrigerant due to its unique thermophysical characteristics and eco-friendly behavior. In this study, thermodynamic evaluation and comparison are conducted between conventional expansion valve and two-phase ejector used in the CO₂ VCC HP cycle in the combined system. The steady state results show that combined system using CO₂ HP ejector cycle has achieved HP COP and ORC thermal efficiency values higher than the expansion valve cycle by 27.2 and 3.7% respectively. In addition, in terms of fuel to heat efficiency, the combined system with CO₂ HP using two phase ejector has achieved a value of around 140% which is higher than the combined system using expansion valve (118.8%). Overall, both combined systems have achieved final water temperature range between 65-79 °C which is suitable for various domestic heating application.

Keywords: CO₂ heat pump, combined heat pump and ORC, two phase ejectors.

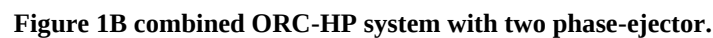
1. Introduction

Around 30% of the UK total national energy is utilized for domestic usages with the heating sector dominating these figures [1]. Likewise, similar percentage of domestic energy consumptions is reported in Italy and this in turn account for 12% of total carbon dioxide emissions [2]. To fulfil the UK and European Union regulations on carbon emission reduction, decarbonization of domestic heating systems is set as a major target. Conventional heating systems have various drawbacks. For instance, gas boiler rejects considerable heat energy to the atmosphere to comply with the second law of thermodynamics. Similarly, electrical heating system such as electric heater stresses the electric national grid especially on peak demand. In contrast, air source heat pump system suffers fluctuation in performance during low winter temperature [3].

Combined heat and power systems (CHP) are a promising technology to meet decarbonization task by reducing fossil fuel consumption while maintaining high efficiency performance. They can achieve this task by converting the rejected wasted heat into useful energy modes. More advantages include low cost and wide range of application [4]. In general, the thermodynamic combination takes place between a thermodynamic prime mover and a heat recovery cycle or device. Most of the heating engines can serve as a prime mover including Stirling engine (SE), Organic Rankine cycle (ORC) and others. These prime movers are usually thermally driven by fossil fuel combustion mostly CH₄ due to its low carbon footprints compared with other types of fossil fuel. Vapor compression cycles (VCC) and Heat exchangers are typical examples of heat recovery devices. Some prime movers can also be used efficiently as a heat recovery device such as ORC [3].

Recently, an innovative combined ORC-HP system thermally driven by a gas boiler is investigated for domestic heating. Collings et al. [5] has proposed a thermodynamic combination between HP, ORC and post heater heat exchanger which is thermally powered by CH₄ gas burner to produce hot water for domestic uses. The novelty of the proposed system is utilizing the released heat from fuel combustion in the gas burner to thermally power the ORC. Simultaneously, the rejected heat in the gas burner exhaust is recovered by the heat pump and post-heater heat exchanger. In addition, extra thermal energy is drawn from the ambient air by the HP cycle to boost the overall system thermal performance. The combined system is theoretically modelled to heat cold water to a value between 60–65 °C by providing heating capacity of 20 kW which is the typical capacity for heating houses in the UK. Hexane is the working fluid for the ORC, while R134a is used in the HP cycle. The combined system efficiency is evaluated by a parameter called fuel to heat efficiency (FHE) which is equal to the total heat generated from burning CH₄ in the gas boiler over the total heat added to the water. The results illustrate that the proposed design has achieved a fuel to heat efficiency of 136–160% which is significantly higher than any other conventional heating system. However, these values are strongly affected by the ambient air temperatures. Due to safety concern of using flammable working fluid in domestic appliance, Liang et al [6] have proposed similar combined system with R245fa as a refrigerant for the ORC cycle instead of Hexane. This study also concluded that the post heater heat exchanger can be removed due to its low heat capacity and to meet the cost saving and design simplicity. The results show that the overall fuel to heat efficiency has achieved a value of up to 147%. More theoretical investigation has been carried out on this innovative heating technology. Al-Tameemi et al. [7] has carried out a thermodynamic comparison between two different combined system layouts with different water inlet to the system to determine the best design configuration. Furthermore, control strategies have been suggested and investigated in order to keep the HP evaporator frost free while achieving the optimum efficiency performance. The results show that the two-stage water heating with HP condenser first then ORC condenser has achieved higher efficiency performance than the inverse route. To keep the HP evaporator frost free when ambient air temperature above 7 °C, higher air mass flow is required to sustain the optimum combined system performance. However, as ambient temperature drops below 7 °C, more CH₄ mass flow is required which results in remarkable drops in the fuel to heat efficiency. Similar system integration has been investigated for other application. A thermodynamic evaluation on a combined ORC-HP system is proposed to provide simultaneous heating and cooling loads. This system is designed to recover 12 kW of wasted thermal energy from a Data center while maintain air temperature between 18–25 °C. The recovered heat is simultaneously utilized to heat water between 50–80 °C for central heating application. This system can theoretically achieve a fuel to heat efficacy of a round 142% [8]. In all above studies, a conventional vapor compression cycle (VCC) with an expansion valve is adopted using synthetic refrigerant namely R134a due to its high performance.

