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EVOLUTION OF CENTRIFUGAL DISTILLATION SYSTEM WITH A THERMOELECTRIC HEAT PUMP FOR SPACE MISSIONS

Part 1. Review of publications on centrifugal distillation in the period of 1990 – 2017

The article describes the main results of the development and testing of a multistage centrifugal vacuum distillation (MCVD) system with a thermoelectric heat pump (THP). For the most part, these works present information on the integral characteristics of the system, namely: distillate capacity, specific energy consumption per unit mass of the obtained distillate and distillate quality during evaporation (concentration) of an aqueous solution of NaCl, urine and mixtures of urine with condensate and urine with condensate and hygienic water. Bibl. 29, Tabl. 5.
Key words: thermoelectricity, heat pump, distiller

Introduction

Purification of liquid human waste is highly relevant for the success in long flights to the Moon and Mars and the work of astronaut teams, both at these space objects and at the International Space Station (ISS).

Within the span of 2000-2009, a team of engineers and researchers from "Thermodistillation" Co ("TD" Co), Igor Sikorsky Kyiv Polytechnic Institute (KPI) and the Institute of Thermoelectricity of the National Academy of Sciences and the Ministry of Education and Science of Ukraine (ITE) developed a wastewater purification system by the method of multistage centrifugal vacuum distillation (MCVD) using a thermoelectric heat pump (THP) as a heat source. Its use can significantly reduce the energy costs for the operation of the system, which makes it competitive among similar space water purification systems.

The purpose of the work is to analyze the evolution of centrifugal distillation system with a thermoelectric heat pump for space missions.

Characteristics of MCVD with 3 stages and THP

The first prototype of MCVD had three stages of distillation and was developed and manufactured as far back as in the 80s by order of NIIKHIMMASH (Russia, Moscow). Brief data about this device was given in the reports [1] and contained information about some of its parameters at a capacity of up to 3l / h.

The publications [2-6] also provide brief information on the characteristics of a 3-stage distiller. In [2], tables are given indicating the distiller's capacity for purified water (G_D = 0.5 - 3.0 kg / h) and specific power consumption (SPC) with no information on the power consumption for THP (W_{THP}) and the degree of water recovery from the initial liquid.

In [3], the calculated values of the distiller's capacity for purified water $G_D = f(W_{THP})$ are given without explaining the method for calculating the parameters, the degree of water recovery, and the rotation speed of heat-exchange surfaces *n* (rpm).

In [4], a table is given with the data: G_D = 2.5 - 3.0 kg / h; SPC = 120 W · h / kg (specific power consumption); *R*ec = 90 % (degree of fluid recovery). Information on W_{THP}, the duration of the distiller operation and the quality of the resulting product is not presented.

In [5], there is a plot of the capacity of a 3-stage distiller versus NTHP and the specific power consumption (155 – 165 W · h / kg), but without specifying the rotor speed and the degree of concentration of the initial liquid.

In [6], a comparison is made of the main characteristics of a three-stage distiller in combination with THP, a vapor compression distiller (VCD), and a TEMES thermoelectric evaporator.

In [7], the operation of the system under extreme conditions was studied, in the event of failure of individual subsystems

Characteristics of MCVD with 5 stages and THP

In [8], the design and operation of a 5-stage distiller in combination with a thermoelectric heat pump was first described, as well as a test bench created on the basis of "TD" Co for testing centrifugal distillers in conjunction with THP under various operating conditions.

In 2001, the first five-stage distiller was developed and manufactured for Honeywell International Inc. [8]. At the suggestion of the customer, it was called the cascade distiller - CD, and the multistage centrifugal vacuum distillation system with a thermoelectric heat pump, manufactured in Ukraine in "TD" Co, was called the cascade distillation system - CDS.

