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JUSTIFICATION OF THERMAL DISILLATION METHOD WITH A THERMOELECTRIC HEAT PUMP FOR LONG-TERM SPACE MISSIONS

This article describes the main methods of thermal distillation that can be used for long-term space missions with humans. Their advantages and disadvantages are shown, the basic information on the characteristics of the systems, namely: productivity of the distillate, specific energy consumption per unit mass of the distillate and the quality of the distillate by evaporation (concentration) of aqueous NaCl solution, urine and mixtures – urine with condensate, with condensate and hygienic water. Restrictions that do not allow them to be used for flights and possible ways to solve them are indicated. Bibl. 36, Fig. 9, Table. 1.
Key words: thermoelectricity, heat pump, distiller.

Introducion

Wastewater treatment (liquid waste of human life) is critical for a successful human flight to the Moon and Mars [1 – 2]. Among all known wastewater regeneration systems, the most promising method is thermal distillation [3 – 4].

The principle of thermal distillation is based on the supply of heat to the initial solution, evaporation of water from the solution and condensation of the obtained steam. Thus, in the process of thermal distillation, there are stages of heat supply (evaporation) and heat removal (condensation), which makes it possible to use a heat pump to increase the efficiency of the system. In the conditions of weightlessness and rather small productivity the thermoelectric heat pump can work effectively. Its obvious advantage is the absence of moving parts, simplicity and reliability of construction.

A thermal vacuum compression centrifugal distiller has been installed at the only inhabited extraterrestrial object, the International Space Station (ISS), to regenerate wastewater. It has been operating since 2008 and has processed more than 13 tons of water. This has significantly reduced the cost of its delivery (the cost of delivering 1 kg of cargo to the ISS is about $ 3.000. However, as already noted in many works, its design does not guarantee work in the case of long missions, and to eliminate this shortcoming is fundamentally impossible [5].

This article provides a brief overview and critical analysis of thermal distillation methods for operating conditions in weightlessness.

Static thermoelectric membrane distiller TIMES

This distiller was developed by Hamilton Seastrand Space Systems International in the 1970s [6-8].

The system uses a polymer membrane that selectively passes water from a wastewater source. Ideally, unwanted dissolved and undissolved solids do not pass through the membrane, and a high-quality distillate is obtained (Fig. 1). An important feature of TIMES is the overall recirculation of the feed stream, which becomes more and more concentrated during the distillation process. Energy consumption is minimized through the use of solid-state (immovable) heat pumps (thermoelectric devices).

The solution heated in the thermoelectric device is taken away by the circulating pump and passes through a special membrane, and the received water vapor condenses on the cold side of the thermoelectric device.

