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ABSTRACT

This article describes one of the solutions of fresh water production by the combined distillation and congelation method at a single heat input (any type of low grade renewable or exhaust heat). While the distillation can be driven by solar thermal or, in certain cases, natural gas combustion heat, the congelation processes performed by the Binary Fluid Ejector Refrigerating System (BERS) at the expense of low grade heat only. Steam from the distiller condenses in the vapor generator and drives Binary Fluid System that produces cold in the ice generator. The congelation process is carried out in a time-dilated manner and with pressure regulation of the freezing ice-salt mixture to obtain the salt concentration in the produced fresh water. In this case, a temperature head in the ice-generating system is minimum, so that the crystallization process approaches a quasi-static state. Freezing is carried out in a multistage way; further water treatment is processed by mixing of the potted water with a distillate. A water desalination is preceded by its liberation from deuterium and tritium ions. Low temperatures in the BERS can be obtained in the two-stage system design. Also, binary fluid mixtures allow increasing the system's efficiency by changing the components' concentration in the evaporator and generator of the BERS.

1. INTRODUCTION

Continuous decrease in fresh water availability is a result of human activity, ever-increasing population, environment pollution that leads also to expansion of the arid zone and, finally, global warming consequences. Such challenges force the humanity to search for the most reasonable ways to produce fresh water in conformity with health standards and quality. Obviously, the fresh water production is a very expensive and energy intensive process that does not always lead to a desired result. Water quality after reverse osmosis leaves much to be desired since membranes pass molecules of "heavy water" and increase its concentration comparing to the initial composition in the solution. Distillation completely releases water from vital minerals that does not allow to use it as drinking water for people, animals and plants. The processes of water congelation and melting were still considered cost inefficient to be suitable for desalination of water with high salt concentrations. This paper offers an approach towards a congelation process, which brings a 9 times decrease of fresh water cost compared to existing technologies, improving its quality to the requirements of the most stringent standards and producing tons of fresh water at the expense of the available natural renewable energy – solar thermal.

2. NOVEL COMBINES DISTILLATION SYSTEM USING EJECTOR THERMOTRANSFORMERS

All conventional distillation systems provide a multistage distillation of salty water by the consequential reducing of the evaporation pressure to 0.05-0.1 bar. This leads to significant heat savings, but at the same time boosting the electric power consumption for vacuum and water pumps, thus increasing capital, operation and maintenance costs. Vapor generator of Binary Fluid Ejector Refrigeration System (BERS) can be included in the distillation system to utilize the excess heat of distillation process (see Fig. 1)

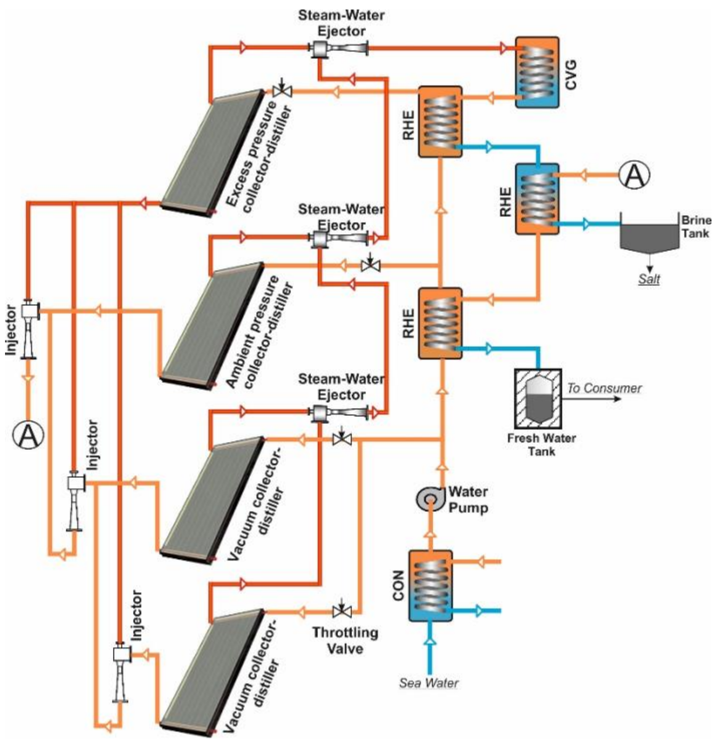

Figure 1: Multistage Solar jet water distillation/heating system with heat recuperation. CVG – Condenser Vapor Generator of BERS, CON – BERS Condenser, RHE – Recuperative Heat Exchanger

The solar thermal highest temperature heat is supplied to the vapor generation, where the working fluid is evaporated, and the vapor is directed to the nozzle of the ejector that produces vacuum with no electricity consumption. Also, injectors ensure circulation of the fresh water condensate, primary salt or waste water and brine concentrate. Number of stages depends on the designed vacuuming processes, brine pumping rates and should not exceed sum of consumed heat for 1 cycle of water evaporation. So, the specific heat for distillation equals to $q=r/n$. In this way, the heat consumption for distillation could be minimized by 5-10 times.