In this study, a natural working fluid namely CO₂ is used in the VCC due to its unique thermophysical properties and eco-friendly behavior. Similar thermodynamic combination concepts of the above-mentioned studies are adopted. Additionally, two proposed transcritical CO₂ VCC are evaluated and compared, the first one uses conventional expansion valve as shown in Figure 1A, and the second one utilizes two phase-ejector as shown in Figure 1B.



In order to simulate the proposed combined system mathematically, two mathematical codes have been developed using MATLAB software. The thermophysical properties of the refrigerants have been acquired from REFPROP database. Some assumptions and working conditions are adopted from the literature as listed below:

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5. CO₂ temperature at the gas cooler exit is 35 °C to keep the working fluid state in the transcritical region.
6. The combined system is modelled to provide heating capacity between 20-25 kW to heat cold tap water to a value between 65-75 °C to be used for domestic application.
7. Mathematical models for the transcritical CO₂ HP ejector and expansion valve cycles are adopted from the open literature [7, 9 and 10].

Fuel to heat efficiency is estimated using the following equation:

$$Fuel - heat - effe. = \frac{Q_{HP-gas\ cooler} + Q_{ORC-condenser}}{Q_g} \quad (1)$$

Where:

$Q_{HP-gas\ cooler}$ is the thermal capacity added to water by HP gas cooler.

$Q_{ORC-condenser}$ is the thermal capacity added to water by ORC condenser.

Q_g total thermal energy released in the gas burner which is equal to CH₄ heating values times the mass flow rate.

3. Results and Discussions

The steady state results of the proposed systems for the combined ORC-HP cycle with expansion valve and two-phase ejector are presented in Table 1.

Table 1 the steady-state results of the proposed system

Cycle	Parameters	Combined system using CO ₂ HP with expansion device	Combined system using CO ₂ HP with two phase ejector
Heat pump cycle	Gas cooler pressure (Kpa)	8460	
	Q gas cooler (kW)	8.03	
	Q evaporator (kW)	6.0726	6.5699
	CO ₂ mass flow (kg/s)	0.0509	0.0904
	Pressure at compressor inlet (kPa)	3721.5	4565.5
	Wcomp (kW)	1.957	1.5388
	COP _h	4.1023	5.2185
ORC	Evaporator press (kPa)	3651	
	Condenser press (kPa)	715.0385	542.5256
	Q evaporator (kW)	18.7646	14.3727
	Q condenser (kW)	17.0721	13.0278
	Refrigerant mass flow (kg/s)	0.0967	0.0687
	ORC thermal efficiency	9.0199	9.3574
	Tw_ORC_out (oC)	78.9505	67.8281
Combined ORC-HP	Total Q added to water	25.1021	21.0578
	Fuel to heat efficiency	118.8040	130.1575
	CH ₄ mass flow kg/s	3.8059e-04	2.9151e-04

Table 1 shows the results of using two different expansion devices in the HP cycle when the combined systems reaches the steady state working conditions. In the heat pump cycle, some parameters are similar between the two compared cycles such as gas cooler pressure and thermal capacity. However, evaporator thermal capacity of the

CO₂ ejector HP cycle is higher by 8.18% than the one with conventional expansion valve. This indicates more heat is extracted from the ambient air to heat the water which reflects into more refrigerant mass flow in the HP ejector cycle is required. Furthermore, the work consumes by the HP compressor in the ejector cycle has declined by 21.36% due to the lower pressure ratio of 1.85 achieved in this cycle compared with 2.27 in the expansion valve cycle. These results have also improved the HP COP of the ejector cycle by 27.2% compared to expansion valve cycle.

For the ORC cycle, evaporator pressure near the CO₂ critical pressure value is adopted to achieve the maximum performance. While the condenser pressure is iterated to secure the designed PPT value of 3 °C between the two thermal fluids exchanging heat in the condenser. The higher-pressure ratio of 6.7 across ORC with HP ejector cycle has increased the ORC thermal efficiency by 3.7% compared with combined system using expansion device. ORC evaporator has lower thermal capacity in the combined system with ejector by 23.4%. In addition, the CH₄ mass flow is lower in the combined system with HP ejector cycle resulting in a higher fuel to heat efficiency of approximately 140% compared to 118.8% in the other system.

Thermal capacity for the ORC condenser in the combined system with expansion valve is high by 31% than the system with ejector HP cycle. The effect of this parameter can be seen clearly on the final water temperature which reached around 79 °C.

4. Conclusions

Thermodynamic comparison evaluation has been carried out on a combined system comprises of a gas burner thermally powers an ORC cycle which mechanically drives an air source transcritical CO₂ HP cycle. The aim is to utilize the mechanical and thermal energies produced by individual cycles of the combined system to produce hot water suitable for various domestic heating application. Two expansion devices have been proposed in the transcritical CO₂ HP cycle namely conventional expansion device and two-phase ejector. The steady state finding show that the combined system with CO₂ HP ejector cycle has achieved higher COP_H, ORC efficiency and fuel to heat efficiency by 27.2, 3.7 and 9.5% respectively compared with the combined system using transcritical CO₂ HP with expansion device. Each combined system has heated cold water from 10 °C to a value between 65-79 °C which is suitable for domestic heating.

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