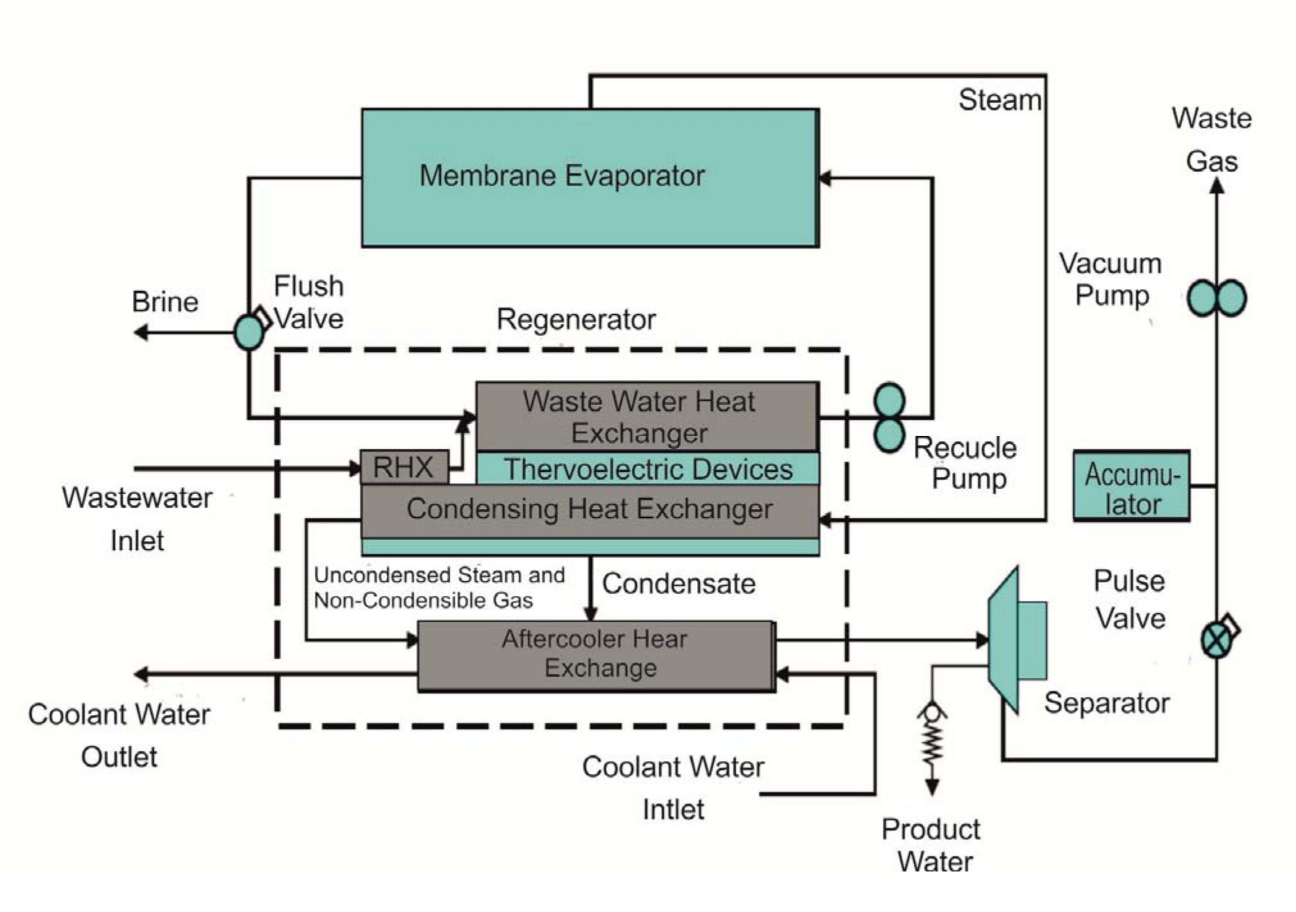


Fig. 1 Schematic diagram of TIMES

Based on the known equations and properties of semiconductors [7], a dimensionless diagram of thermoelectric characteristics was developed, which is shown in Fig.2.

