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A REVIEW ON MULTI-EVAPORATOR REFRIGERATION SYSTEMS

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ABSTRACT

This paper focuses on understanding multi-evaporator refrigeration systems — how they work, their types, and how well they perform. These systems use more than one evaporator to cool different areas that may need different temperatures or humidity levels. This helps in saving energy, improving temperature control, and managing different cooling loads more efficiently. The discussion also covers the main challenges in designing and running such systems, including how to control the refrigerant flow, manage compressors, and avoid interference between evaporators. It also looks at the use of different types of expansion valves, how changes in evaporator pressure affect system COP, and modern control methods that improve system performance. Finally, it highlights how these systems connect with different heat rejection methods and their use in industries, commercial buildings, and other special cooling applications.

Keywords: Vapor compression Refrigeration system, multi-evaporator refrigeration system, Energy, Exergy Optimization, Irreversibility, COP, Ejector

INTRODUCTION

A simple vapor compression refrigeration system uses one evaporator to handle the total cooling load at a single temperature. However, in many modern applications—such as hotels, supermarkets, food storage and processing plants, office buildings, and refrigerated transport vehicles—different areas or products need to be kept at different temperatures and humidity levels. To meet these varied cooling needs efficiently, multi-evaporator vapor compression refrigeration systems (MERS) are used instead of installing separate refrigeration units for each zone. These systems operate with two or more evaporators and are considered multi-stage systems, since they work at more than one low-side pressure. As the global demand for air conditioning and refrigeration continues to grow, these systems consume a large share of total electricity. Therefore, improving the performance of MERS is very important to reduce energy use. One major issue in vapor compression systems is the throttling process, which is irreversible and causes exergy loss. This loss lowers the cooling capacity and may require
a larger evaporator. To reduce these losses, researchers perform exergy analysis, which identifies where energy destruction occurs in the system and helps in optimizing the design. Studies have shown that MERS often perform better than single-evaporator systems, partly because they have a larger surface area for heat exchange, which helps reduce compressor work and improves efficiency.

Research on MERS focuses on improving system design, technology, and control methods:

1. **System Configuration and Design Improvements**: MERS can have multiple evaporators connected in parallel, each with its own expansion valve. Researchers compare different arrangements, such as:
   - *System-1 (Conventional):* Multiple evaporators and compressors with separate expansion valves.
   - *System-2 (Enhanced):* Multiple evaporators and compressors with multiple expansion valves. They also study series vs. parallel connections to find which gives better performance. Techniques like multi-stage expansion with flash chambers or multi- stage compression help increase cooling capacity and COP by reducing compressor work.
2. **Use of Advanced technologies**:
   Devices like ejectors are added to recover some of the throttling losses and improve COP. Hybrid systems combining vapor compression with absorption refrigeration or ejector systems are also being developed to enhance efficiency and utilize waste heat.
3. **Control strategies** :
   Because MERS are more complex, simple ON/OFF control systems are not sufficient. Advanced control methods such as decentralized control and Model Predictive Control (MPC) are used to maintain stable operation, regulate cooling capacity, and improve system efficiency.
4. **Refrigerant Selection**:
   Environmental concerns have led to a shift away from high-GWP and ODP refrigerants like R134a. Researchers are now testing eco-friendly alternatives, such as HFOs (R1234yf, R1234ze) and refrigerant blends (R513A, R450A, R152A), to achieve better efficiency while reducing environmental impact.

Nomenclature

Symbols

A	current supply
η	efficiency
Q	Heat
Ex	Expansion Valve
m^o	Mass Flow Rate
h	specific enthalpy [$kJ\ kg^{-1}\ K^{-1}$]
s	specific entropy [$kJ\ kg^{-1}\ K^{-1}$]

Subscripts and abbreviations

in	inlet
out	outlet
comp	compressor
ev	evaporator
con	condenser
exp	expansion valve
mc	mixing chamber
sc	subcooling
VCRS	vapour compression refrigeration system
MERS	multi evaporator refrigeration system
EES	Engineering Equation Solver
COP	Coefficient of Performance
HFC	Hydrofluorocarbon
HFO	Hydrofuoroolefin
GWP	Global Warming Potential
ODP	Ozone Depletion Potential

Vapor Compression Refrigeration System:

Energy and exergy analyses need some mathematical formulations for the simple vapor compression refrigeration cycle. In the vapor compression system, there are four major components: evaporator, compressor, condenser, and expansion valve.