The system tolerates any type of seawater (3k ≤ TDS ≤ 100k) and operates with solar thermal heat of 170-180°C. BERS produces cold that is utilized for sea water congelation and then freezing of the fresh ice. Schematic of the combined system with water distillation and freezing is represented on Fig. 2.

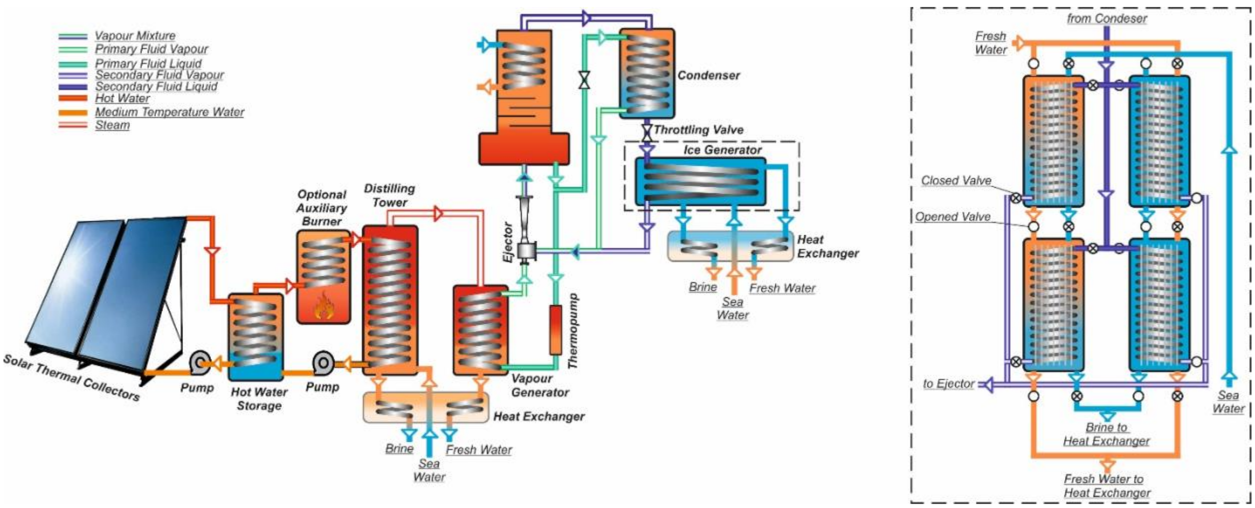

Figure 2: Diagram of Binary Fluid Ejector Refrigerating System designed for cold generation and fresh water production using distillation with simultaneous congelation (patent pending).

First stage provides freezing and removing of "heavy water" at 3.8°C. Second stage ensures freezing of the first portion of water in the ice generator on the outer side of which a slow freezing on a thin crust of ice occurs. After that, the unfrozen solution merges into the next ice generator and formed ice defrosts by cooling the counterflow of cooled solution. Cold recuperation in system reaches 80-90%, that can be achieved by small temperature differences at the end of heat exchangers and quasi-static nature of the process. It means that the recuperation processes in the combined distillation/congelation system with BERS enable reducing the heat consumption for fresh water production down to 150-200kJ/L.

Density of water surface is defined by the Mamaev's equation (Mamaev, 1970):

$$\rho = 1 + 10^{-3}\left[28.152 - 0.0735 t_w - 0.00469 t_w^2 + \left(0.802 - 0.002 t_w\right)\left(S - 35\right)\right] \qquad (1)$$

Increasing of the salinity leads to increasing of the sea water density. As a result, an absolute value increases and its maximum shifts to lower temperatures comparing to clean water.

