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バージョン：

Application of Single Flow Multicomponent Fluid Ejector Refrigerating Systems for Deep Freezing and Storage

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Abstract: *The growing mass-market demand for frozen food products is of a key interest of retailers targeting the consumers with limited income and out of rich for culinary delights, who represents a majority in the modern society. In spite, the food deep freezing is itself an expensive and energy intensive process that contradicts the idea to feed the low-income customers.*

This study provides an analysis of multicomponent ejector systems application with single flow cycle as an alternative method for affordable deep freezing at the expense of exhaust or renewable heat. The presented thermodynamic cycles and economical characteristics of both vapor compression and ***Multicomponent Ejector Refrigerating Systems (MERS)*** *speak in a favor of the last one considering its high reliability and durability, absence of lubrication, low or medium grade heat operation instead of expensive high grade electricity etc. MERS serves to decrease the energy consumption for deep freezing by minimizing cost of the system, since condensers and evaporators at each stage operate at the same pressure levels. The main disadvantages - high heat input to vapor generator and condenser is compensated by low cost and wide availability of the low grade or renewable heat source that in combination with high exergy COP and lower installation and maintenance costs make the multicomponent fluid ejector refrigerating system the promising technology in the long run.*

Keywords: ejector, refrigeration, COP, efficiency, fractionating condensation.

1. INTRODUCTION

Though the vapor compression refrigerating systems are leading the cold generation market their efficiency has reached its maximum limits already, but still consume an expensive electricity. While the all-growing cooling and refrigeration share in the energy mix composes up to 20% of total energy consumption [1,2], a search for alternative technology for deep freezing is one of the possible ways to decrease the overall power consumption. In order to apply the alternative sources, the new technology should be developed an demonstrated as a competitive method to existing refrigerators and freezers.

Regarding a global warming, when the ambient temperature every year exceeds the record temperatures of the same day of the previous years, the problem of condensate heat rejection becomes more and more critical.

When the ambient temperature reaches up to 45°C in the shades and lasts for 10-15 days. all refrigerating systems designed for extreme ambient temperatures of 38-40°C reduced their productivity at least by 1.5-2 times. The low-temperature single stage systems fail to generate cooling capacity due to a limit in compressor volumetric characteristics. In this case it make sense to utilize a single flow cascade ejector system operating on mixtures of several refrigerant fluids, where working fluid has low pressures at condensation temperature 50-60°C. Condensation of other components in the lower cascades is provided by cold produced on the upper stages. At the same time, small amount of water can be used for refrigerant fluid condensation at lower temperatures. After that it heated up in the fractionating condenser and used for domestic applications. Today, such systems are not well introduced on the market, but they seem to have an extremely promising potential, due to its ability to self-regulate and manufacturing/operation simplicity and no friction, lubrication, high end compression temperatures, oil separation after compressor issues. They practically does not require maintenance since they do not have moving parts. The history of such systems starts from Kleemenko cycle [3] and its ejector based modification [4]. Kleemenko cycle well known and widely used, ejector based system is on study stage of its explicit and hidden possibilities.

2. PRINCIPLES AND CYCLE OF MULTICOMPONENT EJECTOR REFRIGIRATING SYSTEM.

2.1 Schema and Thermodynamic cycle of MERS

By analog with the Kleemenko cycle a number of refrigirants are used in single flow. For a single stage, in order to obtain temperature characteristic of modern

