L. I. Anatychuk, *acad. National Academy of Sciences of Ukraine*[1,2]
V. G., Rifert, *doc. techn sciences* [3]
P. O., Barabash, *cand. techn sciences* [3]
R. V., Desiateryk, *cand. techn sciences* [3]
A. S., Solomakha, *cand. techn sciences* [3]
Yu. Yu., Rozver [1]
V. G., Petrenko, *cand. techn sciences* [3]

[1]Institute of Thermoelectricity of the NAS and MES of Ukraine,
1, Nauky str., Chernivtsi, 58029, Ukraine,
e–mail: anatych@gmail.com
[2]Yu.Fedkovych Chernivtsi National University,
2, Kotsiubynskyi str., Chernivtsi, 58012, Ukraine
[3] National Technical University of Ukraine
“Igor Sikorsky Kyiv Polytechnic Institute”, 6 Polytechnichna str.,
Kyiv, 03056, Ukraine,
e-mail: vgrifert@ukr.net, barabash_tef@ukr.net, drv_td@ukr.net,
as_solomaha@ukr.net, petrko@ukr.net

PERFORMANCE TESTING OF A THERMOELECTRIC HEAT PUMP FOR CENTRIFUGAL DISTILLATION OF WASTEWATER OF A SPACE LIFE SUPPORT SYSTEM

The paper describes the test results of a multistage centrifugal vacuum distillation (CMED) system with a thermoelectric heat pump (THP). The paper presents the results of research on the study of the main characteristics of the process of concentrating water and urine when using three- and five-stage distillers. Particular attention is paid to studying the influence of process parameters on the change in the efficiency of a thermoelectric heat pump. Bibl. 26, Fig. 4, Tabl. 3.

Key words: heat pump, distiller.

Introduction

For future long-term human missions to the Moon and Mars, water recovery systems from life support system wastewater are critical. NASA materials note that such a system should ensure maximum recovery of water from urine, moisture condensation and hygienic water.

Features of many technologies - reverse osmosis (RO), electrodialysis (ED), airborne evaporation (AES), mixed technologies (RO, AES, bioreactors), thermoelectric membrane evaporation (TIMES), vacuum compression distillation (VCD) and centrifugal multi-stage distillation (CMED) are considered in [1 – 3]. In doing so, only three technologies (TIMES, VCD, CMED) use the principle (method) of energy reduction, i.e. heat pumps. This paper describes the main characteristics of a thermoelectric heat pump (THP) in a CMED system.

Characteristics of TIMES and VCD

The TIMES system was developed in NASA back in 1975 and is described in reports and papers [4 – 8]. TIMES is a simple and effective system (Gd =1.0-1.5l/h, SPC=150 W*h/kg) with urine concentration up to 20 – 25 %. With increasing concentration, temperature depression increases and productivity sharply decreases (Gd < 1.0 l/h), and specific energy consumption increases to 150 - 250 Wh/kg. These results are explained by the fact that in TIMES the heat transfer coefficients (evaporation and condensation) have low values (according to our calculations, less than 1000 - 2000 W/m^2*°C). Increasing the surface where the processes take place gives insignificant results. Moreover, low liquid flow rates (mainly urine) contribute to an increase in deposits on evaporation surfaces. This also leads to an increase in the total salt content in the distillate (up to 100 µS/cm) and increased ammonia concentrations (up to 100 mg/l or more) [4 – 6].

As with all technologies using membranes in areas of liquid evaporation, the main drawback is contamination of the membranes, which requires their frequent replacement.

Another option for thermal distillation is the vacuum compression distiller (VCD), analyzed in reports [9 – 11]. VCD uses the most efficient heat pump method – a mechanical compressor.

The transformation coefficient of a real vapor-compression heat pump is determined by the formula

$$\varphi = \frac{q_k}{l} = \frac{h_2 - h_3}{h_2 - h_1}$$

where

q_k is heat flow removed from the THP condenser, kJ/kg;

l is energy consumed by the comp ressor, kJ/kg;

h_1 is enthalpy of water vapor at the compressor inlet, kJ/kg;

h_2 is enthalpy of water vapor at the compressor outlet, kJ/kg;

h_3 is enthalpy of water vapour at the condenser outlet, kJ/kg;

Theoretically, at low ΔP on the compressor at the beginning of the concentration, energy consumption is < 10 - 20 W*h/kg. When the vapor pressure in the compressor increases, the density of the vapor increases under vacuum, which leads to a decrease in system productivity. This is also facilitated by the increase in temperature depression with increasing liquid concentration. Therefore, in all VCD tests [9 – 11], during the concentration process, productivity decreases by 2 times and energy consumption increases [12] to 200 Wh/l.

In [13, 14], the reasons for the high salt content of the distillate (up to 50-250 mg/l) are noted. VCD technology consumes only for the evaporation - condensation process (costs for compressor drive and concentration process) about 150-200 Wh/kg).