Second, premixtures in water leads to changes of water freezing temperature and can be defined from eq. 2:

$$\frac{dT_K}{dS_M} = -\frac{k_B N_A T_K^2}{\eta_w - \eta} \qquad (2)$$

Solution of eq. 2 represented in eq. 3

$$t_{sw}=-\frac{k_B N_A T_F^2 S_M}{(\eta_w-\eta)\left(1-\dfrac{k_B N_A T_F S_M}{\eta_w-\eta}\right)}\approx-\frac{k_B N_A T_F^2}{\eta_w-\eta}\left[S_M-\frac{k_B N_A T_F S_M^2}{\eta_w-\eta}+\frac{1}{2}\left(\frac{k_B N_A T_F}{\eta_w-\eta}\right)^2 S_M^3-\dots\right] \quad (3)$$

Since it is difficult to define molar concentration of premixtures in sea water, relative concentration is used and defined by empirical Krummel's equation 4

$$t_{sw}=-10^{-3}\left(3+52.7S+0.04S^2+0.0004S^3\right) \quad (4)$$

Equation 4 is close to theoretical eq. 3, which is strict for weak solutions, but has a free term that proves actual ice formation at partial subcooling. Equations 3 and 4 are valid for atmospheric pressure. Equation of state for water specific volume is shown in eq. 5

$$v_w=v\left(t_w,S,P\right) \quad (5)$$

At the ambient pressure the specific volume depends only from temperature and salinity. If v_w equals to γ only two variables remain in the equation of state– salinity and freezing temperature. The variable pressures and freezing temperatures can be defined by eq. 6

$$\frac{dP}{dt_{sw}}=\frac{1}{t_{sw}}\frac{\eta_w-\eta_g}{v_w-v_g} \quad (6)$$

The experimental data shows that the main mass of brine separates from the ice during it generation, when the ice layer is thin, its temperature in relatively high and also during the defrosting process. The mass of liquid increases in ice if its temperature is increasing. The adhesions between the crystals break down, the ice becomes spongy and the pores open over the brine flows. Minimal salinity of ice can be defined by eq. 7 (Doronin & Heysin, 1975):

$$s_{\min}=\frac{\pi r^2\rho_b j}{A\rho}S \quad (7)$$

Cold consumption in the proposed technology is determined by under recuperation losses, common insulation deficiencies and can be estimated in a range of 32-64 kJ/kg of fresh water. As result, heat consumption for cold production equals 115-230 kJ/kg for BERS (calculated for binary fluid R11/Butane at t_{gen}=150°C, t_{cond}=25-50°C, t_{eva}=-4°C).
Equations 8-10 are simplified equations to determine an amount of the fresh produced water:

$$G_{sum}=G_{distil}+G_{ref} \quad (8)$$

$$G_{dist}=Q_{cons}n/r_{water} \quad (9)$$

$$G_{ref}=Q_{cons}COP_{ERS}/\left(q_{ref}e_{loss}\right) \quad (10)$$

It is possible to reduce the primary heat consumption by 2 times using the Binary Fluid Ejector Heat Pump (BEHP) as a system's component, thus for 1 kg of fresh water only 58-115 kJ of heat will be required. The energy consumption equals to less than 5% of the specific evaporation heat. It should be mentioned, that number of stages in distillation system is limited by capital cost, heat consumption for vacuum pumps. Usually optimum number of stages does not exceed 3-5.
The water production rates using the proposed technology at various cold losses are presented on Fig 3. The system's parameters were selected as follows: COP_{BERS}=0.676, q_{ref}=320kJ/kg, Q_{cons}=1 MW consumed heat, 5 stage distillation.

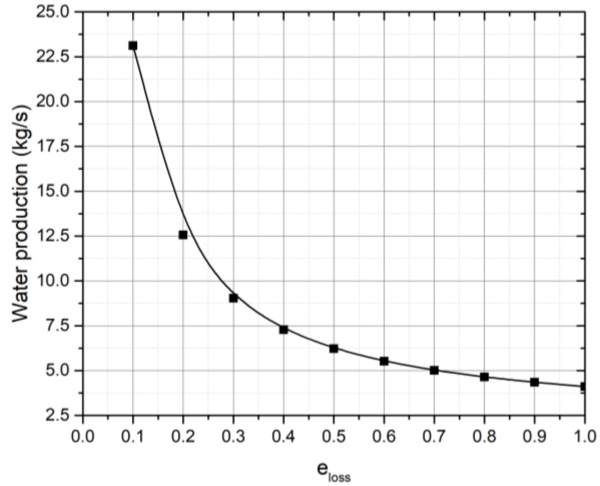

Figure 3. Water Production rate dependence from cold losses

The main focus is the combined distillation system design was made on application of solar thermal energy to make all the processes close to natural. The efficiency and capabilities of solar thermal collectors nowadays reached a very high level proving its primacy as a reliable and affordable heat source. The most efficient flat plate vacuum solar collectors are selected for the study to be integrated with the solar desalination system. Extensive thermodynamic analysis of the system performance and experimental validation of the results were the core research and development efforts to ground the current study (Bhowmik & Amin, 2017; Huang, et.al., 2001; Shepovalova, et. al., 2015).