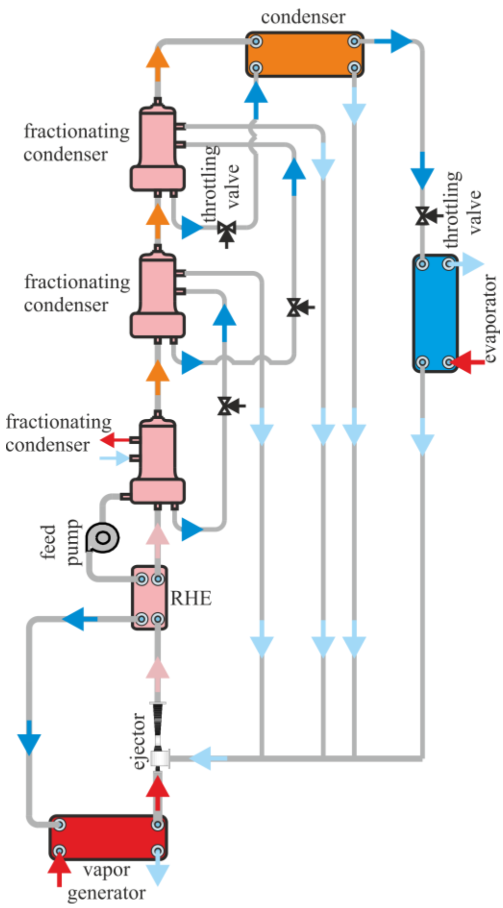

Fig. 1. MERS without recuperation.

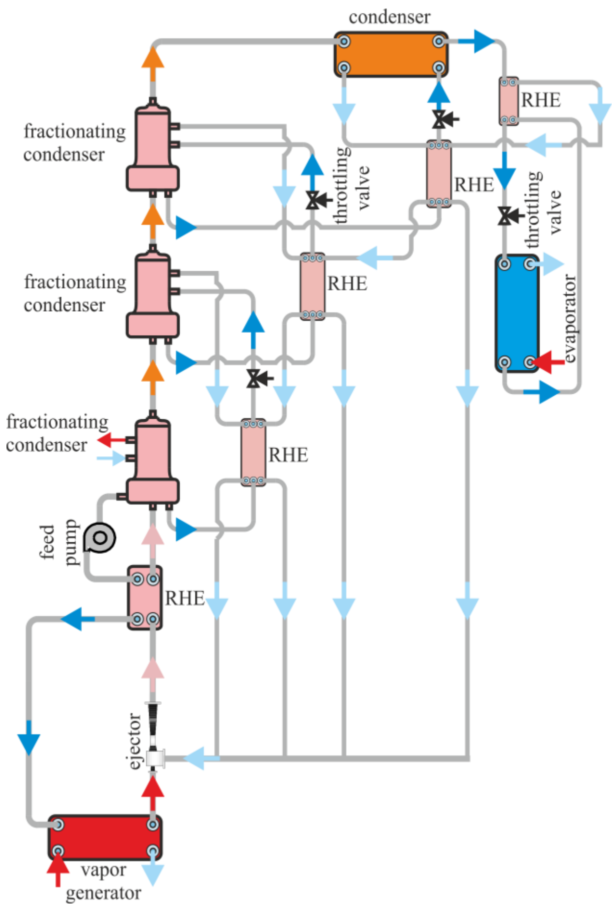

Fig. 2. MERS with full recuperation.