External energy (power) is supplied to the compressor and heat is added to the system in the evaporator, whereas in the condenser heat rejection occurs from the system. Heat rejection and heat addition are dissimilar to different refrigerants, which cause a change in energy efficiency for the systems

Vapor compressor refrigeration systems are used in refrigerator and air conditioning systems. In both cases the same cycles are used. But the application fields are different. So sometimes, different kinds of refrigerants are used. All the vapor compression refrigeration systems consist of condenser, evaporator, expansion valve or throttling valves and compressor. In the refrigeration system, the coefficient of performance is varied with the change in refrigerants or the evaporator and condenser. Irreversibilities are different in the different components of the vapor compression system. The losses in a component should be measured to improve the performance of the whole system. The losses in the cycles need to be evaluated considering individual thermodynamic processes that make up the cycle.

Multi-evaporator Refrigeration System:

A multi-evaporator refrigeration system is an advanced vapor compression system that uses two or more evaporators to maintain different temperature levels in separate cooling spaces while operating with a single or multiple compressors. The refrigerant from the compressor passes through the condenser, where it releases heat and condenses into liquid form. It then flows through one or more expansion valves, reducing its pressure before entering each evaporator. In the evaporators, the refrigerant absorbs heat from different chambers and evaporates, producing cooling at various temperature levels before returning to the compressor. This system is commonly used in refrigerators, cold storage, and air- conditioning systems to achieve efficient and simultaneous cooling for multiple zones, offering better temperature control and energy savings compared to using separate systems.

The multi-evaporator refrigeration system can be designed in different configurations, such as using a single expansion valve for all evaporators or separate expansion valves for each one, depending on the required temperature control and application. Systems with individual expansion valves provide better regulation of refrigerant flow and more precise temperature management. In some advanced setups, multiple compressors are used to handle different pressure levels efficiently. Although the system is more complex in design and control, it offers significant benefits such as higher energy efficiency, compact construction, and reduced maintenance costs. Due to these advantages, multi-evaporator systems are widely used in domestic refrigerators, commercial freezers, cold storage facilities, and multi-zone air conditioning systems.

Two evaporator Two Expansion Valve One compressor:

The refrigeration system consists of two evaporators operating at different temperatures, a single compressor with individual expansion valves for each evaporator, one condenser and evaporator pressure regulator (EPR).

In some commercial refrigeration systems, one condensing unit associated with two or more evaporators are used. This type of refrigeration system is usually used for commercial refrigeration, such as in supermarkets, hotels and restaurants.

Evaporators may have the same or different temperatures according to the situation of the requirement of varied types of cooling loads. [2015 Yataganbaba, A. et.al]