CMED system with a heat pump

The CMED system, developed by engineers and specialists from the Kiev Polytechnic Institute, the Thermodistillation company and the Institute of Thermoelectricity of the National Academy of Sciences of Ukraine, showed the best results: productivity - from 2 to 7 l/h, specific energy consumption - less than 100 - 200 Wh/kg, recovery – up to 98 %. These main characteristics have been published in many reports and articles [15 – 22].

CMED technology uses two scientifically and practically proven methods for reducing energy when concentrating heat-sensitive liquids such as urine - a thermoelectric heat pump (THP) and multi-stage liquid evaporation on a rotating surface.

High heat transfer coefficients during condensation and evaporation on a rotating surface with $n = 500\text{-}1500$ rpm amounted to $\alpha_u = (1 \div 2) \cdot 10^4 \frac{W}{m^2 * {}^\circ\mathrm{C}}$ [23 – 26]. These characteristics ensure high film speed, which prevents salt deposits.

During the period 2000-2016, 2018-2022 a large number of tests were performed on 3 and 5 stage distillers. The identity of three distillers made in Ukraine and two THPs was noted. The purpose of these tests was to ensure the reliability of the CMED technology, study the influence of n, NTHP, type of liquid, improve characteristics (increase *Gd*, reduce SPC, improve distillate quality). Stable operation of the distiller and THP was noted without any shortcomings in the operation of the system. On the example of a study of a 3-stage distiller manufactured and tested back in 1986, it was indicated that long-term idleness of a centrifugal distiller does not affect its start-up and operation after a major shutdown.

Special attention in this paper is directed to the study of the characteristics of a thermoelectric heat pump. The results of tests on water and urine of 3-stage and 5-stage distillers with a thermoelectric heat pump were considered. The effect on Gd and SPC of the number of revolutions $n = 800$, 900, 1000, 1200, 1500 rpm, with NTHP = 100, 150, 200, 300, 400 and 600 Watts was studied. Cycles of each test were performed at $t = 60$, 90, 120 min.

We measured: N_{eng}, N_{THP}, G_d , $G_г$ and G_x, hot circuit temperatures t_1 and t_2, cold circuit temperatures t_3 and t_4. Based on these experimental data, the following characteristics were calculated:

1. amount of heat in the hot circuit

$$Q_{\mathrm{г}} = \mathrm{C_p} \cdot G_{in} \cdot \rho \cdot (t_2 - t_1)$$

where C_P is mass heat capacity of liquid, cm^3/sec;

G_{in} is flow rate of circulating liquid, J/°C*g;

ρ is liquid density, g/cm^3

2. temperature difference in thermoelectric heat pump

$$\Delta T_{in} = t_1 - t_3$$

3. THP efficiency

$$\eta_{THP} = Q_г / N_{THP}$$

4. specific energy consumption in the distiller

$$SPC = (N_{дв} + N_{THP}) / G_d$$

where N_{mot} is electric power consumed by distiller motor, W;

N_{THP} is electric power consumed by the heat pump, W;

G_d is distiller productivity, l/h.

Unpublished data of testing a centrifugal distillation system with a thermoelectric heat pump, performed at the test benches the Thermodistillation company, jointly with the Institute of Thermoelectricity of the National Academy of Sciences of Ukraine and KPI specialists during 2000-2002 and 2022-2023, are presented.

Table 1 shows the results of testing a 3-stage distiller when concentrating water, Table 2 shows the results of testing a 5-stage distiller.

Table 1

№	n_{mot}, rpm, N_{mot}, W	N_{THP}, W	ΔT_{in}, °C	G_d, lph	η_{THP}	SPC, W*h/l	№	n_{mot}, rpm, N_{mot}, W	N_{THP}, W	ΔT_{in}, °C	G_d, lph	η_{THP}	SPC, W*h/l
1	1333 59	145	3.2	0.6	5	340	10	1200 41	214	2.9	2.01	2.45	127
2	1350 86	102	3.2	1.35	3.23	140	11	1200 42	309	7.4	2.48	2.2	141
3	1400 64	155	3.5	2.09	3.35	105	12	1200 42	196	3.5	1.76	2.76	135
4	1400 64	241	3.8	2.54	2.73	120	13	1040 29	392	9.5 9.2	1.91 2.9	2.76 1.98	220 145
5	1400 62	392	6.3	3.68	2.6	123	14	1200 42	196	3.5	1.91	2.6	125
6	1400 63	63	2.5	1.42	3.55	89	15	1380 57	217	5.7	2.18	2.83	126
7	1750 107	65	1.5	1.35	5.4	127	16	1580 75	414	4.9	3.5	2.24	140
8	1400 62	226	4.0	2.16	3.7	133	17	1200 48	235	5.5	1.92	2.56	147
9	1500 74	61.4	6.2	0.8	4.28	168							