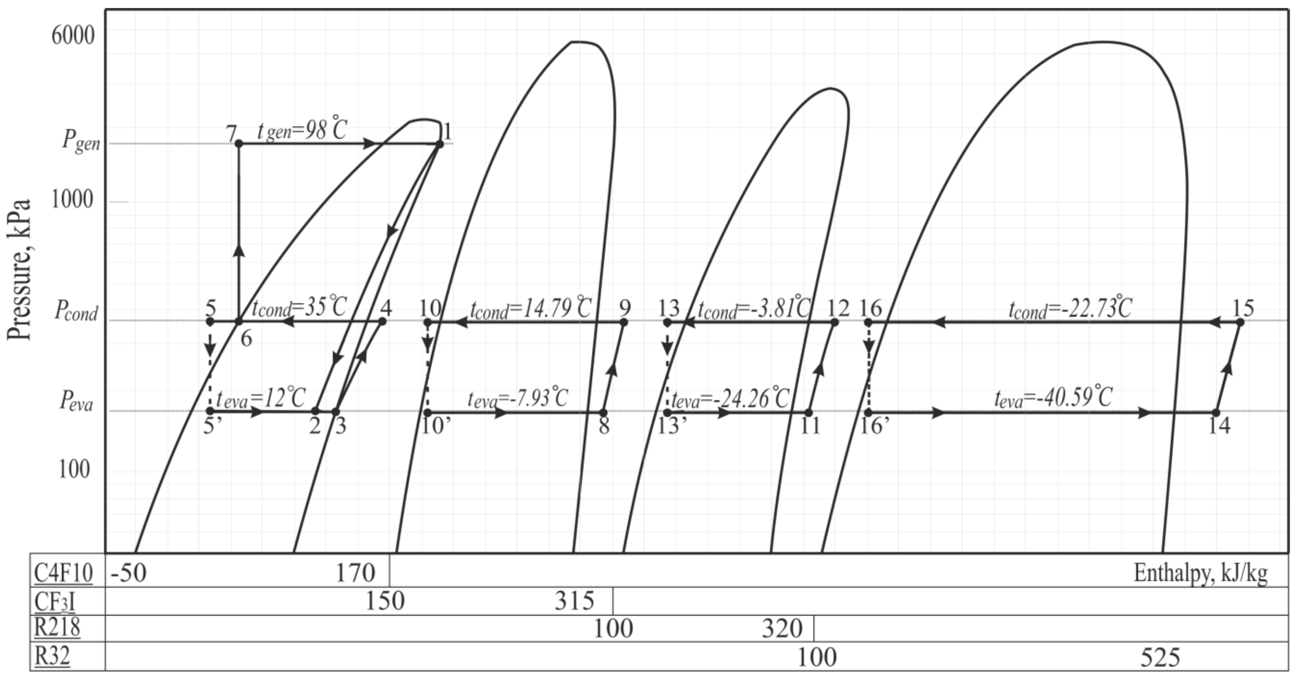

Fig. 3. P-H diagram of thermodynamic cycle of MERS. 1–2, working vapor expansion in the ejector's nozzle; 3–4, working vapor compression in the diffuser part of the ejector; 4–5, working vapor condensation at the fractional condenser; 6–5, condensate supercooling at the recuperative heat exchanger; 50–3, working vapor evaporation at the evaporator of the second fractional condenser; 5–50, working liquid throttling; 6–7, liquid feeding to the vapor generator by a feeding pump; 7–1, liquid heating and its evaporation in the vapor generator; 8–9, 11–12 and 14–15, compression of the refrigerant vapor mixtures in the ejector's diffuser; 9–10, 12–13 and 15–16, compressed vapors condensation and supercooling of the condensate at the specified condensers– evaporators and recuperative heat exchangers; 10–100, 13–13 0 and 16–160, refrigerant liquid throttling; 10–8, 13–11 and 16–14, evaporation of the refrigerant liquid in the specified condensers–evaporators and superheating of vapors in the recuperative heat exchangers

refrigerating system, it is sufficient to used 4 components.

Compared to Kleemenko cycle where all components perform purely refrigerating processes, in the ejector system it is necessary that one substance perform simultaneously two cycles power and refrigerating. Other refrigerants perform refrigerating cycle. The working fluid is selected from high molecular fluids, that have low sound speed. Each subsequent component should have same condensation and evaporation pressures with a minimum temperature difference. During condensation of each component other will pass transit as non-condensed vapors though heat exchangers. Figure 1 represents basic schema of Multicomponent Ejector Refrigerating System. Figure 2 represents Multicomponent Ejector Refrigerating System with full recuperation. Thermodynamic cycle of MERS without recuperation is shown on Fig. 3.

Table 1 represents a sets of fluids at selected operating conditions.

Table 1. Set of fluids for MERS

Pressure, kPa	Temperature, °C			
Fluids	RC318	DME	Propane	R32
Generation, 1969.67	98	-	-	-
Condensation, 425.147	35	14.1	-3.5	-18.8
Evaporation, 201.74	12	-7.7	-25.2	-37.1
Pressure, kPa	Temperature, °C			
Fluids	R245fa	Butene	R134a	R22
Generation, 1209.299	98	-	-	-
Condensation, 211.715	35	14.3	-8.6	-23.8
Evaporation, 89.165	12	-9.5	-28.8	-43.5
Fluids	C4F10	CF3I	R218	R32
Generation, 1713.932	98	-	-	-
Condensation, 365.591	35	14.8	-3.8	-22.7
Evaporation, 172.749	12	-7.9	-24.3	-40.6
Fluids	R1233zd	Butane	R227ea	R1234yf
Generation, 997.812	98			
Condensation, 183.088	35	16.2	-1.7	-15.1
Evaporation, 79.269	12	-6.8	-21.9	-34.9