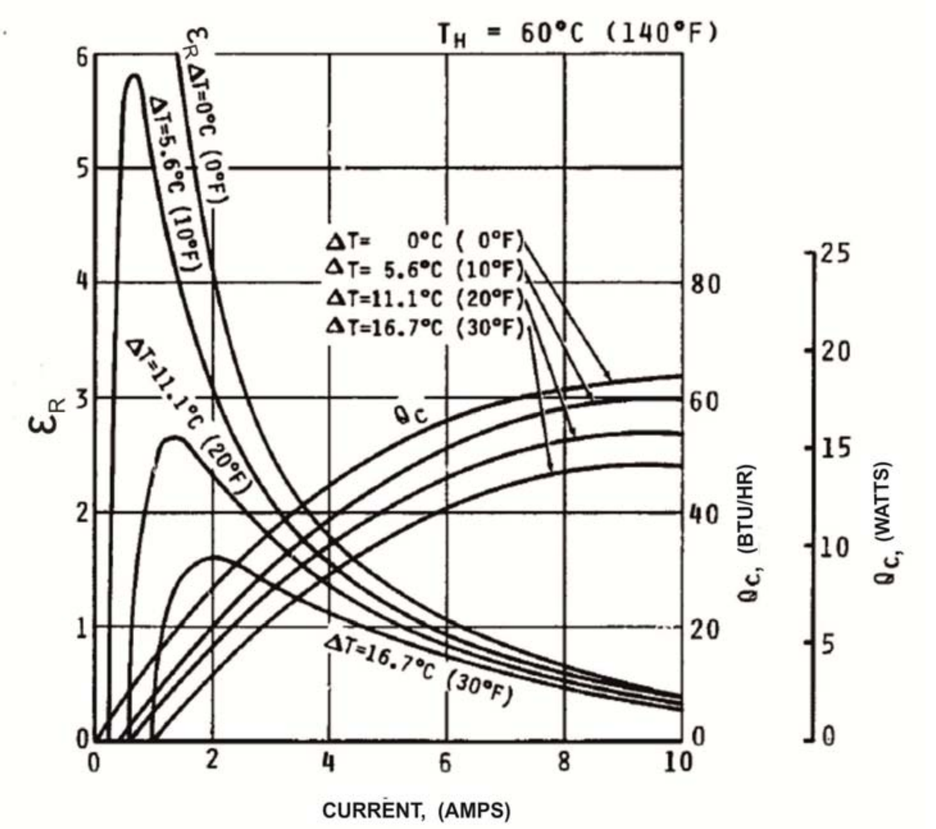


Fig. 2 Technical characteristics of the thermoelectric device

Thermoelectric efficiency (COP_R) is affected not only by the design of the condenser, but also by the area of the membrane, the rate of urine recirculation, the design of the urine heat exchanger, the thermoelectric current and the concentration of solids in wastewater, etc. As a result, in experimental trials in mild urine nominal COP_R approximately equaled 2.8. The main characteristics of the developed system are shown in Fig. 3.

Later TIMES was modified [8] to address the identified shortcomings: the membrane area was increased 2.6 times, the thermoelectric heat transfer area was increased 4.2 times, and the condenser was redesigned. The result of such modernization of the system was an increase in productivity when working on non-concentrated urine by 1.9 times and an increase in thermoelectric COP_R to 3.1 compared with the predicted theoretically $COP_R = 5$. Analysis of the system showed that the condensing heat exchanger is the main reason for this decrease in productivity. First, the flowing part of the condenser inefficiently removed water, which led to flooding of the heat exchange surface, resulting in the cessation of effective heat dissipation during condensation. Second, blocking all channels led to the accumulation of non-condensed gases in the condenser. This caused an increased thermal resistance of the condensation process, which further increased the thermoelectric temperature difference ΔT. Eventually, the pressure in the condenser increased until, at least through some of the channels, water was blown out, and the accumulation process began again. All this led to a very low energy efficiency of the system.

There were serious problems with the quality of the obtained water. Leaks were detected at the junction of the membranes and their collector. The second source of contamination is that dissolved solids inside the membranes are transported directly through the membrane walls when the membranes come into contact with the water condensate of the product inside the evaporator. The formation of condensate in the evaporator can occur during various transient modes of operation. The third reason for the decline in water quality is the formation of water-soluble gases that can pass through membranes. The main undesirable gas is ammonia. Since the formation of ammonia depends on temperature, lowering the operating temperature of TIMES should lead to improved water quality. However, this required a transition to a lower operating pressure, and the design of TIMES condensing heat exchangers was sensitive to operating pressure, becoming less efficient at lower pressures.