3. BERS APPLICATION FOR MULTISTAGE DISTILLATION SYSTEM

Various systems can be used for heat transformation and cold production, but mainly they are limited to 2 major types: absorption and ejector. The LiBr-H2O and LiCl-H2O based absorption systems can be theoretically suitable to replace the BERS, since refrigerant is water and the required temperatures are lower than cryoscopic. But in reality, the water ammonia absorption chillers require high generation temperatures (above 160°C) that make it difficult to generate in a majority of solar collectors. The application of BERS with zeotropic mixtures tends to be the most promising in this case as it operates at lower temperatures and have a number of reliability, cost and maintenance advantages compared to absorption chillers. (Buyadgie, et. al. 2012; Chen, et. al. 2011; Schiichtig, 1963; Zhadan, et.al 1981). Theoretical basis of binary fluid application for the ejector refrigerating systems was developed 50-60 years ago, but BERS is yet to be commercialized up to now. All conditions for carrying out experimental testings of BERS are provided today: CFD models of binary fluid ejectors were successfully created, a new type of the thermopump, simple reliable and economical fractionating condenser were designed and tested (see Fig. 5).
The selected binary fluid components with "tailored" properties made it possible to design BERS operating in various modes, from air-conditioning and refrigeration to congelation and cryogenic temperatures.
COP of the Binary Fluid Ejector Refrigerating System and Binary Fluid Ejector Heat Pumps is defined by eq. 11 and eq.12:

$$COP_{BERS}\frac{Q_{eva}}{Q_{gen}}=U\frac{q^{rf}_{eva}-q^{rf}_{cond}}{q^{wf}_{gen}-q^{wf}_{cond}} \quad (11)$$

$$COP_{EHP}\frac{Q_{eva}+Q_{gen}}{Q_{gen}}=1+U\frac{q_{eva}-q_{cond}}{q_{gen}-q_{cond}} \quad (12)$$

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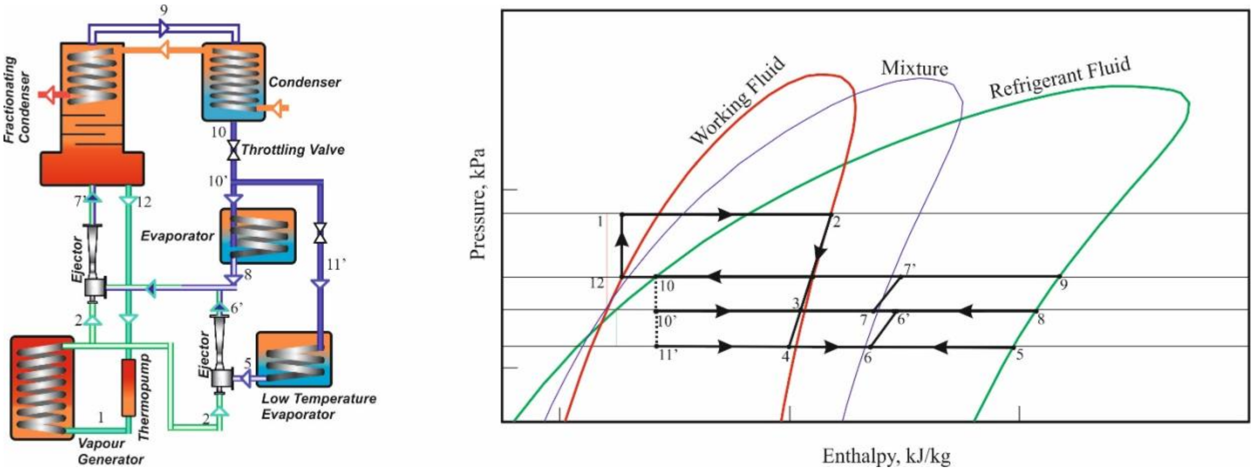