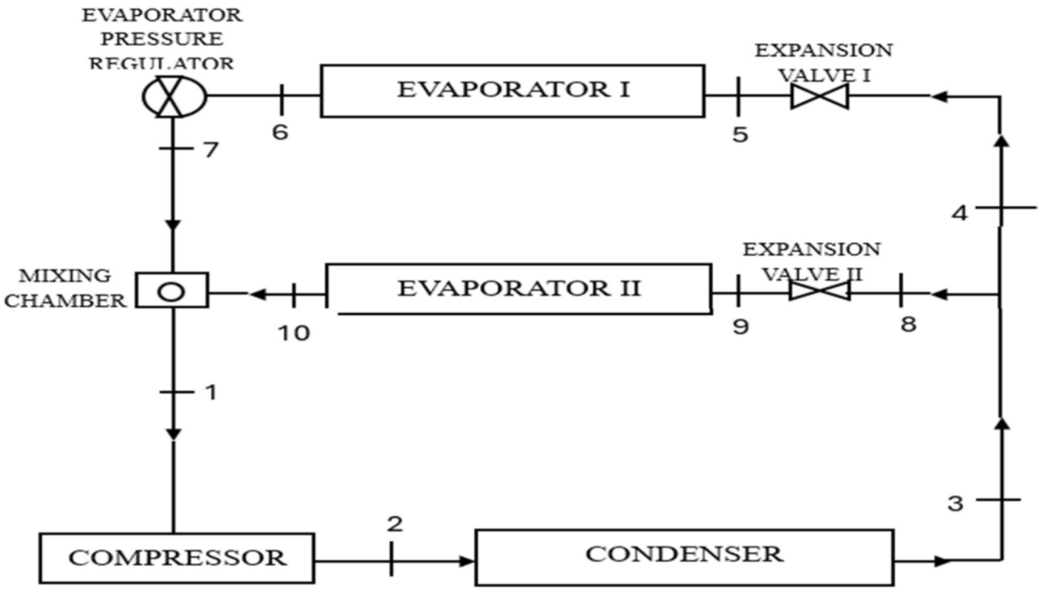

Fig1: schematic diagram of two evaporator two expansion valve one compressor [2015 Yataganbaba, A. et.al]

The system configuration comprises a single-stage vapor compression cycle modified to accommodate two independent evaporators operating at different temperature levels. This configuration is characterized by a single primary compressor unit serving dual evaporators (Evaporator-1 at T_{ev1} and Evaporator-2 at T_{ev2}), individual thermostatic expansion valves (TEV) for each evaporator, evaporator pressure regulators (EPR) installed downstream of each evaporator to maintain desired evaporating pressures, and a common air-cooled condenser unit. The EPR functions as a critical control device, maintaining back-pressure in each evaporator circuit to ensure stable operation at the desired evaporating temperature while preventing excessive pressure drop across the expansion valve.

The analysis was conducted at baseline conditions: T_{ev1} = -5°C, T_{ev2} = -18°C, Tcon = 40°C, T_0 = 25°C. For R1234yf, component-wise exergy destruction is: compressor 2.41 kW (31.59%), condenser 1.78 kW (23.25%), expansion valve-2 1.24 kW (16.20%), EPR 0.87 kW (11.37%), evaporators 0.86 kW (11.23%), and total 7.65 kW with exergy efficiency of 29.5%. The compressor dominates irreversibility generation due to polytropic inefficiencies, non-ideal vapor suction, mechanical friction, and valve clearance throttling. The condenser represents the secondary source from finite temperature differences. The second expansion valve contributes substantially to total irreversibility, highlighting the significance of constant-enthalpy throttling in dual-evaporator systems.

The heat absorbed and the power input of the independent evaporator circuits is given by:

$$Q_{ev1} = \dot{m}_{ref}(h_7 - h_8)$$

$$Q_{ev} = \dot{m}_{ref}(h_9 - h_{10})$$

$$Q_{total} = Q_{ev} + Q_{ev}$$

The compressor power input and EPR pressure drop regulation are expressed as:

$$W_{comp} = \dot{m}_{ref}(h_2 - h_1) \quad \Delta P_{EPR} = P_{evap} - P_{suction}$$

The coefficient of performance for the dual-evaporator system is given by:

$$COP = \frac{Q_{ev1} + Q_{ev2}}{W_{comp}}$$

Temperature Effect	Evaporator-1 (-5 to 0°C)	Evaporator-2 (-18 to -10°C)	Condenser (35-45°C)
R134a Change	+8.2% efficiency	+12.5% efficiency	-6.7% per 5°C
R1234ze Change	+7.8% efficiency	+11.9% efficiency	-6.4% per 5°C
R1234yf Change	+7.1% efficiency	+10.8% efficiency	-6.1% per 5°C

