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ANALYSIS OF A LOW-TEMPERATURE HEAT DRIVEN VAPOUR COMPRESSION COOLING SYSTEM INCORPORATING A SUPER-SONIC EJECTOR

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ABSTRACT

Vapour compression cycle (VCC) is widely used technology of cooling and air-conditioning. Low-quality-industrial-waste-heat driven ejector refrigeration systems (ERS) are promising solutions but limited by lower efficiency and larger system sizes. This paper presents the analysis of a new system which enhances the electrical-COP of the VCC by incorporating supersonic ejectors driven by heat. This new system, ejector-enhanced-vapour-compression-cycle (EVCC), increases the electrical-COP of the whole system while harnessing low-grade-waste-heat. Engineering Equation Solver (EES) has been used to model the system equations and the system performance is compared with VCC, Enhanced-ERS, and ejection-compression-system. In the analysis, R245fa has been used as the working fluid. The proposed system gives lower global-COP value as compared to conventional-VCC and ejection-compression-system because this system is designed to be able to extract as much heat as possible from waste stream, therefore, higher electrical-COP is the focus of this proposed system. It is concluded that, for the base case, the proposed EVCC gives higher value of electrical-COP as compared to all the other three systems.

Keywords: Vapour Compression, Ejector, Energy, Waste Heat, Refrigeration, Efficiency

1. BACKGROUND

Vapour compression cycle (VCC) is commonly used technology for cooling and air conditioning [1]. Global demand for cooling is expected to increase by three times by 2050 [2]. Approximately about 20-50% of industrial energy input is released to the environment through stacks and flares as waste heat [3]. In addition, low-temp. thermal energy (60-100 ºC) is abundantly available from sources like solar energy and geothermal energy. Therefore, low-temp heat recovery can lead to increasing efficiency and the share of renewable energy in the global mix.

A challenge for the adoption of ERS is the availability of amount of heat to meet the requirement of cooling. An excellent solution is to use a hybrid cooling system which is driven by both heat and electricity. Therefore, such ejector based hybrid systems have been studied and recommended by many studies in recent times [4] [5] [6] [7].

Sokolov et al. [8] [9] [10] presented enhanced ejector refrigeration system (EERS) where they used a compressor to help ejector with compression process. The electrical compressor was used before the ejector such that the outlet of the compressor was the entrained fluid for the ejector. A similar system was further studied by Arbel et al. [11] which was designed for about one RT of cooling by using 23.5 m^2 of solar collector area. Lei Wang et al. [7] reported experimental results on an EERS for automobile case such that the exhaust of automobile supplied waste heat and the compressor was run by engine power. They designed the system such that it could operate in three modes; (i) as conventional VCC (ii) as an ERS (iii) as a hybrid-EERS. They reported 35 % improvement of COP in idle condition and 40 % improvement in the COP for driving condition for hybrid-system as compared to conventional system.

A cascade ejection-compression system (CECS) which was studied by Da-wen Sun [12] was designed such that the conventional ERS and VCC were joint such a way that the condenser of VCC acted as evaporator of ERS. This way the compressor of VCC had less pressure ratio to work with hence increasing the electrical COP. Similarly, Chesi et al. [13] reported that CECS saves more electrical energy than simple ERS due to the fact that entrainment ratio of ejectors increases significantly for reduced compression ratio. Petrenko et al. [14] studied a CECS driven by heat of exhaust gases from an IC engine. The ERS was used as topping cycle with R600 as working fluid and VCC was used as a bottoming cycle with carbon di oxide as working fluid. The system was designed as small-scale-tri-generation-system with cooling capacity of 10 kW. It was reported that the COP of bottoming cycle increases from 1.3 to 6.4 when the evaporator temp. varies from -40 ºC to 0 ºC while the condenser of bottoming cycle is kept at the same 20 ºC temp.

The literature survey shows that many researchers have reported good performance for hybrid ejector-compressor cooling systems. It is observed that in most of the systems models, the inlet and outlet temperatures of waste heat streams have been not discussed and system has been modelled by directly assuming the vapour generator temperatures. Because for waste heat driven systems, the heat is available for free, the focus of system modelling should be on reducing the temperature of waste stream to as low as possible thereby extracting maximum amount of heat from waste stream. Keeping this in mind, it is observed that for various heat driven systems, the temperature of rejected heat is still quite high which has the potential to further used. Here, in this research, a new system is proposed which extracts heat from the waste stream at two levels; in high pressure (HP) generator and in low pressure (LP) generator such that the heat still available in the waste stream released by HP generator is used in a LP generator to drive a LP ejector. This novel ejector enhances vapour compression cycle (EVCC) is described in the next section. It has been modelled in Engineering Equation Solver (EES) and its performance results are compared with other systems for a base case. The developed EES model has been used for study the sensitivity of its performance with different operating conditions. It is found that the proposed system is an effective system in extracted more heat from the waste stream and gives better electrical COP.

2. THE PROPOSED SYSTEM

The schematic of the proposed ejector-enhanced vapour compression cycle (EVCC) is given in Fig1 and the corresponding T-s diagram is given in Fig 2.

