support system of manned spacecraft in long space missions and on the International Space Station. However, the majority of publications give the integral characteristics of the CDS operation, namely the production of the Gd system (in distillate), kg/h; specific power consumption SPC, W·h/kg; the degree of water recovery from the original (processed) liquid %; and some indicators of the quality of the water obtained.

To create a theoretical model of CDS with a view to further improve it and optimize the design of the centrifugal distiller and the system as a whole, the data available in the published literature are insufficient. Attempts at modeling CDS were made in [28]. For the development, without proof of their suitability, the authors used some relationships to calculate the heat transfer coefficient during condensation and evaporation and did not take into account the temperature depression that occurs when the initial solutions are evaporated in the distiller. In addition, the thermal resistance of the wall was not taken into account in the calculation of heat transfer, which, as will be shown in part 3 of our article, can make up to 30 % of the total heat transfer. All this leads to a distortion of such important factors in assessing the efficiency of a thermoelectric heat pump (THP) as the difference in the temperature of liquid flows at the inlet of the device Δt_{IN} and the average temperature of liquids in the device Δt_{AV}.

From the data presented in our report [8] it follows that at the same rotational speeds of the distiller rotor, with decreasing THP power, a decrease in the specific energy consumption at CDS is observed, which was also noted in our works [19, 20]. The effect of this factor on the efficiency of THP and the value of system SPC has not been studied in more detail.

An important parameter of the efficiency of CD + THP system is also the degree of recovery. The larger this value, the smaller the amount of residue. In test trials of all works in the period from 1990 to 2017 there is no critical analysis of the possibility of achieving the maximum degree of recovery.

Experimental test bench for the study of integral characteristics of CD with THP

As already mentioned, in the period from 2000 to 2007, three identical five-stage centrifugal distillers were developed and manufactured by “TD” Co: the first one, in 2001, the second in 2002 and the third in 2006. Also, two thermoelectric heat pumps, developed and manufactured by the Institute of Thermoelectricity of the NAS and MES of Ukraine (ITE), were transferred to Honeywell International Inc. These devices were then tested in various versions at several test benches in the United States, including the NASA test bench.

Before shipment to the USA, the devices were tested at the “TD” Co. test bench.

Fig. 1 is a diagram of the test bench which was used by “TD” Co. for testing three distillers and two heat pumps.

The main and auxiliary equipment of the bench is combined by a system of pipelines that form two circulation circuits. In one of them (“hot”) the evaporated solution circulates, and in the other (“cold”) - distillate.

The test bench works as follows. The engine of the distiller 1 is switched on, providing given revolutions of the distiller rotor. The vacuum pump 7 sets the required pressure in the apparatus, which corresponds to the required boiling point of the solution. From the tank 13, the cold circuit is filled with distillate, in which the distillate is circulated through the distiller condenser 1, salimeter 9, rotameter 14, the cold side of the THP 2, heat exchanger-cooler 3 and again the distiller condenser. The “hot” circuit is filled from the tank 4 to the level set by the control valve 6. In the hot circuit, the solution circulates from the evaporator of the distiller 1 through the rotameter 14 to the hot side of the THP 2 and again to the evaporator of the distiller 1. When the electric power is supplied to the THP 2, the condensate is cooled in the "cold" circuit and the solution is heated in the "hot" circuit. The solution superheated in THP 2 relative to the saturation temperature in the evaporator of distiller 1 partially evaporates, and the obtained steam is used as a heating agent in the next stage of distillation evaporation, the steam obtained in the last stage of the distiller is condensed in the contact condenser of distiller 1. Excess distillate from the cold circuit is automatically discharged into the distillate tank 5.

Valve 6 compensates with the fresh solution the evaporated part of the solution circulating in the hot circuit. At the same time, an increase in the concentration of dissolved substances occurs in it. Due to the fact that in THP 2 $Qr = mr \cdot cpr(t2 - t1) > Qx = mx \cdot cpx(t4 - t3)$, to ensure the stationarity of the process, the excess heat is removed by the heat exchanger-cooler 3 to the environment.