Two Evaporator Two Expansion Valve Two Compressor:

The system consists of two stages of compressors, two evaporators, TXV, capillary, BPV, and IHX. The refrigerant is compressed in low stage compressor (1–2), passes through IHX, where it exchanges heat with the low-temperature refrigerant (2–3), and later passes to the high-stage compressor (3–4). It is then condensed in the air-cooled condenser (4–5). The refrigerant is expanded partly in a capillary (5–6) and TXV (5–8). The exit of capillary and the exit of TXV connect with evaporator-1 and 2, respectively. After the refrigerant absorbs heat from evaporator-2 (8–9), it is passed through IHX, where it further absorbs heat from the hot refrigerant from the low stage compressor exit (9–11). Meanwhile, the refrigerant in evaporator-1, after absorbing heat (6–7), passes through a BPV (7–10), and it is mixed with the stream coming from the IHX exit, and the cycle completes accordingly. [2022 Malwe, P.D. et.al]

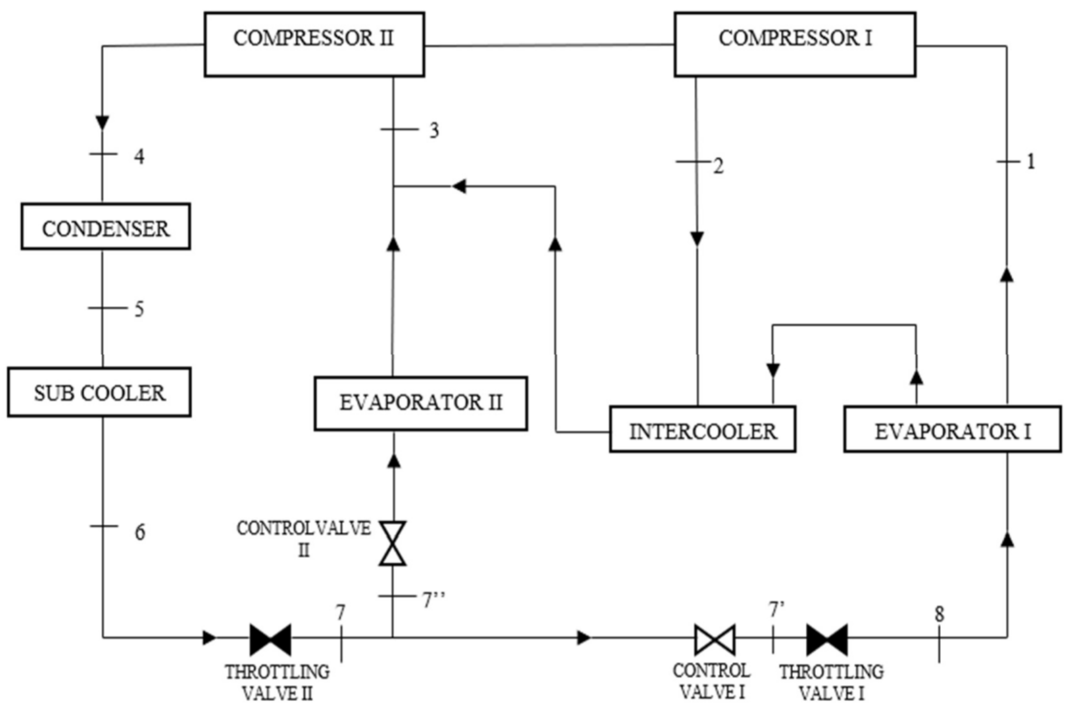

fig2: schematic diagram of two evaporator two expansion two compressor: [2022 Malwe, P.D. et.al]

Parameter	Value
Evaporator-1 Temperature	0°C
Evaporator-2 Temperature	-15°C
Condenser Temperature	25°C
LP/HP Compressor Efficiency	75%
IHX Effectiveness	80%
Total Cooling Load	3 TR (10.56 kW)

