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COMPARATIVE ANALYSIS OF THERMAL DISTILLATION METHODS WITH HEAT PUMPS FOR LONG SPACE FLIGHTS

The work compares technologies currently in use for water recovery from the vital products of astronauts in the conditions of long space missions. The advantage of using centrifugal thermal distillation is demonstrated. Possible failures and disadvantages of a compression vacuum centrifugal distiller compared with a centrifugal multistage distiller with a thermoelectric heat pump are shown. Bibl. 38, Fig. 3, Tabl. 2.
Key words: thermoelectricity, heat pump, distiller.

Introduction

The thermal distillation of the wastewater of the life support system for long space flights was developed with the advent of astronautics. In [1], several distillation methods are described: an air-evaporation system (AES), a vacuum static evaporation system, and a centrifugal vacuum evaporator — an analogue of the Hickman evaporator described in [2].

In 1962, the first vacuum compression centrifugal distiller (VCD) was manufactured - a prototype of a distiller operating since 2008 at the International Space Station (ISS) [3].

In [4], a thermoelectric membrane evaporator is described in which wastewater evaporates in vacuum on porous membranes on one side of a thermoelectric module, and steam condenses on a porous plate on the other side of the module.

In 1961, the Kiev Polytechnic Institute began research on the processes of hydrodynamics and heat transfer during condensation and evaporation in liquid film on a rotating surface.

In [5], the results of studying the liquid flow on a rotating surface are presented. In [6], the research results are presented and a method for calculating the minimum irrigation density, which ensures full coverage of a rotating surface with a liquid film, is substantiated. In [7], dependences are given for calculating heat transfer during condensation, and in [8], dependences are given for calculating heat transfer during evaporation of a laminar and turbulent liquid film on a rotating disk and conical heat transfer surfaces, as well as during evaporation in a rotating liquid ring [9].

From 1974 to 1993, on the instructions of a space company from Russia, scientists and engineers of the KPI developed and tested prototypes of centrifugal distillers made in Ukraine and designed for operation in space.

Several types of centrifugal distillers with various heat pumps were developed [10, 11]:

– thermoelectric centrifugal distiller, in which the heat exchange rotating surface was a thermoelectric heat pump;

– centrifugal steam jet distiller in which a steam jet compressor is integrated in a rotating shaft;

– centrifugal three-stage distiller.

Until 1990, publications in the USSR, which contained data on the design of spacecraft, were not permitted.

In [12-14], brief information is given on a 3-stage distiller (production, total energy consumption) without information on the degree of concentration, the hours of the distiller operation, the number of rotor revolutions, and the quality of the distillate.

Since 1999, “Thermodistillation” company (created by KPI employees) together with the Institute of Thermoelectricity (Chernivtsi) on the instructions of Honeywell Co (USA) began to develop, manufacture and test a new five-stage distiller with an improved thermoelectric heat pump (THP). In the period 2000-2007, three centrifugal distillers and two THPs were manufactured.

From 2000 to 2017, centrifugal distillation systems (distiller + THP) were tested to recover water from various wastewater of life support systems for manned spacecraft at the KPI, Honeywell Co, at the Marshall Center (NASA).

Test results have been published in numerous articles and reports at Life Support Conferences (ICES) and International Astronomical Congresses (IAC) [15-29]. The processes in a centrifugal apparatus with a thermoelectric heat pump are considered in detail in a series of articles [30–32].

These studies show in detail the effect produced on the efficiency of centrifugal distillation with THP by rotation speed, degree of water recovery, liquid flow rate in the circuits of the distillation system, quality factor of thermopile, type of solution.

Almost simultaneously with the development of VCD, a thermoelectric membrane distillation system called TIMES was manufactured in the USA [33 – 35]. In this distiller, evaporation and condensation takes place on the static surface of thermoelectric modules.

This article compares the technical and operational characteristics of three thermal distillation systems:

– static thermoelectric membrane distiller (TIMES);

– vacuum vapor compression centrifugal distiller (VCD);

– centrifugal multistage distiller with a thermoelectric heat pump (CMED + THP).