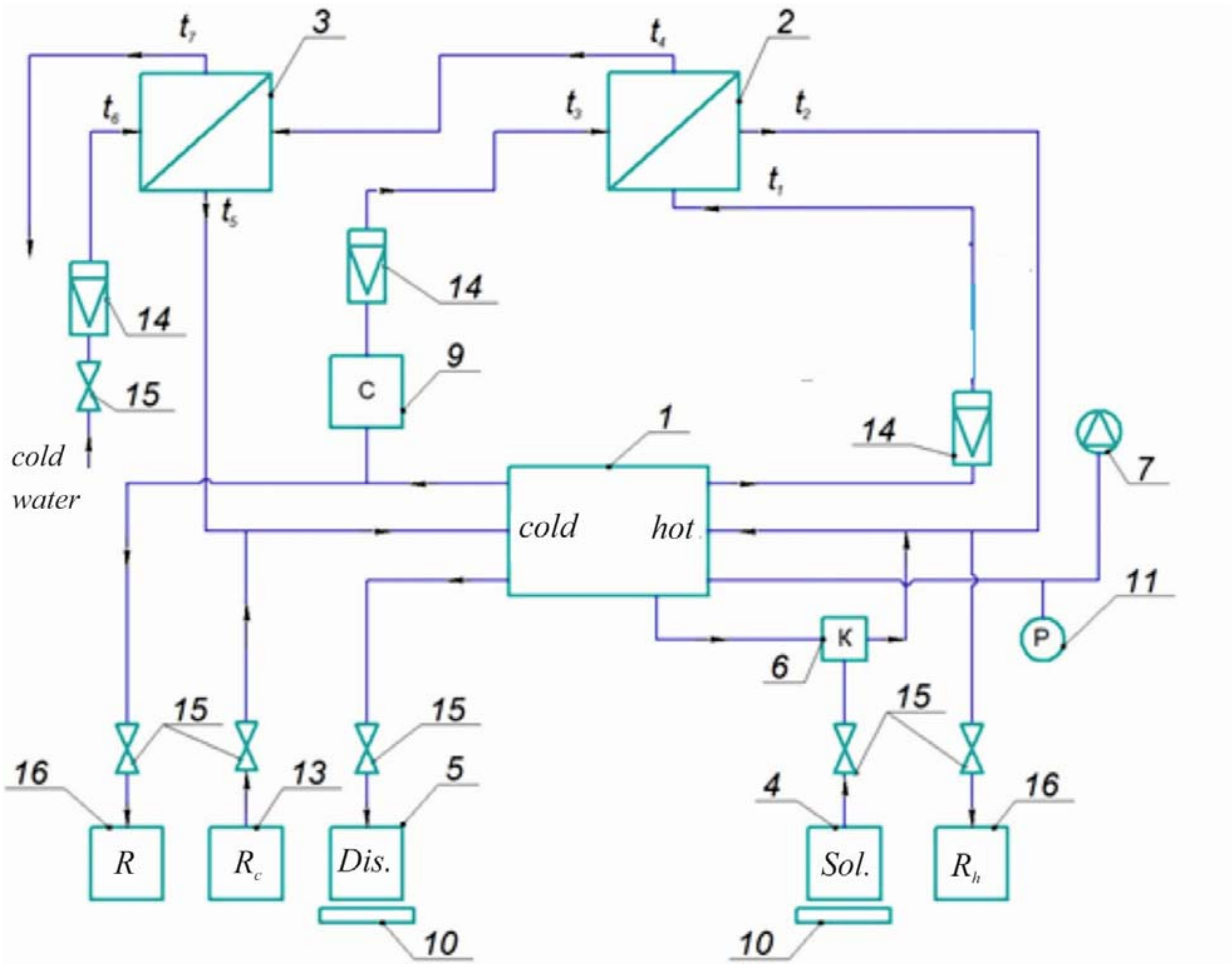

Fig.1. Diagram of the experimental test bench
1 – centrifugal vacuum distiller; 2 – thermoelectric heat pump;
3 – heat-exchanger-cooler; 4 – outlet solution; 5 – distillate collector;
6 – system power control valve; 7 –vacuum pump; 9 –salimeter; 10 –electronic balance;
11 – vacuum gauge; 13 – distillate container for refueling; 14 - rotameters;
15 –shut-off valve; 16 – circuit emptying containers.

After the experiment, the THP 2 power supply is turned off, and the cold and hot circuits are emptied into the corresponding containers 16.

The temperature was measured at the inlet and outlet of the thermal battery on the hot (t_1, t_2) and cold sides (t_3, t_4), behind the heat exchanger-cooler in the cold circuit (t_5) and at the inlet and outlet of the heat exchanger-cooler on the cooling side (t_6, t_7). The temperatures in the hot and cold circuits were measured with chromel-kopel thermocouples at an accuracy of ± 0.1 °C.

The pressure in the apparatus was measured with a vacuum gauge 11 with a measuring scale of -1 ... 0 bar (accuracy class 1.0) complete with a barometer.

The mass of the obtained distillate (product) and the initial solution was measured by electronic balance, the measurement accuracy of ± 2 g, the measurement range of ± 10 kg.

The salinity in the cold circuit was measured with a Hanna salimeter (0 ... 999ppm).

The drive power of the engine and heat pump was measured on the basis of voltmeters and ammeters, accuracy class 0.5. Revolutions were measured with a tachometer with an accuracy of ± 1 rpm.