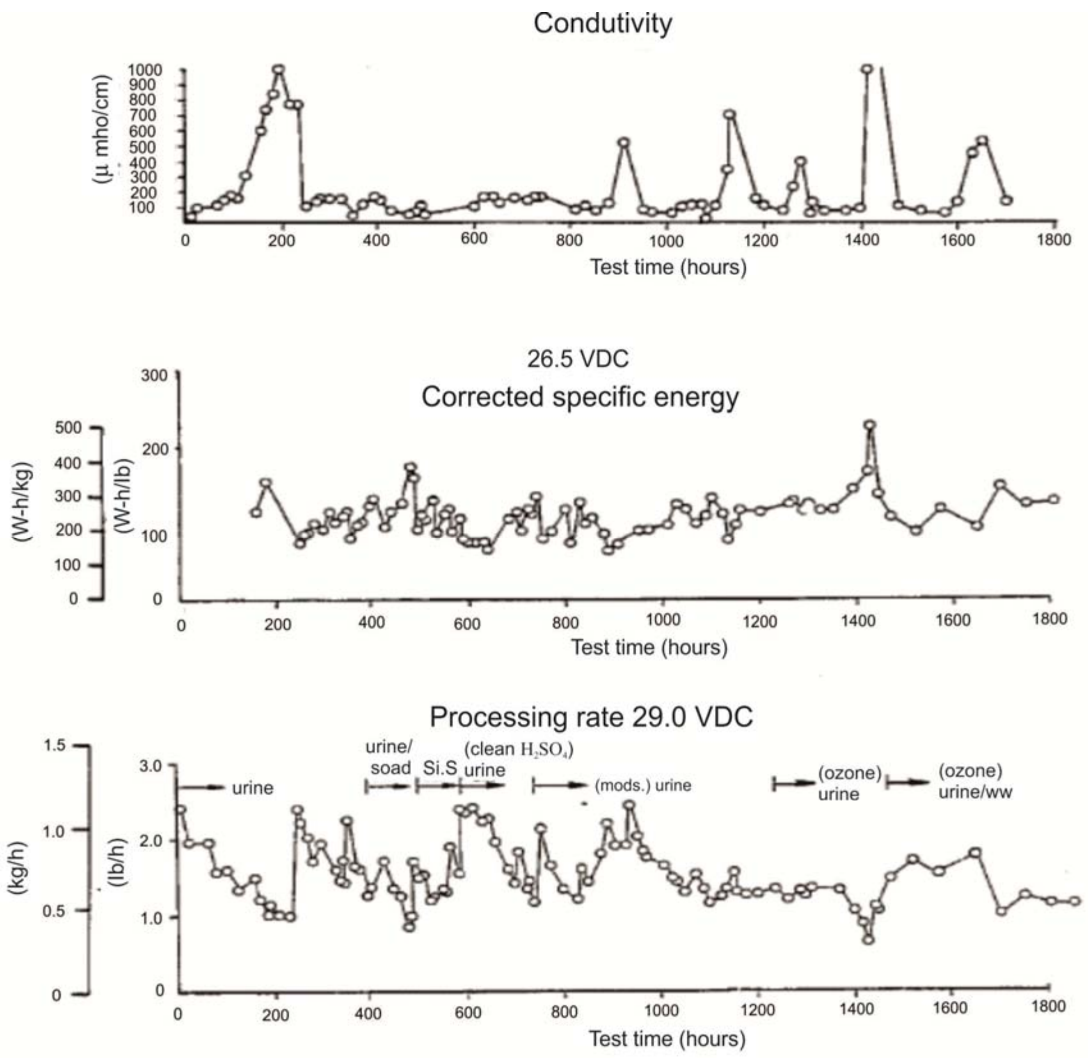


Fig. 3. Operating parameters of TIMES

In addition, the limiting concentration of liquid in the TIMES system is limited due to the deposition of salts in the pores of the membrane evaporator. Similar processes are observed in reverse osmosis membranes in the desalination of salt water with a concentration close to urine and a level of water up to 60 %.

Thus, despite an interesting idea, the TIMES system was unstable, especially in terms of energy efficiency and quality of the distillate. These shortcomings could not be eliminated without a radical change in the concept of the whole system. As a result, in the early 1990s, the development of the TIMES system virtually ceased, and for flight tests for urine processing on the International Space Station, a competitive VCD thermal distillation technology was chosen.

Centrifugal vapor compression distiller (VCD)

The steam compression centrifugal distiller (VCD) was created and manufactured in 1962 by order of NASA [9]. In 2008, the latest version of the VCD was installed on the ISS, where it continues to operate to this day. It produced more than 13 tons of distillate on the ISS [10].