Static thermoelectric membrane distiller TIMES

This distiller was developed by Hamilton Seastrand Space Systems International in the 1970s.

The system uses a polymer membrane, from the surface of which evaporation of pure water from contaminated wastewater occurs. Ideally, solutes and solids do not pass through the membrane. The resulting steam condenses on a cooled membrane. The resulting condensate is aspirated through a cooled membrane and a high-quality distillate is obtained at the system outlet. An important feature of TIMES is total recycling of the feed stream, which is becoming more and more concentrated. Energy consumption is minimized through the use of static heat pumps (thermoelectric devices).

The evaporation of wastewater in this system occurs in vacuum. For terrestrial applications and small capacities (less than 5 liters per hour), the TIMES system is quite simple and effective, especially if there is a slight difference in the temperature of the evaporated liquid and steam condensation in the thermoelectric module. When urine is concentrated to a salt content of 40 %, only due to physicochemical temperature depression, the temperature difference in the thermoelectric module will increase by 4 ... 5 ° C, which significantly reduces the efficiency of the system. In addition, the magnitude of this difference will depend on the pump capacity in the circulation circuit of the source fluid.

The maximum concentration of liquid in the TIMES system is limited due to salt deposits in the pores of the membrane evaporator. Similar processes are observed in reverse osmosis membranes during desalination of salt water with a concentration close to urine and a water recovery level of up to 60% [33]. The data of publications [3, 4, 34] on the TIMES system show that the maximum efficiency of this distiller, taking into account the costs of the distiller's circulation pumps, does not exceed η = 2.5 ... 3 (with ηTHP = 3 ... 3.5). This is close to the theoretical possibilities of such a heat pump when the temperature difference of the liquid from the heating side in the module and the steam from the cooling side is less than 4 ... 5 °C.

Centrifugal vapor compression distiller (VCD)

The vapor compression centrifugal distiller was created and manufactured in 1962 by order of NASA [34]. At the moment, the latest version of VCD is installed on the ISS. With its help, more than 13 tons of distillate have been produced at the ISS since 2008.

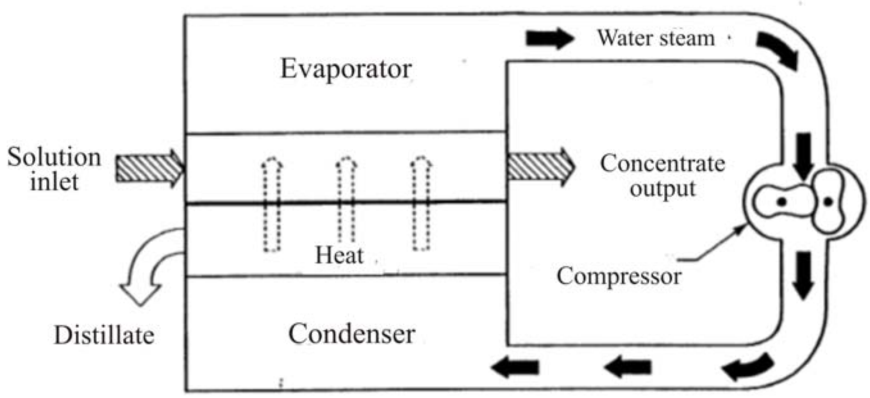

Fig.1. Circuit diagram of VCD

The vapor compression distiller utilizes the latent heat of condensation by compressing the resulting water steam in order to increase its pressure and temperature, followed by condensation on the surface in thermal contact with the evaporator.

The resulting heat flux from the condenser to the evaporator, determined by the temperature difference between saturated steam and liquid, is sufficient to evaporate an equal mass of water from water-containing waste. The need for additional energy is determined by the need to compress water vapor and replenish mechanical and heat losses.

Before delivery to the station, more than 10 prototypes were manufactured with a detailed publication of the test results of these distillers almost every year. According to the results of operation on the ISS, information is given about various damage in operation, both mechanical and problems with the quality of the distillate. Each year, reports on the ICES Life Support Conference provide information on the status of the system.