Calculated values

Production in kilograms per hour:

$$G_d = \Sigma G_\mathrm{d}/\Delta\tau, \tag{1}$$

where ΣG_d is the total mass of the obtained distillate in the tank 13, measured by the weights; $\Delta\tau$ is the measurement time interval.

Power consumption in watts for the main components of the CDS test product:

$$W = W_\mathrm{THP} + W_\mathrm{CD}\ , \tag{2}$$

where W_THP and W_CD is the average power consumed by THP and CD, respectively, over the period from the start to the stop of the distiller. The energy consumption of the vacuum pump was not taken into account at this stage.

Specific power consumption (*SPC*), W·h per kg of produced water:

$$SPC = W/G,\ \mathrm{W\cdot h/kg}. \tag{3}$$

Degree of recovery:

$$R = G_\mathrm{d} / G_{in}, \tag{4}$$

where $\mathrm{G}_{in} = \Sigma G_{in}/\Delta\tau$ is the mass of the consumed solution during the experiment, calculated by the weights in the tank 16.

Heat pump efficiency:

$$COP = Q_r / W_\mathrm{THP}\ , \tag{5}$$

where $Q_r = G_r{\cdot}C_p(t_2 - t_1)$, W, G_r is flow rate of the liquid (solution) in the hot circuit; C_p is the average isobaric heat capacity of the solution, kJ/(kg·K).

Test results

Table presents a typical list of measured key indicators when concentrating urine.

Here, production stands for distiller capacity, TDS is total number of dissolved solids.

Table

Typical table of measured values (urine, n=)1200 rpm

Time	Drive			THP			Weight		TDS	Flow		Production	SPC	Temperature			
	U	*I*	*W*	*U*	*I*	*W*	in	out		hot	Cold			Hot in THP	Hot out THP	Cold in THP	Cold out THP
Min	V	A	W	V	A	W			mg/l	l/h		kg/h	W h/kg	^{0}C			
0	24.2	3.1	75.0	20.5	10.08	206.6	0	0	12	60	82	0.00	0.0	23.2	23.1	22.9	22.9
6	24.2	3.1	75.0	22.5	10.9	245.3	288	184	22	60	82	1.84	174.1	31.8	43.7	23.4	22.7
12	24.2	3.1	75.0	28.5	14.3	407.6	634	602	38	60	82	4.18	174.1	37.5	48.3	24.5	22.4
18	24.2	3.1	75.0	29.2	14	408.8	1122	1070	51	60	82	4.68	103.4	38.7	49.4	25.1	22.3
24	24.2	3.1	75.0	32	14.4	460.8	1584	1528	61	60	82	4.58	117.0	38.8	50.8	25.1	22.0
30	24.2	3.1	75.0	31.8	15.2	483.4	2078	2006	67	60	82	4.78	116.8	39.4	51.5	25.2	22.1
36	24.2	3.1	75.0	32.3	14.22	459.3	2592	2502	73	60	82	4.96	107.7	40.0	52.2	25.4	22.1
42	24.2	3.1	75.0	32.1	15.24	489.2	3110	3004	76	60	82	5.02	112.4	40.0	52.2	25.4	22.3
48	24.2	3.1	75.0	31.9	15.2	484.9	3628	3500	79	61	82	4.96	112.9	40.1	52.1	24.9	22.0
54	24.2	3.1	75.0	32.4	15.36	497.7	4136	3990	82	61	83	4.90	116.9	40.3	52.2	25.1	22.1
60	24.2	3.1	75.0	33	15.6	514.8	4656	4492	84	62	83	5.02	117.5	40.7	53.5	24.9	22.0
66	24.2	3.1	75.0	33.2	15.64	519.2	5182	5006	87	62	83	5.14	115.6	40.9	53.2	24.9	22.1
72	24.2	3.1	75.0	33.1	15.56	515.0	5702	5508	90	63	83	5.02	117.5	40.9	53.1	24.9	22.0
78	24.2	3.1	75.0	33	15.58	514.1	6220	6010	92	64	83	5.02	117.4	40.9	53.2	24.9	22.0
84	24.2	3.1	75.0	33.2	15.72	521.9	6740	6510	94	65	83	5.00	119.4	41.0	53.5	24.8	22.0
90	24.2	3.1	75.0	33.2	15.46	513.3	7250	7010	96	67	83	5.00	117.7	41.0	53.5	24.8	22.0
96	24.2	3.1	75.0	32.8	15.34	503.2	7755	7500	97	68	83	4.90	118.0	41.0	53.1	24.6	22.0
102	24.2	3.1	75.0	32.9	15.4	506.7	8175	8000	98	71	83	5.00	116.3	41.0	53.1	24.8	22.0
108	24.2	3.1	75.0	0	0	0.0	8280	8205	96	71	83						
Average	24.2	3	75.0			492.8			75			4.93	115.1				
Total							8280	8205									

The identity of performance of three models of multi-stage centrifugal distillers with two THPs

Figs. 2 and 3 show the results of the concentration of urine from three distiller models with a heat pump power of N = 400 W and a rotational speed of 1200 rpm for 60 minutes. It can be seen from the figures that the production G_d and the specific power consumption *SPC* of all three samples of centrifugal distillers are close. The discrepancy of data on these indicators at the same time τ does not exceed 5 %.