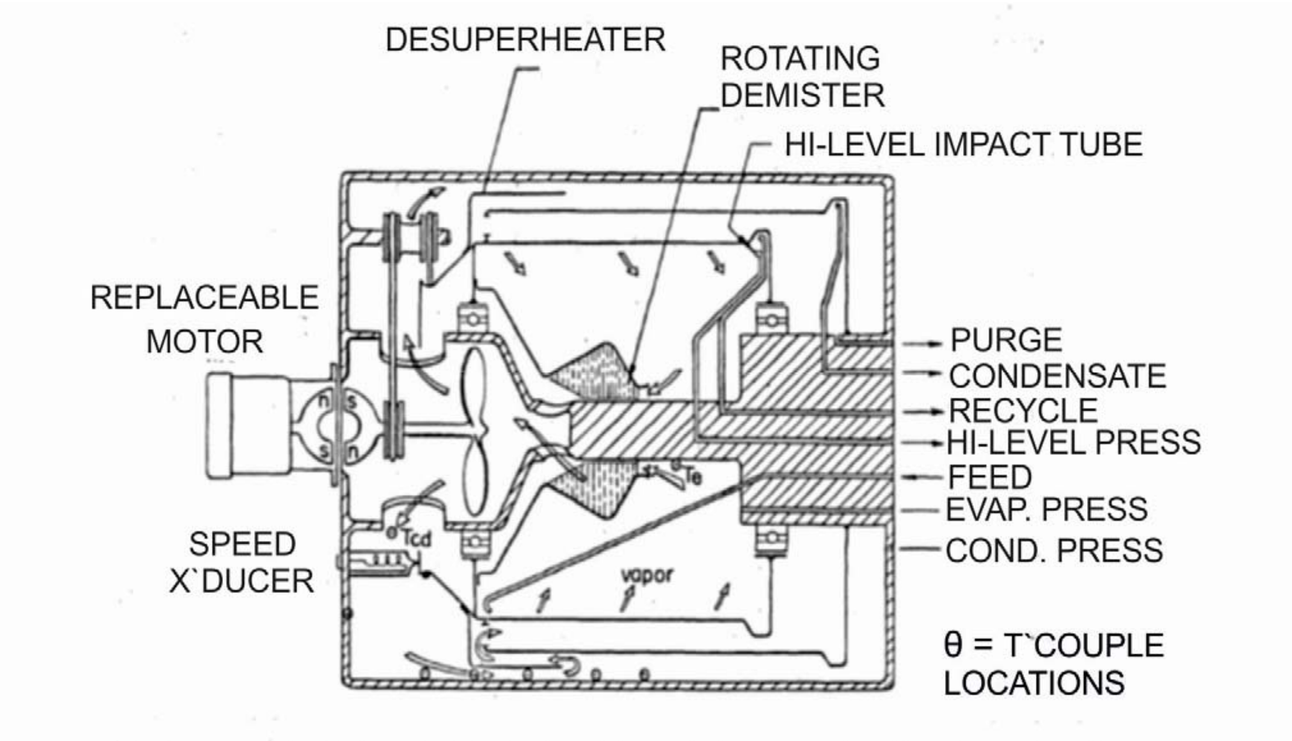


Fig. 4. Schematic diagram of VCD

Figure 5 shows the distillation unit, which is the main working component around which the VCD module is developed. Inside the distiller there are two main parts: a centrifuge for separating liquid and gas phases and a compressor. The centrifuge consists of two cylinders: an inner cylinder through which a film of evaporating liquid flows, and an outer cylinder designed to collect water droplets condensed on its surface. The compressor is designed to remove steam generated by evaporation, increase its temperature and pressure and supply it to the condenser. Not all liquid evaporates as it passes through the rotating cylinder; and the remainder, together with the solids that have been dissolved in the water, are discharged into an annular settler at the opposite end. The kinetic energy of the fluid is converted to static pressure, which is high enough to deliver fluid to the pump inlet without flashing. Similarly, the water condensed on the opposite side of the inner surface is collected in a rotating annular settling tank, taken by a stationary tube and sent to the inlet of the corresponding pump.

The compressor represents the two-rotor car with the drive from the electric motor, with a speed of 3600 rpm. To facilitate access, the engine is located outside the distiller. The synchronous magnetic coupling is used to transmit motor torque across the chamber boundary to the compressor inlet shaft without the need for dynamic shaft sealing. The centrifuge is driven by the compressor shaft through a belt and pulley system (centrifuge speed 290 rpm). A rotating demister is installed at the compressor inlet to exclude the ingress of liquid from the vapor stream. The distiller's water capacity when working on urine is about 1.3 l/h.

The specific energy consumption of the distillation unit significantly depends on the concentration of the solution (see Fig. 7).