Table 2

№	n_{mot}, rpm, $N_{дв}$, W	N_{THP}, W	ΔT_{in}, °C	G_d, lph	η_{THP}	SPC, W*h/l	№	n_{mot}, rpm, $N_{дв}$, W	N_{THP}, W	ΔT_{in}, °C	G_d, lph	η_{THP}	SPC, W*h/l
1	1500 74	90.7	6.1	1.13	3.65	146	9	1000 51	101	3.8	2.4	3.8	63
2	1500 74	244	4.6	2.37	2.9	134	10	1000 90	200	4.9	3.6	3.5	80
3	1570 90	414	5.1	3.47	2.24	145	11	1200 100	200	5.3	3.84	2.97	78
4	1200 90	408	8	5.6	2.1	89	12	1000 90	400	6.4	5.6	2.24	88
5	1000 96	212	5.7	3.66	2.87	84	13	1200 100	400	7	6.0	2.34	83
6	1200 96	236	5.9	3.8	2.7	87	14	1000 92	184	5.0	1.7	2.0	162
7	1200 100	420	7.4	6.0	2.1	87	15	1000 90	313	5.3	2.3	1.8	175
8	1200 100	415	7.4	6.0	2.0	86							

Table 3 shows the results of testing a 5-stage distiller when concentrating urine.

Table 3

№	n_{mot}, rpm, $N_{дв}$, W	N_{THP}, W	ΔT_{in}, °C	G_d, lph	η_{THP}	SPC, W*h/l	№	n_{mot}, rpm, $N_{дв}$, W	N_{THP}, W	ΔT_{in}, °C	G_d, lph	η_{THP}	SPC, W*h/l
1	800 39	400	6.9 7.9	3.5	1.97 2.02	125	9	1100 90	150	5.9 7.9	2.9 2.6	3.5 3.0	83 92
2	800 39	300	6.0 6.7	4.08 3.35	2.27 2.27	83 101	10	900 55	150	5.9 7.0	2.9	2.7	71
3	800 39	150	4.7 6.9	2.6	2.45 2.75	73	11	1000 66	600	8.7 10.1	5.0 4.0	1.91 1.89	133 166
4	800 39	200	6,4 8.8	2.82 2.90	2.41 2.45	85 82	12	1200 96	200	9.1 13.4	3.5	2.5	84
5	900 55	300	9.4 11.8	4.1	2.22	86	13	1100 93	400	9.9 11.4	5.34 5.23	2.16 2.04	92 94
6	1000 73	150	6.4 8.8	3.00 2.52	2.86 2.71	74 89	14	1100 93	200	7.0 7.6	3.25 3.5	3.1 2.73	90 84
7	1100 90	600	11.8 13.1	6.6 5.4	1.89 1.76	104 128	15	1200 114	400	12.5 13.5	5.06	2.74 2.0	102
8	1000 73	200	6.4 7.7	3.4 3.4	2.82 2.62	80 80	16	1060 80	300	7.4 9.0	4.3	2.4	88

In tables 1 and 2 with testing on water, one figure ΔT_{in} is written in all tests, since the temperature at the inlet to the THP does not change after turning on the system for no more than 5-10 minutes after turning on the engine. In table 3 on urine in the hot circuit, the temperature changes during the entire concentration period due to the appearance of temperature depression. Therefore, in these tables, ΔT_{in} increases during the entire concentration cycle. We have written this ΔT_{in}, its values at the beginning of the cycle and at the end of the system work.

Fig. 1 shows data on water evaporation in 3- and 5-stage distillers.

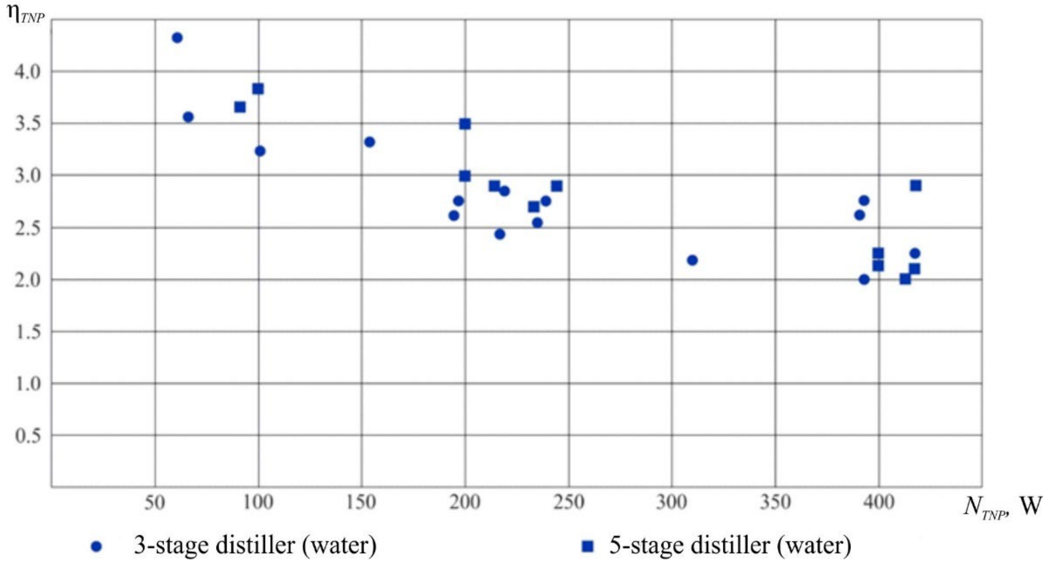

Fig.1. Dependence η_{THP} = f(N_{THP}) at n = 1000...1500 rpm

Fig. 2 shows data on the operation of a 5-stage distiller using urine.