This result allows us in the further analysis of the results of the various tests not to indicate the distiller number.

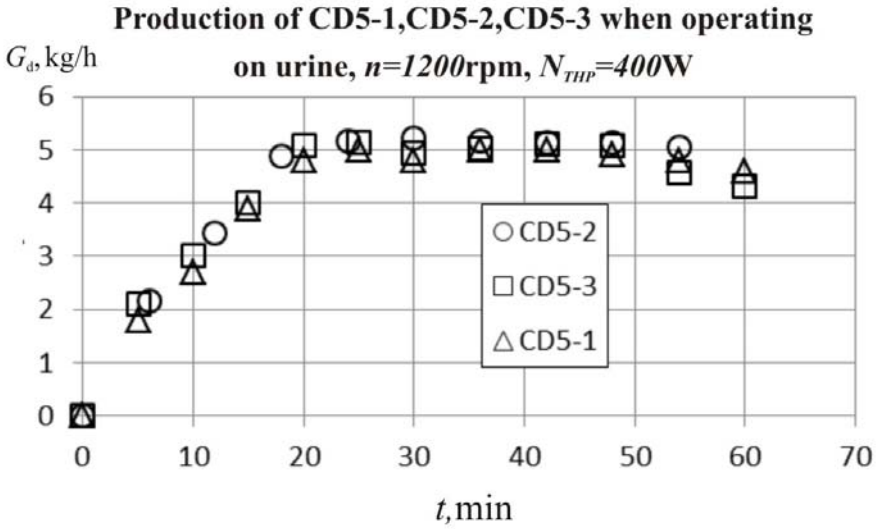

Fig.2 Time dependence of production for different distillerв

Fig.3 Time dependence of specific power consumption for different distillers,
W = 400 W (without account of engine)

The identity of the THP is shown in Fig. 4, from which it follows that when operating on the same sample of the CD5-3 distiller with different heat pumps THP-1 and THP-2, the production with the same heat pump power is identical.

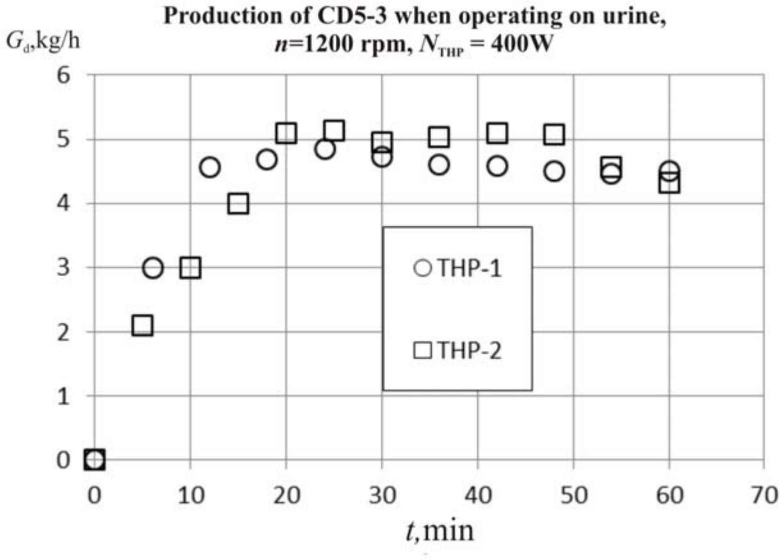

Fig.4. Time dependence of system production for two samples of thermoelectric heat pumps

Temperatures

Fig. 5 shows temperature change in online mode when processing urine with the initial concentration $C = 5$ %, rotations n = 1100 rpm and heat pump power $N_{THP} = 400$ W.

After turning on the distiller, after 10 minutes, the temperatures of the liquids in the hot and cold circuits reach the operating value.