Fig. 1 shows a graph of the total production of distillate by a vapor compressor distiller in the period from 11/21/2008 to 11/21/2018 [35], from which it follows that the average VCD output was 4 ... 5 *l*/day (did not exceed 1.8 l / hour), the degree of water recovery was 75 % and only after 2016 it increased to 85 %.

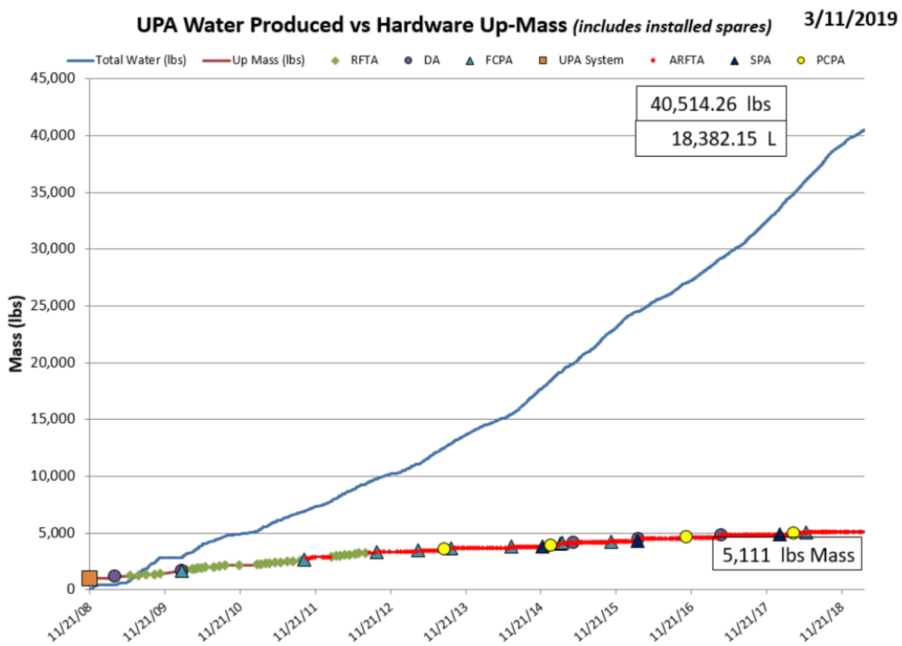

Fig. 2. Total and annual amount of distillate produced on the ISS using VCD [34, graph 7]

Back in 1989, a comparison of three technologies with a phase transition was made in [3]: TIMES, VCD, and AES (air evaporation system on a porous surface). The main characteristics of the three systems are shown in [3, table 12]. VCD has significant advantages over AES and TIMES. Already in 1990, VCD had a significantly longer test time when concentrating various wastewater compared to other systems. Therefore, in the future, VCD was installed on the ISS.

Multistage centrifugal distiller with a heat pump

In a multistage distillation system with a thermoelectric heat pump, as described in [10 – 14], two principles of reducing energy consumption are used to concentrate wastewater under zero gravity conditions: multistage evaporation and thermoelectric heat pump (CMED + THP). Figure 3 shows a centrifugal distillation scheme with a thermoelectric heat pump.