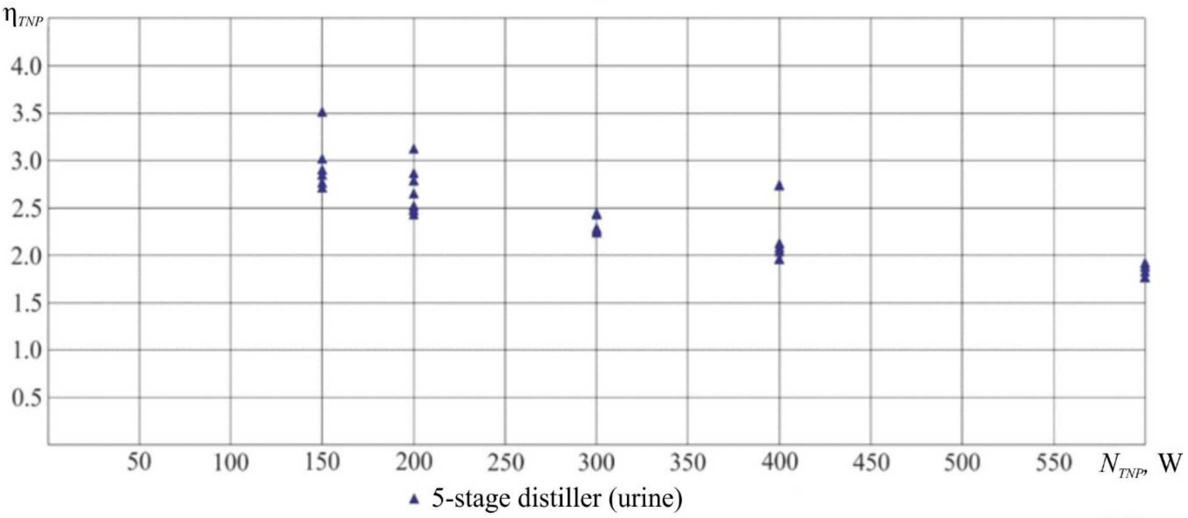

Fig.2. Dependence $\eta_{THP}= f(N_{THP})$ at
n=800...1200 rpm

Figures 3 and 4 present a comparison of theoretical and experimental data on the dependence of the efficiency of a thermoelectric heat pump η_{THP} on power consumption for various coolant temperature differences at the inputs of the cold and hot circuits. Pump efficiency increases significantly as electrical consumption decreases and coolant temperatures become closer. Taking these dependencies into account makes it possible to optimize the energy parameters of the space distillation complex as a whole.

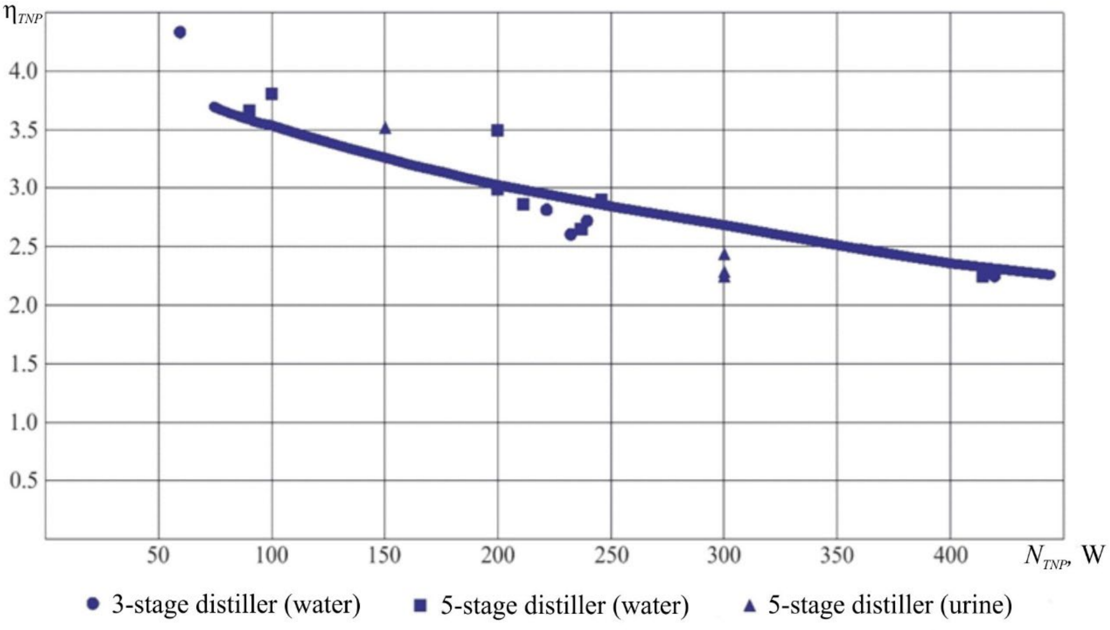

Fig.3. Comparison of experimental data with the results
of theoretical calculations at $\Delta T_{in} = 5°\mathrm{C}$