- The exergy destruction distribution analysis of the system reveals significant insights into the components contributing to overall inefficiency. The compressors collectively account for the largest share of exergy destruction, with a combined value of 668.9 W, representing 39.9% of the total, where both the low-pressure (LP) and high-pressure (HP) stages contribute almost equally. The condenser follows, contributing 333.4 W or 19.9% of the total exergy destruction. The evaporators together account for 448.2 W, corresponding to 26.8%**,** indicating notable losses during the heat absorption process. The internal heat exchanger (IHX**)** contributes a smaller portion, with 47.6 W or 2.8%**,** while the expansion devices exhibit the least exergy destruction at 25.6 W, accounting for 1.5% of the total.

Overall, the total system exergy destruction is calculated to be 1,674.1 W, highlighting that compressors are the primary source of irreversibilities in the system, followed by the evaporators and condenser.

table - refrigerant performance ranking (by exergy efficiency):

Rank	Refrigerant	Efficiency	GWP	Status
1	R141b	42.42%	725	Phased out
2	R123	41.67%	77	Low GWP
3	R1234ze(E)	39.84%	6	**Recommended**
4	R1234yf	38.56%	4	**Recommended**
5	R134a	38.12%	1430	Baseline
6	R407C	36.67%	1770	Worst

The temperature effects analysis reveals that the system's performance is significantly influenced by variations in ambient and evaporator temperatures. The Coefficient of Performance (COP) decreases from 4.2 to 3.6, marking a 14.3% reduction, as the dead state temperature rises from 25°C to 33°C, indicating that higher ambient temperatures adversely affect system efficiency. Among the evaporators, Evaporator-2 demonstrates a more pronounced impact on performance, with the COP varying between 5.2 and 6.0 across an evaporator temperature range of -15°C to -5°C, whereas Evaporator-1 shows minimal influence. Additionally, the exergy efficiency improves at lower temperatures and with a greater allocation of capacity to the second evaporator, highlighting the advantage of optimized evaporator temperature distribution.

This comprehensive study examined eighteen different refrigerants in multistage multi- evaporator vapor compression systems, yielding valuable insights into both component- level performance and environmental aspects. The component analysis identified compressors as the dominant source of exergy destruction, accounting for 56–62% of total losses, followed by the condenser, while the expansion devices contributed negligibly (0.4–0.5%). In terms of refrigerant performance, R141b, R123, and R245ca exhibited superior thermal performance, whereas the environmentally friendly HFO refrigerants such as R1234ze(E) and R1234yf demonstrated comparable efficiency to conventional refrigerants, making them promising sustainable alternatives. The system exergy efficiency was found to range between 36.67% and 42.42**%**, with total exergy destruction varying from 1.47 kW to 1.89 kW, emphasizing the importance of refrigerant selection and temperature optimization for achieving higher system performance.

Governing Equations:

General exergy destruction: $\dot{E}x_D = \dot{E}x_{in} - \dot{E}x_{out} + \dot{W}$

System COP: $COP = \dfrac{Q_{evap1}+Q_{evap2}}{W_{comp1}+W_{comp2}}$

Two evaporator and a Flash Gas Chamber:

This study couples both refrigerator and air conditioner in a two-evaporator system to assess the exergy and energy performance to achieve high efficiency and energy saving. This model consists of one compressor,one condenser, expansion valve-I for the whole cycle, flash chamber, two evaporators, an individual expansion valve
for evaporator-I, and pressure regulating valve (PRV). [(2023) Khatoon, S. and Karimi, M.N]