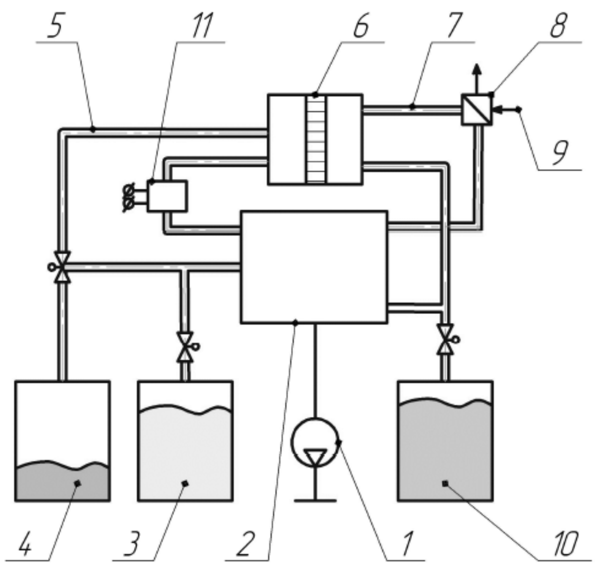

Fig. 3. Schematic of water regeneration system with a centrifugal distiller and a thermoelectric heat pump
1 – vacuum-pump; 2 – distiller; 3 – initial liquid cavity; 4 – concentrate cavity; 5 – "hot" circuit; 6 – thermoelectric heat transformer; 7 – "cold" circuit; 8 – balancing cooler; 9 – cooling liquid delivery; 10 – distillate product collector; 11 – reserve heater

The initial liquid from tank 3 enters the rotating rotor of the centrifugal distiller 2 evacuated by means of a vacuum pump 1, fills the circuit 5 and the heating cavity of the thermopile 6 to the required level of evaporation of the distiller. The cold cavity of the thermopile is connected to the condenser of the distiller using circuit 7 ("cold" circuit). The excess heat is removed from the system using a refrigerator 8. The distillate product, as a result of the evaporation-condensation process, is pumped into tank 10, and the concentrate - into tank 4.

If the thermoelectric heat pump 6 fails, the system will be able to work with reduced efficiency when heating the liquid in the hot circuit using the heater 11.

The distiller is multistage and includes 3 or 5 stages with rotating heat transfer surfaces that separate the brine and condensate. A number of built-in pumps (based on Pitot tubes) provide irrigation of heat-exchange surfaces in each stage of the distiller. Wastewater flows sequentially through each of the evaporation stages. The last evaporation stage is the instant boiling stage of an overheated solution, which is overheated on the hot side of a thermoelectric heat pump. The steam obtained in this stage is heating in the previous stage of the distiller.

The distillate from each stage and the steam of the evaporation stage with the lowest pressure enter the final condenser cooled by the distillate circulating along the circuit: the final condenser - the cold side of the thermoelectric heat pump - the final condenser.

Papers [21 – 32, 36] are concerned with numerous studies of CMED characteristics with the concentration of different types of wastewater [24], distiller simulation and system reliability issues [25 – 26].

In [30 – 32], the local characteristics of the distiller and heat pump are analyzed and the analytical model of centrifugal distillation is refined.

Analysis of the characteristics of vapor compression and multistage distiller with a thermoelectric heat pump

Technical characteristics

The main technical characteristics: production, energy consumption, degree of concentration, distillate quality, weight, volume and scalability. These data are shown in Table 1 [23].

Table 1

Comparison of centrifugal techniques

Technology	VCD	CMED + THP
Mass, kg	216	202
Volume, m^3	0.5	0.5
Production, kg/day	1.63	2…7.5
Recovery, %	Up to 85	Up to 95
Distillate quality	Meets potable water standards	Meets potable water standards
Specific energy consumption, W·h/kg	< 180	< 110

From Table 1 it follows that in CMED, depending on the power of the heat pump, it is possible to vary production over a wide range, which meets the requirements of the system according to the scalability criterion.

In VCD, it is not possible to significantly increase the production of a distiller due to a disproportionate increase in energy consumption with an increase in compressor speed. With an increase in production of more than 1.8 l/h [34], an increase in the degree of concentration of urine leads to an almost directly proportional increase in specific energy consumption.

In CMED with THP, the effect of concentration on the production and energy consumption is significantly lower [30, 32].

System reliability

The operation of the vapor compression distillation system of liquid wastewater (urine, atmospheric moisture condensate) on the ISS for 11 years has been a significant achievement by American scientists and engineers in solving the problem of water regeneration in space flight conditions.

None of the many other technologies for concentrating liquid effluents (reverse osmosis, electrodialysis, static thermoelectric evaporator) has and cannot have such results when working in space.

At the same time, improving thermal distillation using centrifugal forces is of great importance. This is due to the fact that VCD has certain limitations on the production, the possibility of increasing the degree of concentration, as well as in some positions related to the system reliability.

During the 11 years of VCD operation, there have been a large number of failures, incidents of poor water quality and other shortcomings (see Table 2).