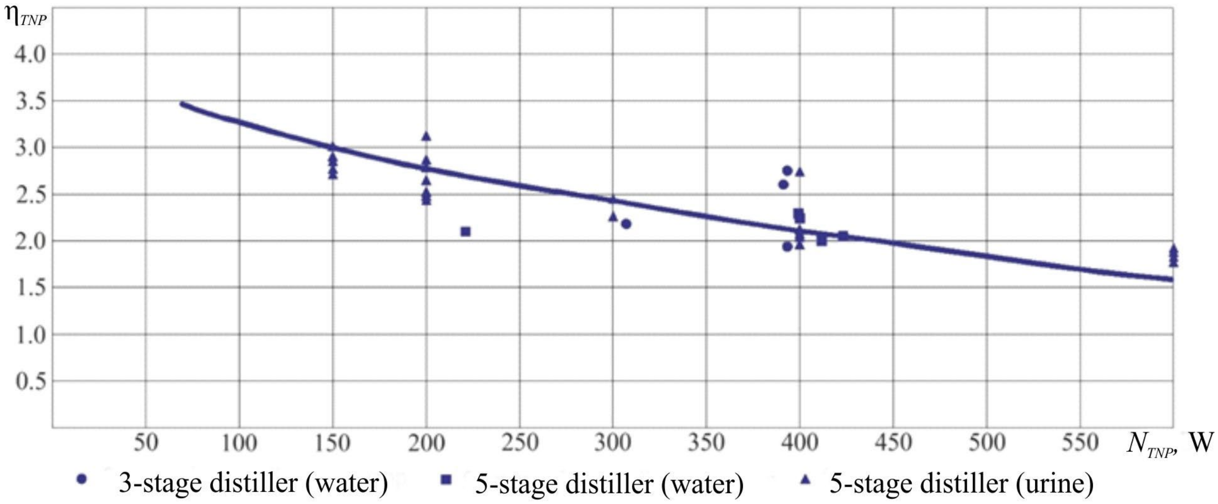

Fig.4. Comparison of experimental data with the results of theoretical calculations at $\Delta T_{in} = 10°\mathrm{C}$

Summary

This paper presents a study of the efficiency factor of a thermoelectric heat pump based on the power it consumes. During the research, the power consumption of the heat pump varied from 60 to 600 Watts, and the distiller engine speed varied from 800 to 2000 rpm. When the heat pump power consumption changes from 400 to 600 Watts, the value of the η_{THP} coefficient changes slightly, while in the range of 200 - 400 Watts the η_{THP} value almost doubles. The maximum value of η_{THP} on the heat pump under study reaches 5 with a power consumption of 145 Watts. The specific energy consumption of SPC to produce one litre of distillate has minimum values precisely at low heat pump powers, which makes it possible to use this fact for the further development of energy-efficient distillation units.

References

1. Rifert, V. G., Anatychuk, L. I., Barabash, P. O., Solomakha A. S., Strykun A. P., Sereda, V. V., Prybyla,A. V. (2019). Evolution of centrifugal distillation system with a thermoelectric heat pump for space missions. *J. Thermoelectricity*, 3, 5 – 19.
2. Rifert V. G., Anatychuk L. I., Barabash P. O., Usenko V. I., Solomakha A. S., Petrenko V. G., Prybyla A. V., Sereda V. V. (2019). Comparative analysis of thermal distillation methods with heat pumps for long space flights. *J. Thermoelectricity*, 4, 5 – 18.
3. Rifert, V., Solomakha, A., Barabash, P. et al. (2022). Centrifugal multiple effect distiller for water recovery for space applications. *CEAS Space Journal*. https://doi.org/10.1007/s12567-022-00480-x
4. Roebelen, G., Jr., Dehner, G., Winkler, H. (1984). Thermoelectric integrated membrane evaporation water recovery technology. *SAE 93,559–570*. https:// doi.org/ 10. 4271/ 820849
5. Dehner, G. F., Reysa, R. P. (1985). Thermoelectric integration membrane evaporation subsystem water recovery technology update. In: *15 Intersociety Conference on environmental systems. Paper 851348*. https:// doi.org/ 10. 4271/ 851348
6. Dehner, G. F., Price, D. F. (1987). Thermoelectric integration membrane evaporation subsystem testing. *SAE Paper 871446*. https://doi.org/10.4271/871446
7. Thibaud-Erkey C., Fort J., Scull T., Edeen M. (2002). Performance testing of a new membrane evaporator for the thermoelectric integrated membrane evaporator system (TIMES) water

processor. In: *32nd International Conference on Environmental Systems. SAE 2002-01-2525.* https:// doi.org/ 10. 4271/ 2002- 01- 2525