2.2 MERS efficiency evaluation

Calculation of the MERS system based on binary fluid ejector efficiency evaluation with the following assumptions:

1. Properties of mixture is calculated additively;
2. Heat of components mixing in ejector is neglected.

Figure 4 represents a schematics of the calculation algorithm:

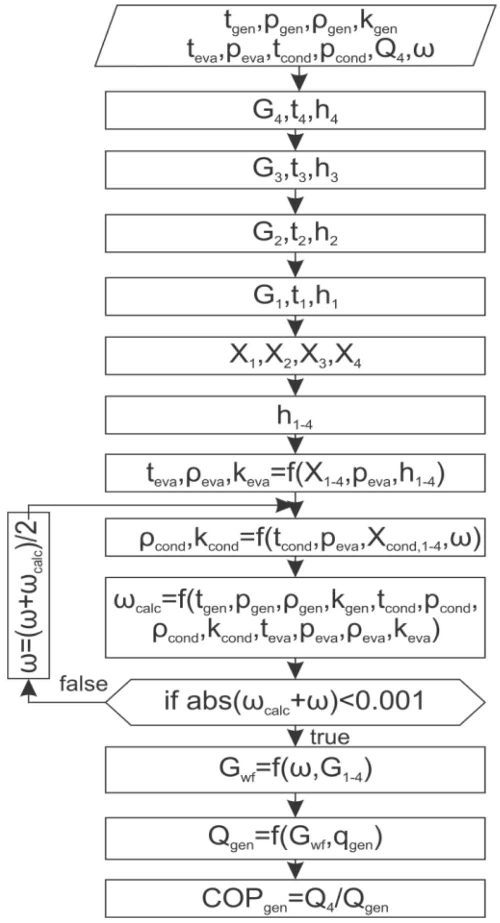

Fig. 4. MERS efficiency evaluation. t – temperature, °C, p – pressure, kPa, ρ – density, kg/m^3, G – mass flow rate, kg/s, ω – entrainment ratio, gen, eva, cond – parameters in generator, evaporator and condenser, 1-4 – number of fluids, X – mass fraction, Q – heat load, kW, Q_4 – cooling capacity.

1. Selected working fluid and refrigerant fluids in order that condensation temperature of upper stage fluid is slightly higher that evaporation temperature of bottom stage fluid;
2. Specified cooling capacity evaluate fluids mass flow rate based on energy balances in heat-exchangers;
3. Calculate mixture properties based on mass fractions, specific properties after each heat exchangers and after ejector using REFPROP 9.1 [5];
4. The entrainment ratio is described as a function of temperatures, pressures, volumes, adiabatic indexes, critical sound speed and main dynamic functions Π, λ, γ [4, 6]. The entrainment ratio is determined by Equation 1.

$$\omega = \frac{K_1\left(a^{wf}_{gen,*} / a^{mix}_{cond,*}\right)\lambda_{pн} - K_3\lambda_{cond,C}}{K_4\lambda_{cond,C} - K_2\left(a^{rf}_{eva,*} / a_{cond*}\right)\lambda_{eva,B}} \qquad (1)$$

where:

$$K_1 = \varphi_1\varphi_2\varphi_3 = 0.834\,,\ K_2 = \varphi_2\varphi_3\varphi_4 = 0.812$$

$$K_3 = 1 + \frac{\Pi_{cond,C} - \dfrac{P^{rf}_{eva}}{P^{mix}_{cond}}\left\{\beta - \dfrac{(\beta-1)}{2}\Pi_{eva,B}\left[1+\left(\dfrac{P^{mix}_{cond}}{P^{rf}_{eva}}\right)^{1-\alpha}\left(\dfrac{\Pi_{cond,C}}{\Pi_{eva,B}}\right)^{1-\alpha}\right]\right\}}{\left(\dfrac{1}{\varphi_3}\dfrac{a^{mix}_{cond,*}}{a^{wf}_{gen,*}}\dfrac{P^{wf}_{gen}}{P^{mix}_{cond}}\right)k_{gen}\Pi_{gen,*}\lambda_{cond,C}\gamma_{gen,A}\beta}$$