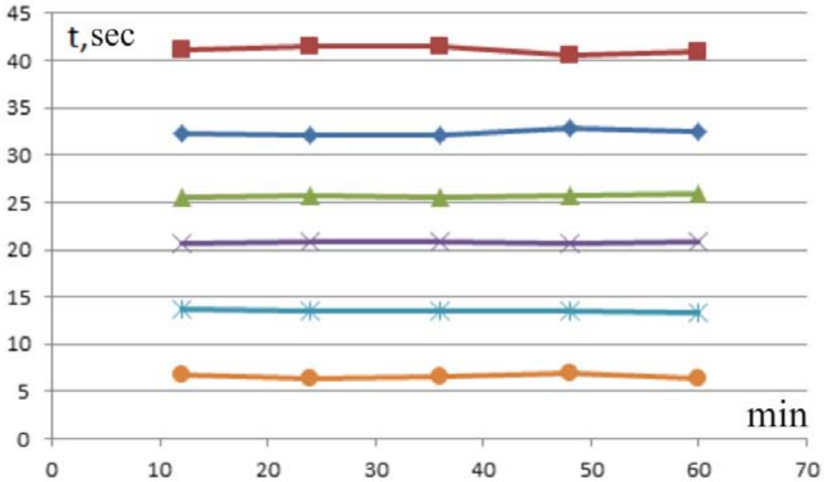

Fig.5a The dependence of temperatures on the time of the experiment (Water)

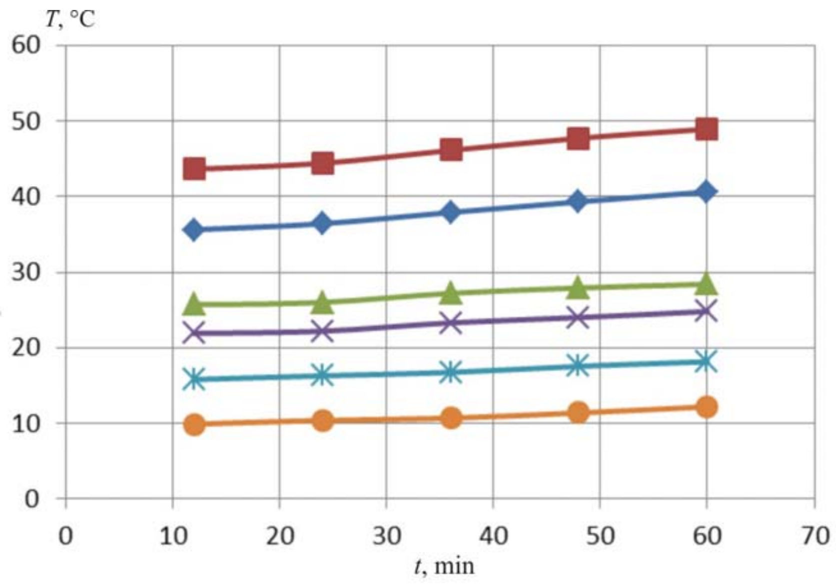

Fig.5b The dependence of temperatures on the time of the experiment (Urine)

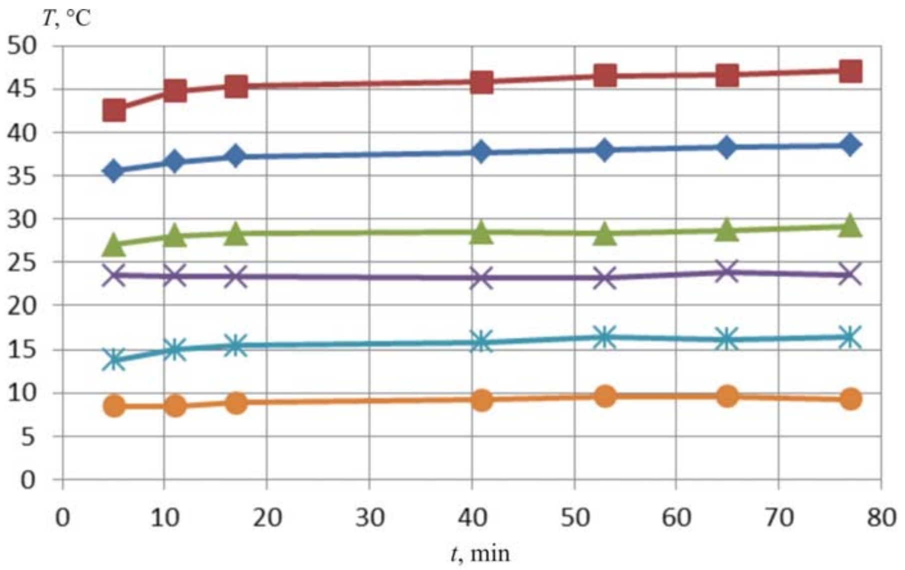

Fig.5c The dependence of temperatures on the time of the experiment (NaCl)

◆ hot-in *solution temperature at the inlet to the heat pump in the “hot” circuit (t_1), °C;*

■ hot-out *solution temperature at the outlet of the heat pump in the “hot” circuit (t_2), °C;*