Figure 4: Schematic of two stage BERS and thermodynamic cycle diagram. 1-2 – working fluid heating and evaporation in the vapor generator, 2-3 – working vapor expansion in the upper stage ejector nozzle, 2-4 – working vapor expansion in the bottom stage ejector nozzle, 4-6 and 5-6 – working flow and refrigerant flow mixing in the bottom stage ejector confusor, 6-6' – mixture compression in the cylindrical mixing chamber, 3-7,8-7 and 6'-7– working flow and refrigerant flow mixing in the upper stage ejector confusor, 7-7' – mixture compression in the cylindrical mixing chamber, 7'-12 working fluid condensation in the fractionating condenser, 9-10 refrigerant fluid condensation, 10-10' – refrigerant fluid throttling, 10'-8 – refrigerant fluid evaporation in evaporator, 10'-11' – refrigerant fluid throttling to low temperature evaporator, 11'-5 – refrigerant fluid evaporation in evaporator,12-1 – working fluid pumping into the vapor generator.

The schematic drawings of the ejector flow part profile is shown on Figure 6.

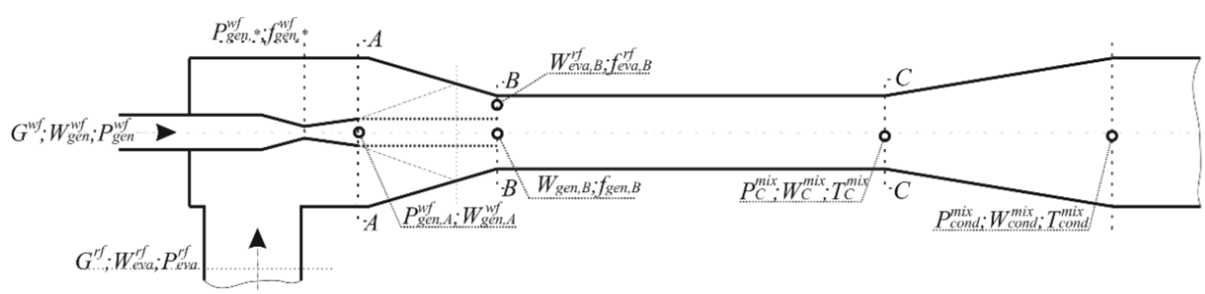

Figure 6: Schematic diagram of an ejector. (A) Nozzle outlet cross-sectional area, (B) cylindrical mixing chamber inlet cross-sectional area and (C) cylindrical mixing chamber outlet cross-sectional area

Entrainment ratio of the ejector is calculated based on modified Sokolov-Zinger method (Buyadgie et al., 2012; Sokolov & Zinger, 1989):

$$U = \frac{K_1 \left(a^{wf}_{gen,*} / a^{mix}_{cond,*} \right) \lambda_{рн} - K_3 \lambda_{cond,C}}{K_4 \lambda_{cond,C} - K_2 \left(a^{rf}_{eva,*} / a_{cond*} \right) \lambda_{eva,B}} \tag{14}$$

Where

$$K_1 = \varphi_1 \varphi_2 \varphi_3$$
$$K_2 = \varphi_2 \varphi_3 \varphi_4$$

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

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

$$\lambda = \sqrt{(k+1)/(k-1)} \sqrt{1 - \Pi^{(k-1)/k}}$$

$$\Pi = \frac{P}{P_{eva}}$$

$$\varphi_1 = 0.95, \varphi_2 = 0.975, \varphi_3 = 0.9, \varphi_4 = 0.925$$

$$\alpha = 0.5, \beta = 2$$

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

COP's of the BERS and BEHP are shown in Table 1.

Table 1: COP's of BERS and BEHP

Fluid/Mixture	**t_{gen}, °C/ (x_{wf},x_{rf})**	**t_{cond}, °C/ (x_{wf},x_{rf})**	**t_{eva}, °C/ (x_{wf},x_{rf})**	**U**	**COP_{BERS}**	**COP_{BEHP}**
R123/Butane	85(1/0)	35(0.704/0.296)	12(0/1)	0.42	0.822	-
R21/Isobutane	85(1/0)	35(0.677/0.323)	12(0/1)	0.475	0.63	-
R123/R21	85(1/0)	35(0.634/0.366)	12(0/1)	0.576	0.694	-
R11/Butane	85(1/0)	35(0.68/0.32)	12(0/1)	0.468	0.864	-
R365mfc/Isobutane	160(0.8/0.2)	90(0.71/0.29)	70(0.6/0.4)	0.68		1.6
R123/Butane	150(1/0)	90(0.76/0.24)	70(0.1/0.9)	0.352		1.66
R11/Butane	150(0.9/0.1)	90(0.67/0.33)	70(0.2/0.8)	0.483		0.688
R11/Butane	150(1/0)	35(0.69/0.31)	-4(0/1)	0.439	0.676	
R123/Butane	150(1/0)	35(0.66/0.34)	-4(0/1)	0.517	0.8	
R365mfc/Isobutane	150(1/0)	35(0.6/0.4)	-4(0/1)	0.647	0.845	