$$K_4 = 1 + \frac{\Pi_{cond,C} - \Pi_{cond,B}\left\{\beta - \dfrac{(\beta-1)}{2}\left[1+\left(\dfrac{P^{mix}_{cond}}{P^{rf}_{eva}}\right)^{1-\alpha}\left(\dfrac{\Pi_{cond,C}}{\Pi_{eva,B}}\right)^{1-\alpha}\right]\right\}}{\left(\dfrac{1}{\varphi_3}\dfrac{a^{mix}_{cond,*}}{a^{rf}_{eva,*}}\dfrac{P^{rf}_{eva}}{P^{mix}_{cond}}\right)k_{eva}\Pi_{eva,*}\lambda_{cond,C}\gamma_{eva,B}\beta}$$

$$\lambda = \sqrt{\frac{k+1}{k-1}}\sqrt{1-\Pi^{\frac{k-1}{k}}}\ ,\ \gamma = \sqrt{\frac{k+1}{k-1}}\left(\frac{\Pi}{\Pi_*}\right)^{\frac{1}{k}}\sqrt{1-\Pi^{\frac{k-1}{k}}}$$

$$\varphi_1 = 0.95, \varphi_2 = 0.975, \varphi_3 = 0.9, \varphi_4 = 0.925, \alpha = 0.5, \beta = 2$$

3. COMPARATIVE ANALYSIS OF COMPRESSOR AND EJECTOR BASED CYCLES

Single stage vapor compression systems were selected for the comparison. In the most cases, the natural refrigerants like ammonia, propane, or mixtures were selected to be used in refrigerating machines. In first case, systems with condensation temperatures 35°C vapor compression systems operates with high efficiency (Table 2,3). VCRS efficiency evaluated using CoolPack [7]. Reduced COP of the VCRS is calculated by eq. 2

$$COP_{red} = COP * \eta_{Carnot} \qquad (2)$$

where:

$$\eta_{Carnot} = 1 - T_{cond} / T_{gen} = 1 - 308.15 / 371.15 = 0.169$$

Table 2. COP of the VCRS at t_{cond}=35°C, Q_{eva}=1kW

Fluid	t_{eva}, °C	W_{comp}, kW	Q_{cond}, cond	COP	COPred
R404a	-35	0.681	1.681	1.47	0.249
R404a	-37.1	0.717	1.717	1.39	0.236
R404a	-40.6	0.783	1.783	1.27	0.216
R404a	-43.5	0.840	1.840	1.19	0.202
R290	-35	0.609	1.609	1.64	0.278
R290	-37.1	0.640	1.640	1.56	0.265
R290	-40.6	0.695	1.695	1.44	0.244
R290	-43.5	0.742	1.742	1.34	0.228
R717	-35	0.586	1.586	1.70	0.289
R717	-37.1	0.616	1.616	1.62	0.275
R717	-43.5	0.713	1.713	1.40	0.238
R717	-40.6	0.668	1.668	1.49	0.254
R22	-35	0.587	1.587	1.70	0.289
R22	-37.1	0.616	1.616	1.62	0.275
R22	-40.6	0.666	1.666	1.50	0.254
R22	-43.5	0.710	1.710	1.40	0.239

Table 3. COP of the MERS at t_{cond}=35°C.

Fluids	t_{eva}, °C	Q_{gen}, kW	$Q_{gen,rec}$, kW	COP	COP_{rec}
RC318 DME Propane R32	-37.1	10.41	7.93	0.096	0.126
R245fa Butene R134a R22	-43.5	11.23	9.34	0.089	0.107
C4F10 CF3I R218 R32	-40.6	14.92	12.19	0.067	0.082
R1233zd(E) Butane R227ea R1234yf	-34.9	12.05	9.09	0.083	0.11

Comparison analysis has shown that MERS requires up to 3-4 times higher heat rejection than in VCRS. At the same time, MERS consumes only low-grade heat Comparing the price for compressor and additional units like oil separator, oil filters, etc. to ejector is 100:1, and with thermopump is about 40:1. Fractionating condensers is vertical oriented units, that occupies small area. Taking into account high heat and mass transfer characteristics of the fractionating condenser its mass and dimensional characteristics as the same in VCRS. Operating at higher condensation temperatures 55°C which corresponds 45°C ambient temperatures, is serious problem for compressor on a number of the refrigerants. The volumetric and energy efficiencies of the compressor decreases significantly. Secondary, for some fluids high compression temperature is obtained.