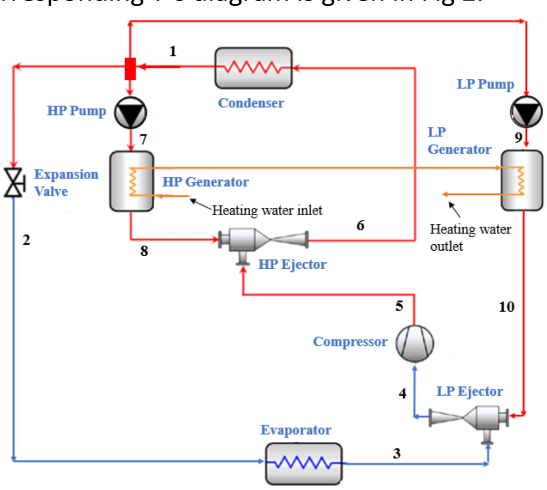

Fig 1: Schematic of the proposed system (EVCC)

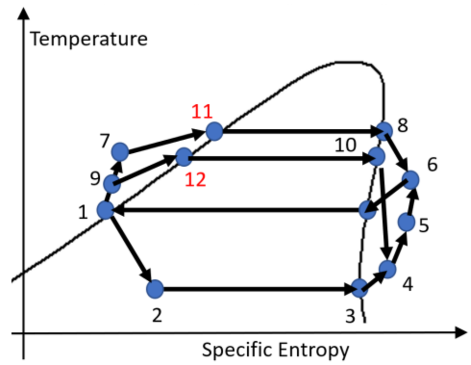

Figure 2: T-s diagram of the proposed system

As shown, the heating water is supplied to high-pressure (HP) generator and the hot water exiting the HP generator is then used by low-pressure (LP) generator which further extracts heat from the heating water (source). The HP-generator supplies the saturated vapour of working fluid (at point 8) which acts as motive fluid for the HP ejector. Similarly, the LP generator supplies the motive fluid for LP ejector (at 10). The LP ejector entrains the saturated vapour coming from evaporator (at 3) and compresses and delivers it to electrical compressor (at 4).

The compressor compresses the working fluid to state 5 which is entrained by HP-ejector. The HP-ejector delivers the working fluid to the condenser at the condenser pressure (at superheated state at 6). After the condenser condenses the fluid into a liquid, it is divided in three streams going towards HP-pump, LP-pump and expansion valve as shown. The novelty of this system lies in using LP-generator and LP ejector such that LP-generator extracts additional heat from the stream exiting the HP-generator and LP-ejector shares the compression load with electrical-compressor and reduces its compression ratio.

3. MODELLING

The system has been modelled in EES. The governing equations for all the components have been programmed to calculate the properties of working fluid at all the states as mentioned in schematic and T-s diagram of system above. R245fa has been used as a suitable working fluid and the thermodynamic properties are obtained by built-in data in EES. The following assumptions have been made:

- Heat losses from all components are neglected
- Pressure losses in heat-exchangers are neglected
- Saturated-vapour conditions are assumed at the exit of evaporator, HP-generator and LP-generator.
- The condenser outlet is taken as saturated liquid

The ejector model used in the system is a new model is the same as proposed by J. Chen et al. [15] who proposed a 0-D model that calculated the optimum performance of ejector for given operating conditions. This model uses a combination of ideal gas equations and real working fluid properties. This model is a double-iteration model. First, the model assumes a value of pressure in the constant area section (P') it corrects later in a loop against the condenser (delivery) pressure and then it assumes a value of entrainment ratio (μ') which is corrects later with a calculated value (μ) as shown in Fig. Because of the double iterative process, the programming is more challenging, and the model is difficult to integrate with other models.

4. RESULTS AND DISCUSSION

For comparison, a base case has been selected. Table1 shoes the performance results at the base case. At the base case, the proposed EVCC gives better electrical COP as compared to other systems. An electrical COP of 5.972 is obtained for our proposed cycle which is 58.4% higher than conventional VCC. It is found that by using the second ejector at the upstream of the electrical compressor, the electrical COP is increased by 8.7 % as compared to a single ejector system (EERS). The global COP (COPg) for our system is 1.37 which is less than ECS (2.88). Because ECS was designed to reduce the size of solar panel and make the system compact, it used least amount of heat and therefore has highest COPg. Whereas, our EVCC has been designed to utilize the waste heat to a maximum extent and to reduce the exiting temperature of heating stream to as low as possible, therefore, it is able to use 51.44 kW of waste heat and has lower COPg.