8. Development of a prototype TIMES wastewater recovery subsystem. Roerelen G. J., Denher G. F. PREPARED UNDER CONTRACT NO. NAS 9-15471, 1982 and 1984
9. Rifert Vladimir G., Barabash Petr A., Usenko Vladimir, Solomakha Andrii S., Anatychuk Lukyan I., Prybyla A.V. Improvement the cascade distillation system for long-term space flights. *68th International Astronautical Congress (IAC), Adelaide, Australia, 25-29 September 2017*. IAC-17-A1.IP.25.
10. *Vapor compression distillation module* (Contracts NAS9-13714 & NAS9-14234), Prepared by P. P.Nuccio, 1975
11. Noble Larry D., Schubert Franz H., Pudoka Rick J., Miernik Janie H. (1990). Phase change water recovery for the space station free domand future exploration missions. *20th lntersociety Conference on Environmental Systems. Williamsburg, Virginia, July 9-12, 1990. SAE Technical Paper 901294.*
12. Wieland P., Hutchens C. and Long D., B. Salyer Final Report on Life Testing of the Vapor Compression Distillation / *Urine Processing Assembly (VCD/UPA) at the Marshall Space Flight Center (1993 to 1997) NASA/TM —1998–208539*
13. Carter L., Williamson J., Brown C.A., Bazley J., Gazda D., Schaezler R., Thomas Frank. (2018). Status of ISS water management and recovery. *48th International Conference on Environmental Systems. 8 - 12 July 2018, Albuquerque, NewMexico*. ICES-2018-088.
14. Carter L., Williamson J., Brown C.A., Bazley J., Gazda D., Schaezler R., Thomas Frank (2017). Status of ISS water management and recovery. *47th International Conference on Environmental Systems, 17 – 20 July 2017, Charleston, South Carolina*. ICES-2016-036
15. Rifert V. G., Anatychuk L. I., Barabash P. O., Solomakha A. S., Usenko V. I., Petrenko V. G. (2021). Justification of thermal distillation method with a thermoelectric heat pump for long-term space missions. *J. Thermoelectricity*, 1, 5 – 22. http://jt.inst.cv.ua/jt/jt_2021_01_en.pdf
16. Rifert V. G., Anatychuk L. I., Solomakha A. S., Barabash P. O., Petrenko V. G., Snegovskoy O. P. (2021). Influence of thermodynamic characteristics of a thermoelectric heat pump on the performance and energy consumption of a centrifugal distiller. *J. Thermoelectricity*, 2, 5 – http://jt.inst.cv.ua/jt/jt_2021_02_en.pdf
17. Rifert Vladimir G., Anatychuk Lukyan I., Solomakha Andrii S., Barabash Petr A., Usenko Vladimir, Prybyla A.V., Naymark Milena, Petrenko Valerii (20190. Upgrade the centrifugal multiple-effect distiller for deep space missions. *70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.* IAC-19-A1,IP,11,x54316.
18. Solomakha A.S., Anatychuk L.I., Rifert V.G., Barabash P.A., Usenko V., Petrenko V. (2020). Thermal distillation system for deep space missions: rationale for the choice. *71st International Astronautical Congress (IAC) – The Cyber Space Edition, 12-14 October 2020*. IAC-20- A1,VP,15,x61344. 7 pages. https://www.iafastro.org/assets/files/publications/iac-publications/IAC2020-Virtual-FinalProgramme-2020-10-07-FINAL-online-Lowres.pdf
19. Rifert V., Barabash P., Goliad N. (1990). Methods and processes of thermal distillation of water solutions for closed water supply systems. *The 20th Intersociety Conference on Environmental Systems, Williamsburg, July 1990. SAE Paper 901249.*
20. Rifert V., Usenko V., Zolotukhin I., MacKnight A., Lubman A. (1999). Comparison of secondary water processors using distillation for space applications. *SAE Paper 99-70466, 29th International Conferenceon Environmental Systems, Denver, July 1999.*

21. Rifert V., Stricun A., Usenko V. (2000). Study of dynamic and extreme performances of multistage centrifugal distiller with the thermoelectric heat pump. *SAE Technical Papers 2000. 30th International Conferenceon Environmental Systems; Toulouse; France; 10-13 July 2000.*
22. Rifert V. G., Usenko V. I., Zolotukhin I. V., MacKnight A. and Lubman A. (2003). Cascaded distillation technology for water processing in space. SAE Paper 2003-01-2625. *34st International Conferenceon Environmental Systems. Orlando, July 2003.*
23. Rifert V. G., Barabash P. A., Solomakha A. S., Usenko V., Sereda V. V., Petrenko V. G. (2018). Hydrodynamics and heat transfer in centrifugal film evaporator. *Bulgarian Chemical Communications, 50, Special Issue K, 49 - 57.*
24. Rifert V. G., Solomakha A. S., Barabash P. A., Usenko V., Sereda V. V. (2020). Justification of the method for calculating heat transfer in film evaporators with a rotating surface. *Bulgarian Chemical Communications, 52, Special Issue F, 95-102. DOI: 10.34049/bcc.52.F.0016*
25. Solomakha A. S., Rifert V. G., Barabash P. A., Petrenko V., Yaroshevych M. (2021). Centrifugal flash distiller for life support system. *72 International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021.* IAC-21- A1, IP,6, x 66795. 7 pages.
26. Butuzov A. I. and Rifert V. G. (1973). Heat transfer in evaporation of liquid from a film on a rotating disc. *Heat Transfer Soviet Research*, 5, 1.