Altogether, in the period from 2000 to 2007, three identical five-stage centrifugal distillers were developed and manufactured by "TD" Co: the first one, as mentioned above, in 2001, the second in 2002, the third in 2006. All three appliances complete with thermoelectric heat pumps ALTEC 7005, developed and manufactured by the Institute of Thermoelectricity of the NAS and MES of Ukraine (ITE) [21-29], were transferred to Honeywell International Inc. These devices have been tested in various versions at several test benches in the United States, including the NASA test bench.

Before shipment to the USA, each of the devices was tested at the "TD" Co. test bench.

Table 1 presents the first test results of a 5-stage distiller in the process of urine processing at different speeds and power of the THP.

In total, over 300 tests with the following range of input parameters were carried out at the test bench of "TD" Co in the period of 2000-2007 in the process of working out the design and passing tests of five-stage distillers (3 copies) and heat pumps (2 copies): the rotation speed of the rotor 100 - 1500 rpm, THP power (40 - 520) W, initial (recyclable) liquids: water, aqueous *NaCl* solution (2-4%), urine. Results obtained: capacity (max.) - 6.7 kg / h; liquid recovery rate (max.) - 0.95, specific power consumption (min.) – 76 W · h / kg.

[8 - 16] describe the stages of CDS development and testing at the test benches of TD Co,

Honeywell International Inc. and the Marshall Center (NASA JSC), which confirms the priority authorship of TD Co and ITE of NASU in the design and manufacture of relevant CDS elements.

In [10–12], CDS submitted by Honeywell International Inc to Johnson Space Center (NASA JSC) for testing were described in detail. The results of tests on concentrating in a centrifugal distiller an aqueous solution of *NaCl* in an amount of 21 l and urine in an amount of 111.8 kg, as well as the evaporation of 25.5 kg of distillate are presented. Data is given on the capacity of the distillers (2.7 - 5.1) kg / h, specific power consumption (88.8 - 116) W · h / kg and the degree of water recovery 0.88 - 0.95.

Table 1

Results of testing 5-stage distiller (urine)

Rotation rate, rpm	Power CD-5, W	Power THP, W	THP Efficiency	Average capacity, l/h	Specific power consumption W h s /l	Degree of water recovery
1100	65	255	2.07	3.70	86.5	0.89
1100	65	382	1.88	4.72	94.7	0.91
1200	84	251	2.30	3.84	87.2	0.88
1200	85	380	2.02	4.90	94.9	0.91
1200	90	400	1.77	5.04	97.2	0.92
1250	96	406	1.90	4.95	101.4	0.95
1300	106	379	2.08	5.08	95.5	0.92
1300	106	411	1.89	5.38	96.1	0.90

In [12, 13] the results of tests on concentration in CD of urine, condensate of atmospheric moisture and sanitary water are presented. The data obtained is close to the results contained in [9, 10] in terms of capacity (~ 5 kg / h), specific power consumption (~ 100 W · h / kg) and the quality of the distillate obtained. There is no data on the power consumed by the heat pump and the rotation speed of the distiller rotor.

[14] outlines the results of CDS testing during purification of wastewater in the amount equivalent to that which can accumulate within 30 days of flight of a crew of 4 people. In total, about 1500 kg of wastewater was recycled as two different solutions. Solution 1 consisted of urine and atmospheric moisture condensate, solution 2 consisted of urine, atmospheric moisture condensate and sanitary water.

The integral test parameters for each of the solutions are as follows:

– solution 1 - capacity 4.1 kg / h with a power of THP 300 W ;.

– solution 2 - capacity 5.2 kg / h with a THP power 400 W;

– the degree of water recovery (recovery) from solution 1 - 93.4 ± 0.7%, from solution 2 - 90.3 ± 5%;

– the specific power consumption in both cases was ~ 100 W hour / kg ;.

– the quality of the distillate upon evaporation of both solutions corresponded to the requirements for drinking water, except for the *pH* value, which was < 5.

In [15], the characteristics of three centrifugal distillation technologies were compared: a vacuum compression distiller (VCD) developed in the USA from 1962 to 2008 (currently operating in the ISS system), a centrifugal evaporator with a wiped-film rotating disk (WFRD) and cascade distillation systems (CDS).