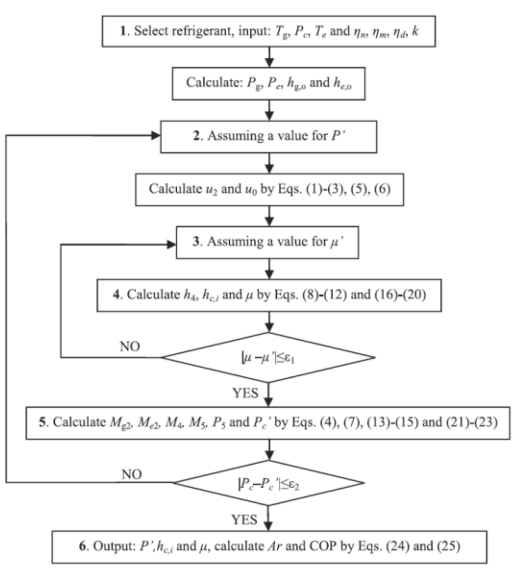

Fig 3: Computation procedure used by J. Chen et al for their 0-D model [15]

Table 1: Comparison of our proposed system with other systems

	T_e	T_c	T_g	Q_{ref}	COP$_e$	COP$_g$	P_{ele}	Q_g
	[C]	[C]	[C]	[kW]	-	-	[kW]	[kW]
VCC	5	45	90	10	3.77	-	2.65	-
Ejection-Compression system [4]	5	45	90	10	4.67	2.88	2.14	12.15
Our proposed system (EVCC)	5	45	90	10	5.972	1.37	1.68	51.44

Fig 4 shows the effect of evaporator temperature on the electrical coefficient of performance (COPe). The COPe of the proposed system increases with the increase of evaporation temperature. While the increase of COP for Ejector-Compression system (ECRC) is like that of conventional VCC, the increase of COP for the presented novel cycle much more as we move towards higher evaporation temperatures.

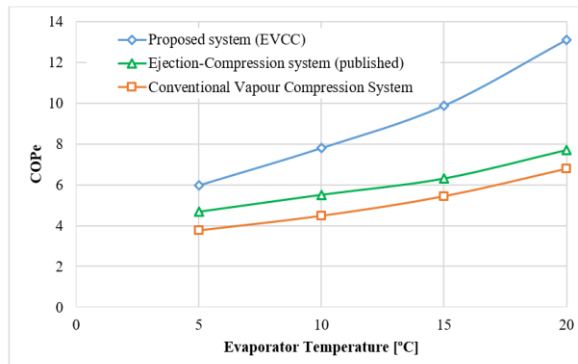

Fig 4: Effects of evaporator temperature on electrical-COP

With the increase in evaporation temperature, the saturation pressure of the working fluid in the evaporator increases which decrease the overall compression ratio for the system. Both the ejectors of the novel system experience decrease in their individual compression ratios hence their entrainment ratios increase which increases the electrical COP.

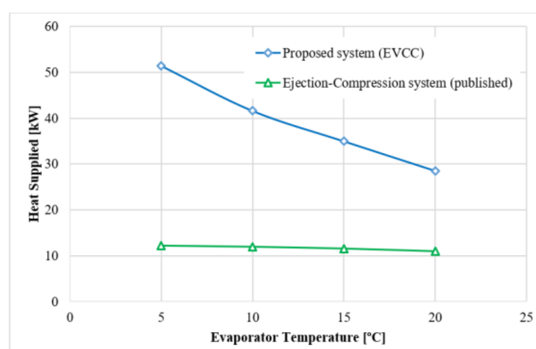

Fig 5: Effects of evaporator temperature on heat-supplied (Qg)

Due to the increase in evaporation temperature and the entrainment ratios of both the ejectors, less flow rate of motive fluid is needed to generate the same refrigeration effect of 10kW. Therefore, the heat supplied by the heat source decreases rapidly with increase in the evaporation-temperature. As shown by Fig 5, a decrease in heat supplied for ECS is not significant and the heat supplied is almost constant with only slight decrease in its value. At 5 ºC evaporator temperature, to produce 10kW of cooling, the heat supplied to EVCC is 51.4kW which is 321.3 % higher than the heat supplied to ECS which is 12.2 kW. At 20ºC evaporator temperature, the supplied to EVCC drops to 28.4 kW which is 161 % higher than the heat supplied to ECS which is 10.9kW. This mean that our presented novel system is much more efficient and effective for higher temperature cooling application because its COP is significantly higher, and its heat input is significantly lower for higher evaporator temperature.

5. CONCLUSION

This paper presents the thermal analysis of an ejector enhanced vapour compression cycle (EVCC) which utilizes waste heat to boost the performance of a conventional VCC in an effective way. The heat is extracted from waste stream in two stages by using two vapour generators and two ejectors operating as different pressures. The heat rejected by HP generator is further utilized by LP generator such that more heat is extracted from waste stream to make the system more effective. HP ejector is used downstream of compressor while LP ejector is used upstream of the compressor. The performance of the proposed system has been compared with conventional VCC and ejection-compression system (ECS) at base-case working conditions. The proposed EVCC gives better electrical COP as compared to other systems. The use of second ejector at the upstream of the electrical compressor increases the electrical COP by 8.7% as compared to a single ejector system at the base case. The system sensitivity was studied for varying evaporator temperatures. The sensitivity analysis shows that the COP of the proposed system increases exponentially at higher evaporator temperature making it very suitable for higher temperature cooling applications.

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