Submitted 18.01.2023

Анатичук Л. І., *акад. НАН України* [1,2]
Ріферт В. Г., *док. техн. наук* [3]
Барабаш П. О., *канд. техн. наук* [3]
Десятерик Р. В., *канд. техн. наук* [3]
Соломаха А. С., *канд. техн. наук* [3]
Розвер Ю. Ю., *науковий співробітник*[1]
Петренко В. Г., *канд. техн. наук* [3]

[1] Інститут термоелектрики НАН та МОН України,
вул. Науки, 1, Чернівці, 58029, Україна,
e-mail: anatych@gmail.com, y.rozver@chnu.edu.ua
[2] Чернівецький національний університет імені Юрія Федьковича,
вул. Коцюбинського 2, Чернівці, 58012, Україна, *e-mail: anatych@gmail.com*
[3] НТУ «КПІ» ім. І.Сікорського, вул. Політехнічна, 6, Київ, 03056, Україна,
e-mail: vgrifert@ukr.net, barabash_tef@ukr.net, drv_td@ukr.net, as_solomaha@ukr.net, petrko@ukr.net

ЕКСПЛУАТАЦІЙНІ ВИПРОБУВАННЯ ТЕРМОЕЛЕКТРИЧНОГО ТЕПЛОВОГО НАСОСУ ДЛЯ ВІДЦЕНТРОВОЇ ДИСТИЛЯЦІЇ СТІЧНИХ ВОД КОСМІЧНОЇ СИСТЕМИ ЖИТТЄЗАБЕЗПЕЧЕННЯ

У статті описано результати випробувань системи багатоступінчастої відцентрової вакуумної дистиляції (CMED) з термоелектричним тепловим насосом (THP). В роботі *наведено результати досліджень з вивчення основних характеристик процесу при концентруванні води та урини в разі використання дистиляторів трьох- і п'ятиступінчасної конструкції. Особливу увагу приділено вивченню впливу параметрів процесу на зміну коефіцієнта ефективності термоелектричного теплового насосу. Бібл. 26, рис. 4, табл.3.*

Ключові слова: тепловий насос, дистилятор.

References

1. Rifert, V. G., Anatychuk, L. I., Barabash, P. O., Solomakha A. S., Strykun A. P., Sereda, V. V., Prybyla,A. V. (2019). Evolution of centrifugal distillation system with a thermoelectric heat pump for space missions. *J. Thermoelectricity*, 3, 5 – 19.
2. Rifert V. G., Anatychuk L. I., Barabash P. O., Usenko V. I., Solomakha A. S., Petrenko V. G., Prybyla A. V., Sereda V. V. (2019). Comparative analysis of thermal distillation methods with heat pumps for long space flights. *J. Thermoelectricity*, 4, 5 – 18.
3. Rifert, V., Solomakha, A., Barabash, P. et al. (2022). Centrifugal multiple effect distiller for water recovery for space applications. *CEAS Space Journal*. https://doi.org/10.1007/s12567-022-00480-x
4. Roebelen, G., Jr., Dehner, G., Winkler, H. (1984). Thermoelectric integrated membrane evaporation water recovery technology. *SAE 93,559–570*. https:// doi.org/ 10. 4271/ 820849
5. Dehner, G. F., Reysa, R. P. (1985). Thermoelectric integration membrane evaporation subsystem water recovery technology update. In: *15 Intersociety Conference on environmental systems. Paper 851348*. https:// doi.org/ 10. 4271/ 851348
6. Dehner, G. F., Price, D. F. (1987). Thermoelectric integration membrane evaporation subsystem testing. *SAE Paper 871446*. https://doi.org/10.4271/871446
7. Thibaud-Erkey C., Fort J., Scull T., Edeen M. (2002). Performance testing of a new membrane evaporator for the thermoelectric integrated membrane evaporator system (TIMES) water processor. In:*32nd International Conference on Environmental Systems. SAE 2002-01-2525.* https:// doi.org/ 10. 4271/ 2002- 01- 2525
8. Development of a prototype TIMES wastewater recovery subsystem. Roerelen G. J., Denher G. F. PREPARED UNDER CONTRACT NO. NAS 9-15471, 1982 and 1984
9. Rifert Vladimir G., Barabash Petr A., Usenko Vladimir, Solomakha Andrii S., Anatychuk Lukyan I., Prybyla A.V. Improvement the cascade distillation system for long-term space flights. *68th International Astronautical Congress (IAC), Adelaide, Australia, 25-29 September 2017*. IAC-17-A1.IP.25.
10. *Vapor compression distillation module* (Contracts NAS9-13714 & NAS9-14234), Prepared by P. P.Nuccio, 1975
11. Noble Larry D., Schubert Franz H., Pudoka Rick J., Miernik Janie H. (1990). Phase change water recovery for the space station free domand future exploration missions. *20th lntersociety Conference on Environmental Systems. Williamsburg, Virginia, July 9-12, 1990. SAE Technical Paper 901294.*
12. Wieland P., Hutchens C. and Long D., B. Salyer Final Report on Life Testing of the Vapor Compression Distillation / *Urine Processing Assembly (VCD/UPA) at the Marshall Space Flight Center (1993 to 1997) NASA/TM —1998–208539*
13. Carter L., Williamson J., Brown C.A., Bazley J., Gazda D., Schaezler R., Thomas Frank. (2018). Status of ISS water management and recovery. *48th International Conference on Environmental*