▲ cold-in *distillate temperature at the inlet to the heat pump in the “cold” circuit (t_3), °C;*

✕ cold-out *distillate temperature at the outlet of the heat pump in the “cold” circuit (t_4), °C;*

✳ Δt¯ *average temperature head at the heat pump, $\Delta t_{av} = 0{,}5(t_1 + t_2) - 0{,}5(t_3 + t_4)$, °C;*

● Δt_in *average temperature head at the inlet to the heat pump, $\Delta t_{in} = t_1 - t_3$, °C;*

When concentrating a *NaCl* solution and urine, the temperatures in the hot circuit increase throughout the experiment due to an increase in the physical-chemical temperature depression during evaporation. In turn, this increases the overall average temperature head at the heat pump (Δt_{av}) and the average temperature head at the inlet to the heat pump (Δt_{in}), which affects the efficiency of the heat pump.

Production

It can be seen from Fig. 6 that when *NaCl* and urine are concentrated, the production is lower than that obtained when working on the distillate and decreases during the experiment due to an increase in temperature depression.

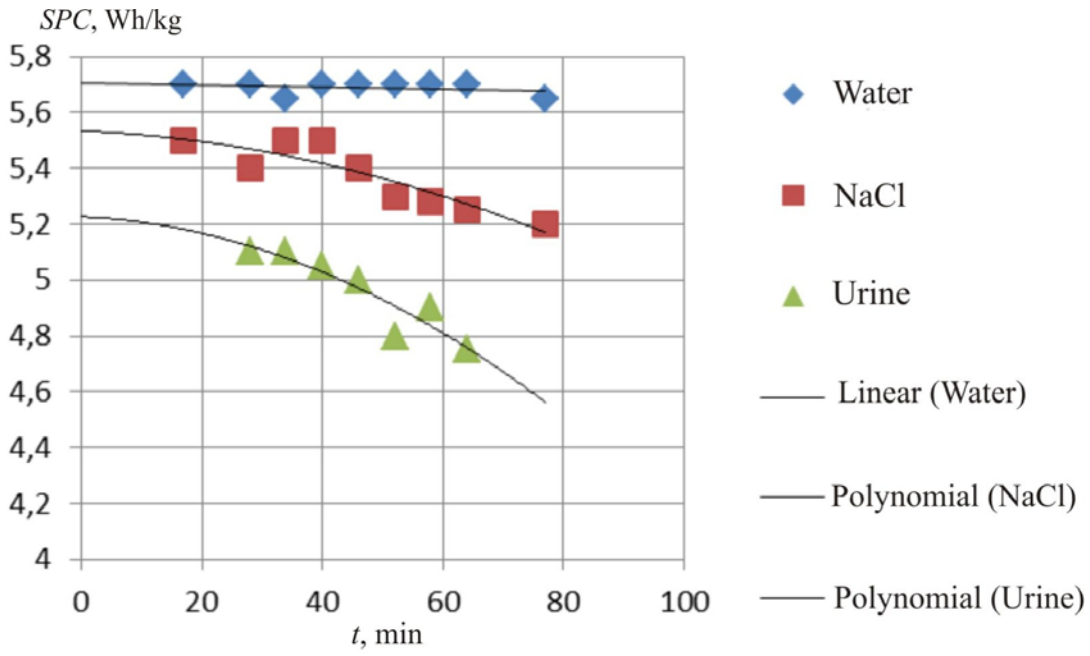

Fig. 6 The production of the distiller depending on the type of processed solution (n = 1100 rpm; N = 400 W).

Figure 7 shows the effect of heat pump power on the production of the distiller. The experiments were performed on urine at the same distillation speed ($n = 1000$ rpm). The amount of distillate obtained in all experiments was 5 kg, which corresponded to recovery ≈ 0.9. The greater the power of the heat pump, the higher the system production. In so doing, for each power in the initial 15 minutes there is an increase in the production (the device enters the operating mode), after which, due to an increase in the concentration of the solution in the hot circuit, the temperature depression increases and the production decreases. At the same time, the higher the power, the greater effect on the production is produced by temperature depression.

At the same time, as can be seen from Fig. 8, the higher the power supplied to the heat pump, the higher the specific energy consumption for producing one kg of distillate. Thus, from an energy point of view, it is more efficient to work at low heat pump powers.

In all tests performed, the quality of the obtained distillate met all the requirements to potable water. When processing NaCl, TDS in the “cold” circuit did not exceed 10 ppm. When processing urine, TDS < 100 ppm; COD (chemical oxygen demand) < 15 mg/*l*; ammonia NH3 + NH4 <5 mg/*l*.