Table 2

The list of failures in the operation of the urine processing assembly (UPA) of the US segment on the ISS in comparison with the prototype Centrifugal Multieffect Distiller (CMED) (as of 2019)

№	VCD problem name	Source of information	CMED + THP
1	VCD Centrifuge Drive Belt Slip	[37]	There is no such drive
2	Leakage of urine into the distillate through the shaft bearing of a VCD centrifuge	[37]	In the CMED design, bearings do not come into contact with urine
3	Liquid level sensor malfunctions	[37]	There is no sensor
4	Leakage of water vapor from the condenser into the stationary housing.	[37]	CMED design eliminates steam leakage
5	Water condensation in a fixed housing	[37]	Condensation in the CMED housing is eliminated
6	Evaporation of accumulated condensate in the heater housing reduces the efficiency of the distiller	[37]	There is no such problem, since condensation in the CMED housing does not accumulate
7	Wear and breakdown of centrifuge bearing and compressor	[37]	Ceramic bearings of CMED eliminate the problem
8	Insufficient service life of the peristaltic pump	[38]	There are no peristaltic pumps
9	Worn compressor drive gears	[38]	There is no compressor
10	Failures in the transmission of the pump assembly	[38]	In CMED, fluid is pumped by a Pitot tube
11	Failures of flow control valves in the pump assembly	[38]	No pump assembly

The right column of this table contains comments regarding the possibility of a similar problem in the CMED system. Another particularly important case of damage to the heat pump and the consequences of such a case should be added to this table. In VCD, when the compressor is damaged, the system ceases to function. In CMED, when shutting down due to complete or partial damage to the heat pump, the system switches to a conventional heat exchanger-heater, in which the solution of the first stage will circulate (see pos. 11, Fig. 3). Such an accident will lead to an increase in the specific energy consumption by about a factor of 1.5 ... 2, but will not affect the performance of the entire system.

Conclusions

Comparison of different technologies for water recovery with a phase transition showed that VCD at the time of installation on the ISS had significant advantages compared to AES and TIMES. During operation, it was possible to regenerate and obtain more than 13 tons of distillate, which greatly reduced the cost of delivering fresh water to the station. At the same time, a number of significant design flaws of the system were identified during the operation, which almost completely eliminates the possibility of using VCD for long-range space missions to the Moon and Mars. In this regard, there is a need to develop a reliable and efficient water recovery system for long-range space missions. The stated requirements are most closely met by CMED with a thermoelectric heat pump.

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ПОРІВНЯЛЬНИЙ АНАЛІЗ МЕТОДІВ ТЕРМІЧНОЇ ДИСТИЛЯЦІЇ З ТЕПЛОВИМИ НАСОСАМИ ДЛЯ ТРИВАЛИХ КОСМІЧНИХ ПОЛЬОТІВ

У роботі проведено порівняння відомих технологій для витягання води з продуктів життєдіяльності космонавтів в умовах тривалих космічних місій. Показана перевага використання відцентрової термічної дистиляції. Показані можливі відмови і недоліки компресійного вакуумного відцентрового дистилятора в порівнянні з відцентровим багатоступінчастим дистилятором з термоелектричним тепловим насосом. Библ. 38, рис. 3, табл. 2.

Ключові слова: термоелектрика, тепловий насос, дистилятор.

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ МЕТОДОВ ТЕРМИЧЕСКОЙ ДИСТИЛЛЯЦИИ С ТЕПЛОВЫМИ НАСОСАМИ ДЛЯ ДЛИТЕЛЬНЫХ КОСМИЧЕСКИХ ПОЛЕТОВ

В работе проведено сравнение известных технологий для извлечения воды из продуктов жизнедеятельности космонавтов в условиях длительных космических миссий. Показано преимущество использования центробежной термической дистилляции. Показаны возможные отказы и недостатки компрессионного вакуумного центробежного дистиллятора по сравнению с центробежным многоступенчатым дистиллятором с термоэлектрическим тепловым насосом. Библ. 38 , рис. 3, табл. 2.

Ключевые слова: термоэлектричество, тепловой насос, дистиллятор.

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