More than 10 prototypes were manufactured for delivery to the station with detailed publication of the test results of these distillers [11]. Based on the results of operation on the ISS, information is provided on various damages in operation, both mechanical and problems with the quality of the distillate. Annually, reports at the ICES Life Support Conference provide information on the state of the system [10, 12 – 13].

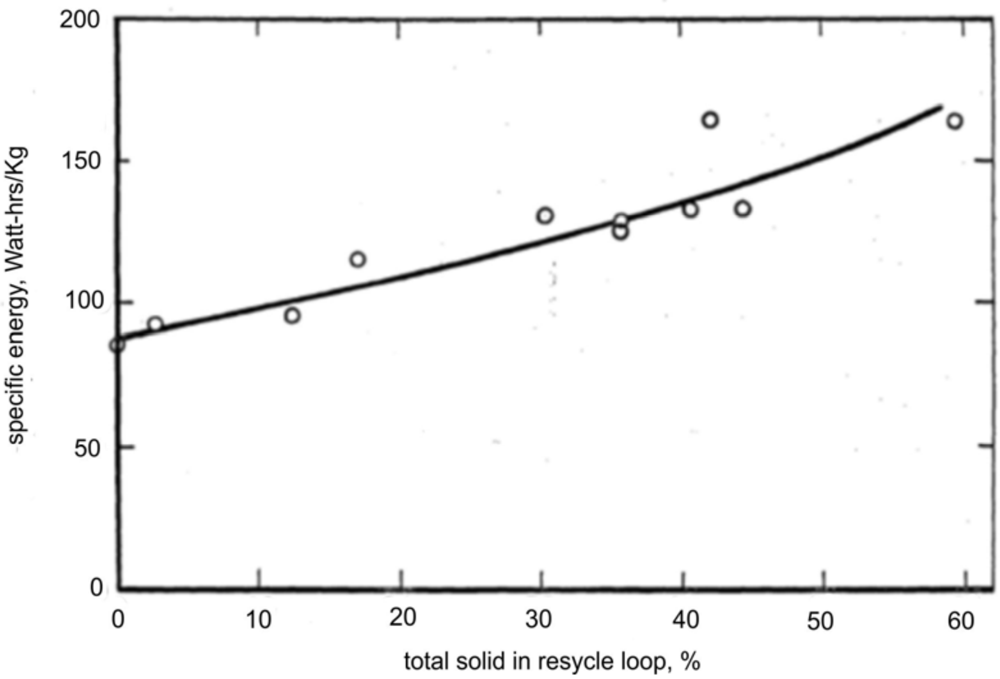


Fig. 5 The influence of concentration in the recirculation circuit on the specific energy consumption

Fig. 8 shows a graph of the total productivity of a vapor compression distiller in the period from 21.11.2008 to 21.11.2018 [10]. The average VCD productivity was 4 ... 5 l/day, did not exceed 1.8 l/h, the degree of water extraction was 75 %, and only after 2016 it was possible to increase it to 85 %. The main reason for low performance is the low heat transfer coefficient, which does not exceed 800 W/m^2. This is due to the low speed of the distiller centrifuge. Also in [9] it is noted that due to the peculiarity of the compressor, the inlet to the heat exchanger receives superheated steam. As a result, a significant part of the heat exchange surface is used for the inefficient process of cooling superheated steam and only then begins the condensation of steam.

As a result, despite the successful experience of VCD operation on the ISS, recent publications point to the impossibility of using this distiller for long space missions. For full-fledged space travel it has very low productivity (< 2 l/h), low efficiency (which also strongly depends on the solution being processed), in the design of the system there are inefficient peristaltic pumps for pumping liquid streams, the degree of regeneration 85 % is also insufficient for long missions. And what is very important, the presence of a complex steam compressor, in principle, does not allow guaranteeing uninterrupted operation for a long period of time, which is critically important for long space missions. These disadvantages cannot be eliminated without a complete restructuring of the distiller design.

Thus, there is a need to develop a system that would meet all the requirements for long flights.