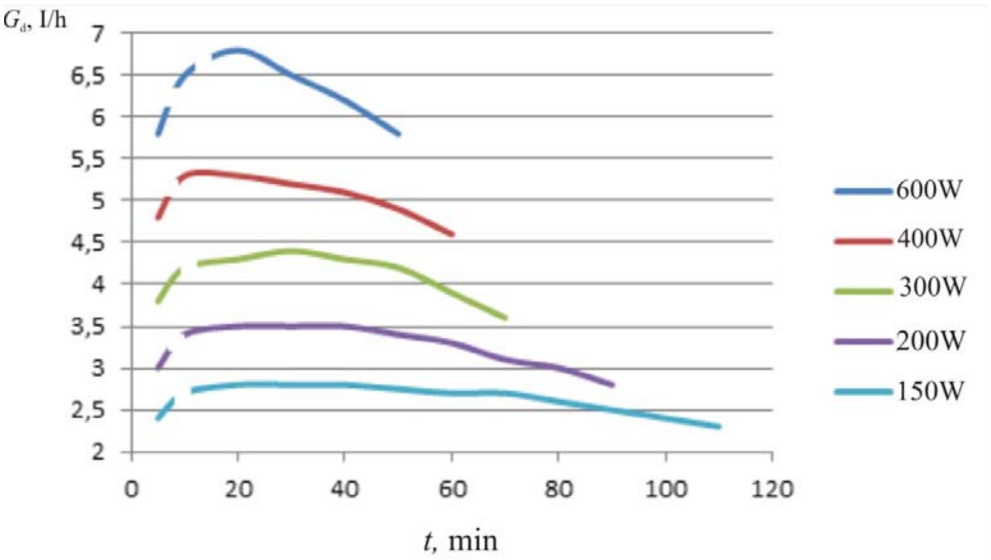

Fig. 7 Effect of heat pump power on the distiller production (n = 1000 rpm)

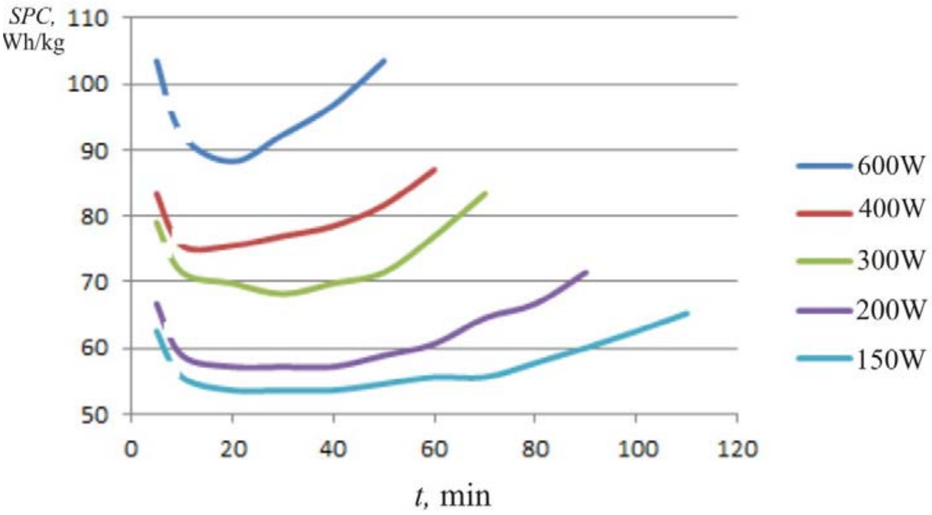

Fig. 8 Effect of heat pump power on the specific power consumption of the distiller without account of engine power (n = 1000 rpm)

Conclusions

1. This paper presents the results of measuring local parameters of distillation system (temperature in the "hot" and "cold" circuits, production, specific power consumption, TDS) in online mode with a change in testing time from 30 to 200 min, rotation speed n = 800…1200 rpm, NTHP = 150…600 W.
2. The identity of three manufactured multi-stage centrifugal distillers with 5 stages and 2 thermoelectric heat pumps is shown.
3. A decrease in SPC with a decrease in NTHP both locally, i.e. at a certain value of time τ, and on the average for the concentration of urine and *NaCl* solution at the same speed and total amount of distillate obtained has been noted.
4. Measured in all the tests, the main characteristics of distillate quality TDS, NH4, TOC meet the requirements to potable water.