Systems. 8 - 12 July 2018, Albuquerque, NewMexico. ICES-2018-088.

14. Carter L., Williamson J., Brown C.A., Bazley J., Gazda D., Schaezler R., Thomas Frank (2017). Status of ISS water management and recovery. *47th International Conference on Environmental Systems, 17 – 20 July 2017, Charleston, South Carolina*. ICES-2016-036
15. Rifert V. G., Anatychuk L. I., Barabash P. O., Solomakha A. S., Usenko V. I., Petrenko V. G. (2021). Justification of thermal distillation method with a thermoelectric heat pump for long-term space missions. *J. Thermoelectricity*, 1, 5 – 22. http://jt.inst.cv.ua/jt/jt_2021_01_en.pdf
16. Rifert V. G., Anatychuk L. I., Solomakha A. S., Barabash P. O., Petrenko V. G., Snegovskoy O. P. (2021). Influence of thermodynamic characteristics of a thermoelectric heat pump on the performance and energy consumption of a centrifugal distiller. *J. Thermoelectricity*, 2, 5 – http://jt.inst.cv.ua/jt/jt_2021_02_en.pdf
17. Rifert Vladimir G., Anatychuk Lukyan I., Solomakha Andrii S., Barabash Petr A., Usenko Vladimir, Prybyla A.V., Naymark Milena, Petrenko Valerii (20190. Upgrade the centrifugal multiple-effect distiller for deep space missions. *70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.* IAC-19-A1,IP,11,x54316.
18. Solomakha A.S., Anatychuk L.I., Rifert V.G., Barabash P.A., Usenko V., Petrenko V. (2020). Thermal distillation system for deep space missions: rationale for the choice. *71st International Astronautical Congress (IAC) – The Cyber Space Edition, 12-14 October 2020*. IAC-20-A1,VP,15,x61344. 7 pages. https://www.iafastro.org/assets/files/publications/iac-publications/IAC2020-Virtual-FinalProgramme-2020-10-07-FINAL-online-Lowres.pdf
19. Rifert V., Barabash P., Goliad N. (1990). Methods and processes of thermal distillation of water solutions for closed water supply systems. *The 20th Intersociety Conference on Environmental Systems, Williamsburg, July 1990. SAE Paper 901249.*
20. Rifert V., Usenko V., Zolotukhin I., MacKnight A., Lubman A. (1999). Comparison of secondary water processors using distillation for space applications. *SAE Paper 99-70466, 29th International Conferenceon Environmental Systems, Denver, July 1999.*
21. Rifert V., Stricun A., Usenko V. (2000). Study of dynamic and extreme performances of multistage centrifugal distiller with the thermoelectric heat pump. *SAE Technical Papers 2000. 30th International Conferenceon Environmental Systems; Toulouse; France; 10-13 July 2000.*
22. Rifert V. G., Usenko V. I., Zolotukhin I. V., MacKnight A. and Lubman A. (2003). Cascaded distillation technology for water processing in space. SAE Paper 2003-01-2625. *34st International Conferenceon Environmental Systems. Orlando, July 2003.*
23. Rifert V. G., Barabash P. A., Solomakha A. S., Usenko V., Sereda V. V., Petrenko V. G. (2018). Hydrodynamics and heat transfer in centrifugal film evaporator. *Bulgarian Chemical Communications, 50, Special Issue K, 49 - 57.*
24. Rifert V. G., Solomakha A. S., Barabash P. A., Usenko V., Sereda V. V. (2020). Justification of the method for calculating heat transfer in film evaporators with a rotating surface. *Bulgarian Chemical Communications, 52, Special Issue F, 95-102. DOI: 10.34049/bcc.52.F.0016*
25. Solomakha A. S., Rifert V. G., Barabash P. A., Petrenko V., Yaroshevych M. (2021). Centrifugal flash distiller for life support system. *72 International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021.* IAC-21- A1, IP,6, x 66795. 7 pages.
26. Butuzov A. I. and Rifert V. G. (1973). Heat transfer in evaporation of liquid from a film on a rotating disc. *Heat Transfer Soviet Research*, 5, 1.

Submitted: 18.01.2023