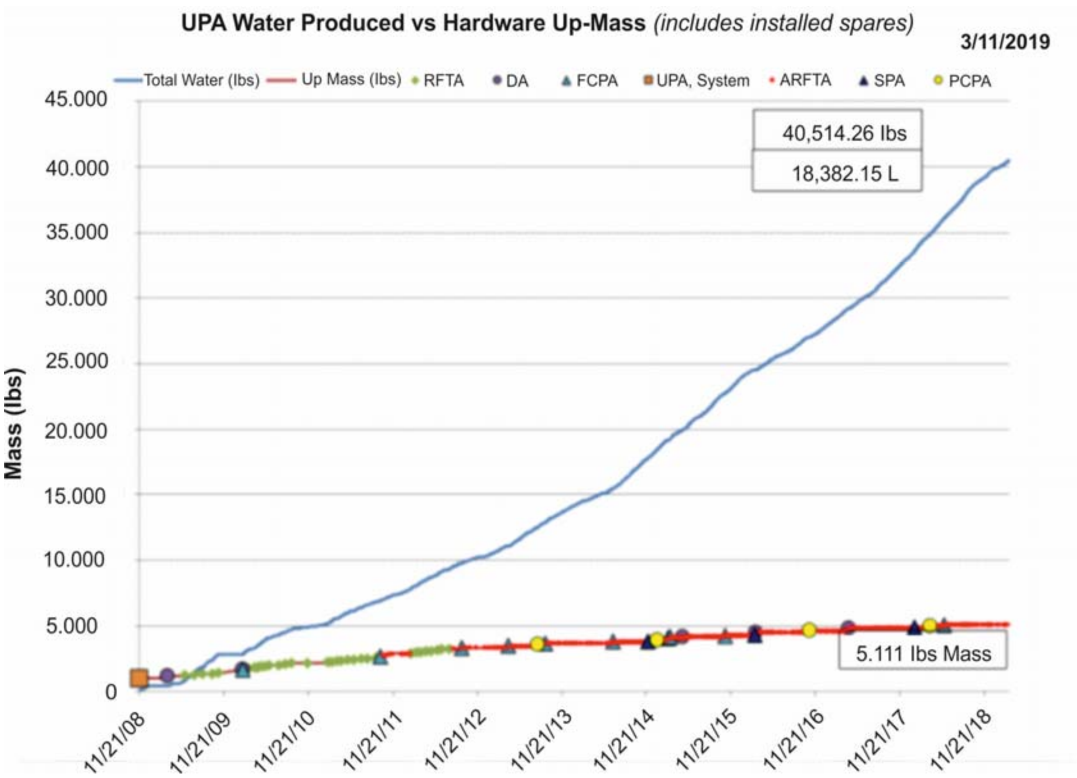


Fig. 6. Total and annual amount of distillate produced at ISS using VCD

Centrifugal wiped-film rotating disk distiller (WFRD)

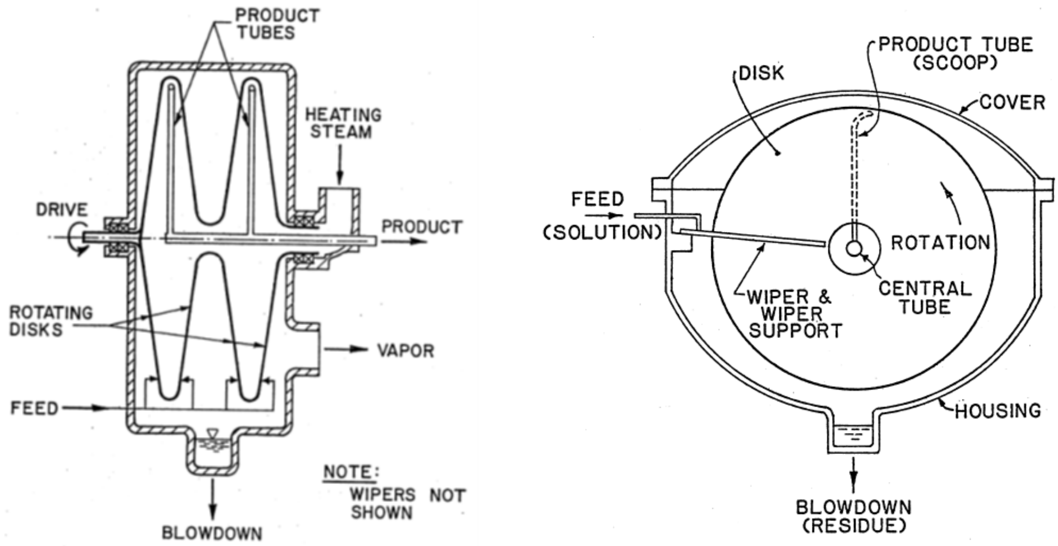
The rotating disk evaporator was designed and tested at the UC Berkeley Water Technology Center [14 – 16].