For complicated operating parameters, single stage VCRS is not suitable for all refrigerants. Switching two stage system is not practical because beyond the critical operating parameters the second stage is not needed for the great part of the cold period and off-season. The same problem for cascade system, its full time work is short and is necessary a lot of additional expensive equipment. Table 4 represents efficiencies of VCRS and MERS for 55°C condensation temperature.

Table 4. COP of the VCRS and MERS at t_{cond}=55°C, Q_{eva}=1kW

Fluids	t_{eva}, °C	W_{comp}, kW	Q_{gen}, kW	COP_{rec}	COP_{red}
R123 Butane R161	-50	-	31.25	0.038	-
R1233zd Butane R161	-42.7	-	33.3	0.03	-
R290	-40	1.069	-	0.93	0.13
R404a	-40	1.429	-	0.69	0.10
Propylene	-40	1.05	-	0.95	0.13

Fluid selection for MERS requires analysis not only P-T data, but P-T-X properties of mixtures since fluid separation after ejector is important for system operation. Example of T-X diagram represented on Fig 5a and Fig 5b. Black line shown how many plates in fractionating condenser is required to separate fluids.

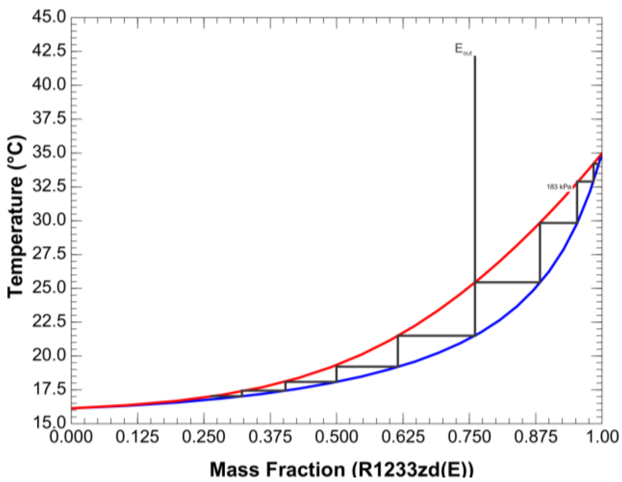

Fig. 5a. T-X diagram for R1233zd(E)/Butane

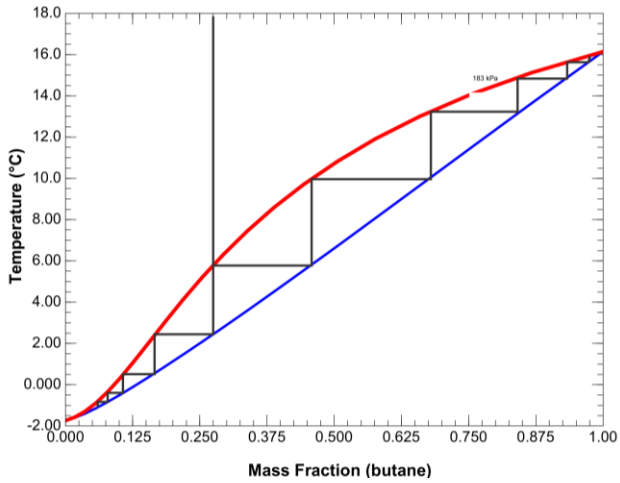

Fig. 5b. T-X diagram for Butane/R227ea

4. CONCLUSIONS

1. MERS is a competitive to VCRS in range t_{cond}=35°C, t_{eva}=-45°C, but requires additional study.
2. It is necessary to use additional energy for example hot water. That simultaneously solves the problem of compactness of units and reduces the total cost of production.
3. The search of new substances that can be used for MERS can significantly improve their efficiency and simplify the working schemas

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