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Submitted 30.04.2019

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ЕВОЛЮЦІЯ СИСТЕМИ ВІДЦЕНТРОВОЇ ДИСТИЛЯЦІЇ З ТЕРМОЕЛЕКТРИЧНИМ ТЕПЛОВИМ НАСОСОМ ДЛЯ КОСМІЧНИХ МІСІЙ

Частина 2. Дослідження змінних характеристик системи багатоступінчастої дистиляції (СМЕД) з термоелектричним тепловим насосом (ТНР)

У роботі наведені результати випробувань багатоступінчастого (5 щаблів) відцентрового дистилятора (СМЕД) з використанням для зниження енергоспоживання термоелектричного теплового насоса (ТНР). У досвідах заміряли локальні (у режимі он-лайн) дані системи дистиляції, такі як температура рідин (вихідної й дистиляту) продуктивність, що тече, загальний солевміст, питому витрату енергії при різних швидкостях обертання ротора дистилятора, потужності ТНР, ступінь концентрування. Загальна тривалість випробувань склала більш 700 годин, кількість переробленої рідини (NaCl і урини) склала більш 2000 кг. Дослідження трьох дистиляторів і двох ТНР і порівняння їх результатів показало їхню ідентичність, що характеризує висока якість виготовлення цих пристроїв. Отримані дані параметрів експлуатації (оберти n і потужність ТНР), можуть бути використані для оптимізації конструкції й режимів експлуатації роботи всієї системи СД + ТНР. Бібл. 28, рис. 8, табл. 1.

Ключові слова: термоелектрика, тепловий насос, дистилятор

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ЭВОЛЮЦИЯ СИСТЕМЫ ЦЕНТРОБЕЖНОЙ ДИСТИЛЛЯЦИИ С ТЕРМОЭЛЕКТРИЧЕСКИМ ТЕПЛОВЫМ НАСОСОМ ДЛЯ КОСМИЧЕСКИХ МИССИЙ

Часть 2. Исследование переменных характеристик системы многоступенчатой дистилляции (СМЕД) с термоэлектрическим тепловым насосом (THP)

В работе приведены результаты испытаний многоступенчатого (5 ступеней) центробежного дистиллятора (СМЕД) с использованием для снижения энергопотребления термоэлектрического теплового насоса (THP). В опытах замеряли локальные (в режиме он-лайн) данные системы дистилляции, такие как температура жидкостей (исходной и дистиллята), текущую производительность, общее солесодержание, удельный расход энергии при разных скоростях вращения ротора дистиллятора, мощности THP, степень концентрирования. Общая продолжительность испытаний составила более 700 часов, количество переработанной жидкости (NaCl и урины) составила более 2000 кг. Исследование трех дистилляторов и двух THP и сравнение их результатов показало их идентичность, что характеризует высокое качество изготовления этих устройств. Получены данные параметров эксплуатации (обороты n и мощность THP), могут быть использованы для оптимизации конструкции и режимов эксплуатации работы всей системы СД + THP. Библ. 28, рис. 8, табл. 1.

Ключевые слова: термоэлектричество, тепловой насос, дистилятор.

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Submitted 30.04.2019

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COMPUTER SIMULATION OF HUMAN SKIN CRYODESTRUCTION PROCESS DURING THERMOELECTRIC COOLING

The paper presents the results of computer simulation of human skin cryodestruction process with regard to thermophysical processes, blood circulation, heat transfer, metabolic processes and phase transition. The physical, mathematical and computer models were built for human skin, on the surface of which there is a cooling element at a temperature of -50 ° C. The distribution of temperature and heat fluxes in human skin was determined in cooling mode. The obtained results make it possible to predict the depth of freezing of the skin and, accordingly, biological tissue at a given temperature effect.

Key words: human skin, temperature exposure, cryodestruction, phase transition, computer simulation.

Introduction

It is well known in medical practice that temperature exposure is an important factor in the treatment of many diseases of human body [1-3]. One of the promising lines is cryodestruction - a set of surgical treatment methods based on local freezing of the biological tissue of human body. Such cooling is mainly realized using special cryotools using liquid nitrogen [4 8]. However, the use of liquid nitrogen has several drawbacks: nitrogen does not provide the ability to provide cooling with the necessary accuracy of maintaining the temperature; there are also risks of hypothermia with negative consequences. In addition, liquid nitrogen is a rather dangerous substance and requires proper care when used, and the delivery of liquid nitrogen is not always available, which limits the possibility of using this method. An alternative to nitrogen cooling can be thermoelectric, which implements a decrease in temperature to 0 ÷ -80 ° C. Thermoelectric medical devices make it possible to precisely set the required temperature of the working tool, the time of temperature effect on the corresponding part of human body and provide a cyclic change of cooling and heating modes [1 – 2, 9 – 12].

Computer models created so far for human skin, on the surface of which there is a cooling element, make it possible to simulate thermophysical processes taking into account blood circulation, heat transfer, and metabolic processes [13 19]. However, existing computer models do not take into account the phase transition in the biological tissue when it is cooled, which leads to errors in computer simulation of temperatures and heat fluxes.

Therefore*, the purpose of this work* is to take into account the phase transition in the biological tissue during computer simulation of human skin cryodestruction process.