The initial (evaporated) liquids were the same two solutions as in [11], and in the same quantities (as for the 30-day mission).

The total characteristics of the test results are shown in tables 2 and 3.

The work also presents data on the quality of the product obtained during the experiment. CDS performed better in all test modes when they met the requirements of drinking water standards.

Expert evaluation of the test results: the VCD system will be successful with a probability of 84 % - 90 % and a risk of 3 %; CDS will be successful with a probability of 84 % -87 % and a risk of 5 %; the WFRD system will be successful with a probability of 52 % -61 % and a risk of 7 %.

Table 2

Testing results (1 solution)

	CDS	VCD	WFRD
Capacity (kg/h)	3.7	1,63	16.1
Specific power consumption (W h/kg)	109	188	85
Average power (W)	375	279	1252

Table 3

Testing results (2 solution)

	CDS	VCD	WFRD
Capacity (kg/h)	4.88	1.87	16.8
Specific power consumption (W h/kg)	110	163	86
Average power (W)	485	296	1293

[16] claims that CDS is one of two distillation technologies that are currently being developed to support closed-loop water recovery from mixed waste streams expected for long missions.

The same report presents the results of experiments at the test bench of Honeywell International, Inc., in which the effect of the rotation speed of the distiller rotor on the quality of the resulting product was studied. It was found that the best water quality using CDS can be achieved at a rotor speed of 1300 ... 1400 rpm.

The report concludes as follows. "At the current stage of CDS development testing, the system worked as expected and with acceptable performance when processing reference test solutions (water, aqueous NaCl (2-4%), urine). A preliminary comparison of the reference data with previous tests shows that upgrading the system prior to the current CDS prototype did not show any significant impact on system performance. Similarly, the current testing cycle has shown that CDS is capable of handling analog ISS waste streams and performance values are close to those observed for less complex basic test solutions. This final result is an important step towards demonstrating CDS technology as part of the ISS payload. CDS testing will continue to evaluate updated THP projects, a management system, and new wastewater stabilization methods. In addition, the CDS prototype will also continue to be used as a test bench to inform of currently developed generation 2.0 of CDS system".

The reports [17, 18] present the main parameters of CDS obtained by processing six solutions (see Table 4 [18]) in order to determine the possibility of using CDS for the recovery of all types of wastewater under the conditions of the international space station. In the experiments, 8 to 9.8 kg of each solution was processed. The quality of the distillate obtained, the temperature level and the mass flow rate satisfy the required requirements (Expected distillate delivery specification) (see Table 5). As a result, it was concluded that CDS can be used on the ISS and there is a need for additional tests to improve the operation of the heat pump and control system in long space missions (Generation 2.0 of CDS).

Table 4

Parameters of CDS

Solution type	Batch, kg	Recovery, %	Capacity, kg/h	Specific power consumption, W h/kg
Deionized water	9.01 ±1.39	84.6 ±4.7	4.56 ±0.11	74.8 ± 7.9
2% NaCI (1)	9.78 ± 0.02	85.3 ±1.2	4.27 ±0.03	86.5 ±0.9
OxonePTU	9.81 ±0.01	83.1 ±2.7	4.40 ±0.04	97.2 ± 0.3
ISSPTAU	5.79 ±0.03	78.4 ±'1.6	3.89 ±0.00	95.9 ±6.3
JSSAIt-PTAU	9.77 ±0.03	84.4 = 0.8	3.98 ±0.04	105.0 ±2.7
2% NaCI (2)	9.76 ±0.02	83.0 ±0.6	4.32 ±0.09	84.6 ±1.5

Table 5

Quality of CDS distillate obtained

Parameter	Specification	Oxone	ISS Baseline	ISS Alt
Temperature level	61-99 °F	~ 72.0	~ 72.0	~ 72.0
Flow rate	0-5 lb/hr	10.0	8.6	8.8
Conductivity	< 400 µmho/cm	46	100	67
pH	3-8	4.1	3.8	3.9
Ammonium	≤ 3 ppm	< 0.6	< 0.6	< 0.6
Total organic carbon	≤ 150 ppm	8.27	18.7	26.6