The application of the binary fluids in the ejector-based cooling systems has boosted the energy efficiency as much as 80-120% that potentially makes the binary fluid ejector system the most advanced thermally-driven heat pump ever created.

The binary fluid application in BERS allows energy losses reduction by decreasing the velocity difference between working and refrigerant fluids. Binary fluid systems unlike single fluid ones perform a power cycle with a working fluid, that consumes relatively less heat, while the reverse cycle is performed by the most efficient refrigerant fluid, which removes 2-3 times more heat from the low temperature source per refrigerant fluid unit mass. It is important to achieve the maximum entrainment ratio and the lowest ratio of the specific cooling capacity to the specific heat consumption. The contact between primary flow and the secondary flow in the ejector is required for kinetic energy and momentum transfer, which results in both fluids mixing and thereafter requires the formed binary fluid separation by the single components. In order to separate the flows, it is necessary to condense high temperature fluid (working fluid) in fractionating condenser, where, as a result of heat and mass transfer, the concentration of working fluid increases in liquid phase and refrigerant fluid - in vapor phase.

6. CONCLUSIONS

1. In the coming decades, the problem of acute shortage of fresh water can become a source of social and political destabilization worldwide. In order to prevent the conflict of interests it is necessary to create the efficient, cost-effective and environmentally safe methods of water desalination and purification.
2. One of the promising concept of an integrated approach towards the reliable process of high quality fresh water production is proposed, combining distillation and congelation driven by the renewable or exhausted heat.
3. The best thermotransformers for the combined distillation system are BERS and BEHP. The BERS has 1,5 times higher efficiency than a single fluid ERS, while the BEHP doubles the amount of consumed useful heat. In addition to the best energy and performance indicators, the combined system has the lowest price and the highest durability.
4. It is unfeasible to utilize only high-grade energy sources for desalination process, since their use is associated with the depletion of hydrocarbons and nuclear resources, the potential of hydro resources, environmental pollution, especially contamination of the natural fresh water reservoirs. Alternatively, a combined application of a simple and affordable solar thermal collectors with high temperature vacuum collectors can be successfully used to produce an unlimited amount of fresh water.

NOMENCLATURE

Acronyms

BERS	Binary Fluid Ejector Refrigerating System		
BEHP	Binary Fluid Ejector Heat Pump		
ERS	Ejector Refrigeration System		
TDS	total dissolved solids	ppm	

Symbols

$\varphi_1, \varphi_2, \varphi_3, \varphi_4$	experimental velocity coefficients		
G	flow rate	kg/s	
j	quantity of pours per area A		
K_1	integrated velocity coefficient of working flow		
K_2	integrated velocity coefficient of ejected flow		
K_3,K_4	integrated velocity coefficient		
n	number of distillation stages		
P	pressure	Pa	
Π	relative pressure		
ρ	density of water surface	kg/m^3	
k_B	Boltzmann constant		
N_A	Avogadro constant		
η_w-η	enthalpy difference of water and ice/molar crystallization		kJ/kmol
r	specific heat of evaporation	kJ/kg	
S	salinity of water	ppm	
S_M	molar concentration of salt		
t	temperature	°C	
T	temperature	K	
v	specific volume	m^3/kg	
q	specific heat	kJ/kg	
Q	heat load, kW		
e_{loss}	cold losses		

Subscript

A	nozzle outlet cross-section area
B	cylinrical mixing chamber inlet cross-section area

C	cylinrical mixing chamber outlet-cross-section area
gen	generation
cond	condensation
eva	evaporation
*	critical property
F	fresh water freezing point
sw	sea water freezing point
k	freezing point
ref	water produced be freezing
distil	distillation
cons	consumed

Subscript

mix	mixed flowoutlet cross-section area
wf	working fluid
rf	refrigerant fluid

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