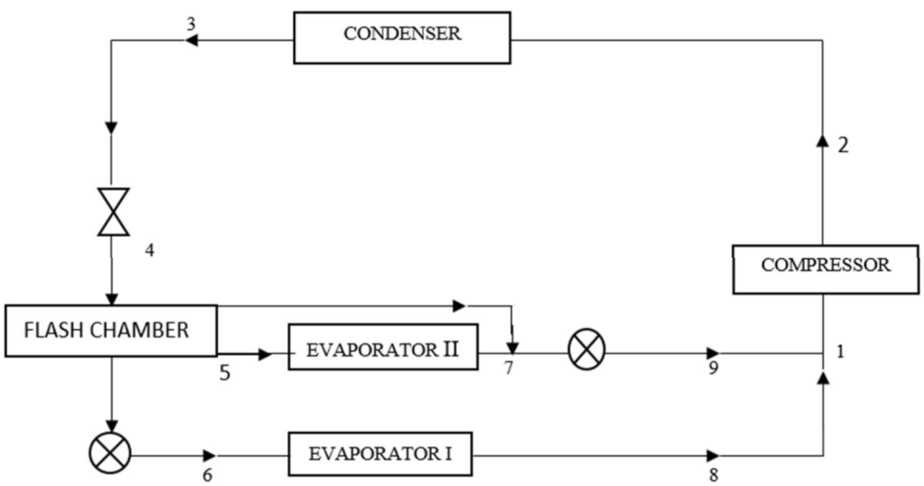

Fig3: schematic diagram two evaporator and a flash gas chamber [(2023) Khatoon, S. and Karimi, M.N]

The most recent study examined two-evaporator systems with flash chambers specifically designed for automotive applications, addressing the integration of refrigeration and air conditioning in vehicles.[4]

The key research achievements highlight significant advancements in refrigerant optimization, system integration, and component-level analysis. Among the studied refrigerants, HFO1336mzz(Z) emerged as the most efficient, achieving a COP of 2.47 and an exergy efficiency of 31.50%, thereby outperforming the widely used R134a in both energy and exergy terms. In terms of system integration, the study successfully demonstrated the feasibility of eliminating separate air-conditioning and refrigeration units, resulting in an overall COP improvement of 2.34–2.62%, which signifies enhanced energy utilization and reduced system complexity. Furthermore, the component contribution analysis revealed that the flash chamber accounted for 9.38–11.84% of the total exergy destruction, while the compressors continued to be the major source of irreversibility, contributing between 56% and 62% of total system losses. These findings collectively emphasize the potential of advanced refrigerants and integrated configurations in improving the performance and sustainability of vapor compression systems.

Governing Equations General Exergy destruction :

$$ExD,FC = \dot{m}(h3 - Ta \cdot s3) - [(\dot{m}2 + \dot{m}1)(h5 - Ta \cdot s5) + \dot{m}3(h7 - Ta \cdot s7)]$$

System COP :

$$COP = Qev,I + Qev,II/Wcomp$$

Efficiency :

$$5ex = 1 - ExD,total/Wcomp$$

Multi-Evaporator with Ejector

The first cycle (CYC1) employs ten components: a compressor, an ejector, a gas cooler, two separators, two evaporators, and three expansion devices. The refrigerant vapor at state 1 at low pressure and temperature is compressed to the gas cooler pressure. The fluid leaving the compressor at state 2 enters the gas cooler where it cools to state 3 by rejecting heat to the surroundings. The fluid at state 3 enters evaporator 1 via expansion device 1 between states 3 and 4. The two-phase refrigerant from evaporator 1 at state 5 is separated into two tributaries: the vapor refrigerant at state 6 flows to the ejector, and the liquid refrigerant at state 14 flows to expansion device 2 and mixes with liquid from separator 2 via expansion device 3. Thus, the two evaporators have different matching evaporation temperatures. The fluid entering evaporator 2 is vaporized from state 16 to state 7 and produces cooling effect by absorbing heat from the refrigerated space. The primary flow (state 6) and the secondary flow (state 7) are going through primary and secondary nozzles, respectively, to the constant pressure mixing and diffuser sections of the ejector and then separated in forms of vapor (state 1) and liquid (state 12). [(2010) Sarkar, J.]