Our works, in particular, [20, 21], present the results of studying the influence of primary parameters, namely the distiller rotor rotational speed (n CD) and the thermoelectric heat pump NTHP power on the CDS capacity (GCDS) and the system specific power consumption (SPC). It was found that with decreasing W_{THP} the SPC value decreases. For example, with W_{THP} = 200 W and a rotational speed of 1000 rpm with the same value of SPC = 82 – 87 W h / kg, and with W_{THP} = 400 W, SPC = 100 – 110 W · h / kg.

Conclusions

The works from 1990 to 2017 have been reviewed which describe the results of the development, manufacture and testing at the test benches of TD Co, Honeywell Co and NASA of centrifugal distillers CD with 3 and 5 stages and a thermoelectric heat pump THP. During the tests, by means of CD an aqueous *NaCl* solution, a mixture of urine and sweat condensate, and a mixture of urine, atmospheric moisture condensate, and sanitary water were concentrated (evaporated). The stability of the distillers with the high quality of the resulting product – water was shown. In the JSC Center alone, 1575 kg of wastewater were processed in 352 hours, which corresponded to an average system capacity of about 5 l / h. The degree of water recovery in these tests reached 93 %. In 2015, NASA plans (roadmap) recorded that the CDS system was chosen for promising space flights. For unknown reasons, the works on CDS are currently stopped.

It should be noted that in the majority of publications devoted to the study of the functioning of various centrifugal distillers, their integral, average for the full cycle of operation, characteristics (capacity, SPC, product quality) are given, and practically no information is available on the effect produced on the operation of the distiller by such important indicators as heat pump power NTHP and the distiller rotor rotational speed.

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ЕВОЛЮЦІЯ СИСТЕМИ ВІДЦЕНТРОВОЇ ДИСТИЛЯЦІЇ З ТЕРМОЕЛЕКТРИЧНИМ ТЕПЛОВИМ НАСОСОМ ДЛЯ КОСМІЧНИХ МІСІЙ

Частина 1. Огляд публікацій по відцентровій дистиляції в період 1990 – 2017 рр.

У статті описані основні результати розробок і випробувань системи багатоступінчастої відцентрової вакуумної дистиляції (СМЕД) з термоелектричним тепловим насосом (ТНР). У цих роботах дані в основному відомості по інтегральних характеристиках роботи системи, а саме: продуктивності по дистиляту, питомій витраті енергії на одиницю маси одержуваного дистиляту і якості дистиляту при випарюванні (концентруванні) водяного розчину NaCl, урини й сумішей – урини з конденсатом, урини з конденсатом і гігієнічною водою. Бібл. 29, Табл. 5.
Ключові слова:

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ЭВОЛЮЦИЯ СИСТЕМЫ ЦЕНТРОБЕЖНОЙ ДИСТИЛЛЯЦИИ С ТЕРМОЭЛЕКТРИЧЕСКИМ ТЕПЛОВЫМ НАСОСОМ ДЛЯ КОСМИЧЕСКИХ МИССИЙ

Часть 1. Обзор публикаций по центробежной дистилляции в период 1990 – 2017 гг.

В статье описаны основные результаты разработок и испытаний системы многоступенчатой центробежной вакуумной дистилляции (СМЕД) с термоэлектрическим тепловым насосом (ТНР). В этих работах даны в основном сведения по интегральным характеристикам работы системы, а именно: производительности по дистилляту, удельному расходу энергии на единицу массы получаемого дистиллята и качеству дистиллята при выпаривании (концентрировании) водного раствора NaCl, урины и смесей – урины с конденсатом, урины с конденсатом и гигиенической водой. Библ. 29, Табл. 5.

Ключевые слова: термоэлектричество, тепловой насос, дистиллятор.

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