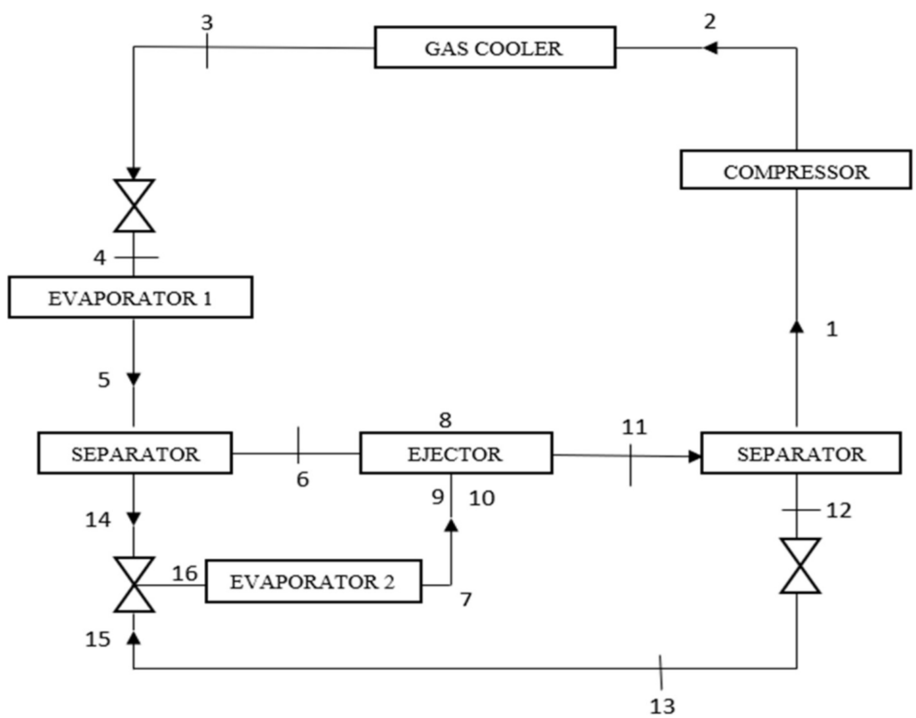

Fig4: schematic diagram of multi-evaporator with ejector[(2010) Sarkar, J.]

The second cycle (CYC2) employs nine components: a compressor, an ejector, a gas cooler, a separator, two evaporators, and three expansion devices. Evaporator 1 has a higher evaporation temperature, and the saturated vapor leaving evaporator 1 is used as the ejector motive fluid (state 6) to compress the refrigerant vapor leaving evaporator 2 (state 7), increasing the suction pressure of the compressor and decreasing the pressure ratio and work of the compressor. The refrigerant exiting from ejector (state 11) separates in forms of vapor and liquid. The vapor enters the compressor at low pressure at state 1 and is compressed to the high-side pressure at state 2. The fluid enters the gas cooler where it cools to state 3 by rejecting heat to the surroundings. Then the refrigerant is divided into two flows: one enters evaporator 1 after a pressure reduction in the expansion device 1 (state 4) and gives useful cooling effect by evaporating (states 4–6); the other mixes with expanded liquid from separator (states 12 and 13) after a pressure reduction in expansion device 2 (states 3–5) and then enters evaporator 2 at state 14 to give useful cooling effect at lower temperature.

For CYC1 and CYC2, respectively, flow through the expansion devices gives:

$$h_3 = h_4 \quad h_{12} = h_{13} \quad h_{14} = h_{15}$$

$$h_3 = h_4 = h_5 \quad h_{12} = h_{13}$$

Energy balance in separator 1 for CYC1 gives:

$$h_5 = (1 - m_1)h_6 + m_1 h_{14}$$

Based on the above assumptions, the following energy balance equations can be set up in the primary and secondary nozzle sections of the ejector:

$$h_6 = h_8 + \frac{u_8^2}{2}$$

$$h_7 = h_9 + \frac{u_9^2}{2}$$

Exit areas of primary and secondary nozzles are given by:

$$a_8 = \frac{1 - m_1}{\rho_8 u_8}$$

$$a_9 = \frac{m_1 + m_2}{\rho_9 u_9}$$

The ejector geometric area ratio is given by:

$$\varphi = \frac{a_8 + a_9}{a_9}$$

The following momentum and energy equations in the constant pressure mixing section of ejector can be identified:

$$(1 + m_2)u_{10} = (1 - m_1)u_8 + (m_1 + m_2)u_9$$

$$h_{10} = \frac{1 - m_1}{1 + m_2}\left(h_8 + \frac{u_8^2}{2}\right) + \frac{m_1 + m_2}{1 + m_2}\left(h_9 + \frac{u_9^2}{2}\right) - \frac{u_{10}^2}{2}$$

For the diffuser section, the energy balance is given by:

$$h_{11} = h_{10} + \frac{u_{10}^2}{2}$$

The overall energy balance in the ejector is given by:

$$(1 - m_1)h_6 + (m_1 + m_2)h_7 = (1 + m_2)h_{11}$$

The entrainment ratio can be obtained as follows:

$$\mu = \frac{m_1 + m_2}{1 - m_1}$$

Energy balance in separator 2 for both CYC1 and CYC2 gives:

$$(1 + m_2)h_{11} = h_1 + m_2 h_{12}$$

Energy balance in mixing for CYC1 and CYC2, respectively, gives:

$$(m_1 + m_2)h_{16} = m_1 h_{15} + m_2 h_{13} \quad (m_1 + m_2)h_{14} = m_1 h_5 + m_2 h_{13}$$

Compressor discharge enthalpy for both cycles can be found by:

$$h_2 = h_1 + \frac{h[p_{co}, \text{entropy}_1] - h_1}{\eta_c}$$

The compressor work for both CYC1 and CYC2 can be found by:

$$w_c = (h_2 - h_1)$$

For CYC1, the cooling capacities are given by:

$$q_{ev1} = (h_5 - h_4)$$

$$q_{ev2} = (m_1 + m_2)(h_7 - h_{16})$$

For CYC2, the cooling capacities can be found by:

$$q_{ev1} = (1 - m_1)(h_6 - h_4)$$

$$q_{ev2} = (m_1 + m_2)(h_7 - h_{14})$$

The cooling COP of both CYC1 and CYC2 can be calculated by:

$$COP = \frac{q_{ev} + q_{ev2}}{w_c}$$

It can be noted that the configurations of corresponding basic expansion cycles of CYC1 and CYC2 are not the same. However, the values of cooling COP will be the same for both cases and given by:

$$COP_b = \frac{h_1 - h_3}{h_2 - h_1}$$

The COP improvement using ejector has been evaluated by:

$$COP_i = \frac{COP - COP_b}{COP_b}$$

CONCLUSION:

Multi-evaporator vapor compression refrigeration systems (MERS) have emerged as a practical and efficient solution for applications requiring multiple temperature zones, such as supermarkets, hotels, and cold storage facilities. By using multiple evaporators within a single system, MERS provide improved temperature control, enhanced energy utilization, and reduced overall power consumption compared to conventional single- evaporator systems.

The review highlights that the main sources of inefficiency in these systems are compressors and condensers, while modern enhancements such as flash chambers, ejectors, and multi-stage compression significantly improve both COP and exergy efficiency. The selection of suitable refrigerants also plays a vital role in system performance and environmental impact. Low-GWP and zero-ODP refrigerants, particularly the new generation of HFOs like R1234yf and R1234ze(E), have shown strong potential to replace traditional refrigerants such as R134a without major efficiency losses. Furthermore, the integration of advanced control strategies, including model predictive and decentralized control, has enhanced the precision and stability of MERS operation. Future research should focus on hybrid systems combining ejectors or absorption cycles, intelligent control algorithms, and environmentally sustainable refrigerants to further improve performance and reduce energy consumption.

Overall, multi-evaporator systems represent a significant step forward toward energy- efficient and eco-friendly refrigeration technologies, aligning with global efforts to reduce electricity use and environmental impact in the cooling industry.

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