Fig. 9*a* schematically shows the cross section of the distiller, and Fig. 9*b* is a schematic section of two pairs of disks. The rotor consists of disks connected together at the periphery to form cavities, and the cavities are also connected together at the periphery of the inner holes. The rotor is mounted on a hub closed at one end and open at the other. Steam is introduced through the open end and condenses on the inner surfaces of the rotary disks. The condensate formed on the inner surfaces of the discs is discharged to the periphery, where it enters the stationary product tubes (scoops) connected to the central tube and flows out of the evaporator as a distillate. The rotor rotates along a horizontal axis inside the chamber, into which an aqueous solution is fed along the length of stationary scrapers (Fig. 9*b*, and is distributed in the form of a thin uniform film on the outer surfaces of the rotary discs without the formation of dry spots. Non-evaporated liquid is discharged to the periphery of the discs and removed from the chamber. The use of centrifugal force and a scraper leads to a decrease in the thickness of the distillate film, which increases the heat transfer coefficient.

The system operated stably at an evaporation temperature of 60 °C, flat disks were made of copper with a thickness of 0.036 inches, the heat transfer coefficient reached 60 kW/m^2 at a temperature difference of 0.1 to 3 °C.

The initial solution was passed through a cartridge type filter, regenerative heat exchanger, degasser and then fed to the evaporator. Part of the liquid was evaporated from the initial solution, and the residue was pumped from the bottom of the chamber into a regenerative heat exchanger for cooling. The formed steam was removed by an external compressor, compressed to increase the pressure and saturation temperature, and then fed into the cavity for condensation.

The disadvantage of the proposed distiller (just as for VCD) is the presence of a compressor and the presence in the system of circulating pumps. In addition, there is no removal of the product (condensate) in weightlessness. In terms of technical characteristics, the distiller was also inferior to its competitors (see comparison below).



a) *b)*

Fig. 7. Schematic diagram of a centrifugal film scraper distiller (a) and a section of its evaporating section (b)

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Thermal centrifugal distillers with thermoelectric heat pumps, developed at Kyiv Polytechnic Institute (KPI)

From 1974 to 1993, KPI scientists and engineers, on the instructions of a Russian company involved in the manufacture of equipment for space missions, developed and tested several types of centrifugal distillers with thermoelectric heat pumps for operating conditions in space.

Among them:

– thermoelectric centrifugal distiller, in which the heat exchange rotating surface was also a thermoelectric heat pump [17];

– centrifugal multistage distiller, which works in combination with a stationary thermopile.

Multistage centrifugal distiller with a heat pump

The cascade distillation system in a simplified form is shown in Fig. 10 [18 – 22]. The system consists of two main components: a multistage vacuum centrifugal distiller and a thermoelectric heat pump. The working liquid is fed to a multistage vacuum centrifugal distiller, where water evaporates and condenses. Several stages work in parallel to ensure high performance. Energy for the process comes from a heat pump in which the distillation water is cooled and the source working fluid is heated. Both streams circulate, respectively, through the cold and hot circuits of the heat pump and return to the distiller. The temperature in the hot circuit is 35 ... 45 °C and in the cold one is from 20 to 25 °C. The supply and removal of liquids is controlled by valves with adjustable pressure and does not require a digital controller. The working fluid is contained in the working tank and is supplied to the hot circuit through a pressure regulated valve. The system operates under vacuum, and when the volume of the hot circuit decreases during evaporation, the pressure in it decreases, and additional source liquid is sucked into the distiller. The product or condensate is fed into the product tank through a pressure-adjustable valve. The product tank is also maintained under vacuum. As the volume of the cold circuit increases, the pressure increases and the valve opens to drain the distillate (product).

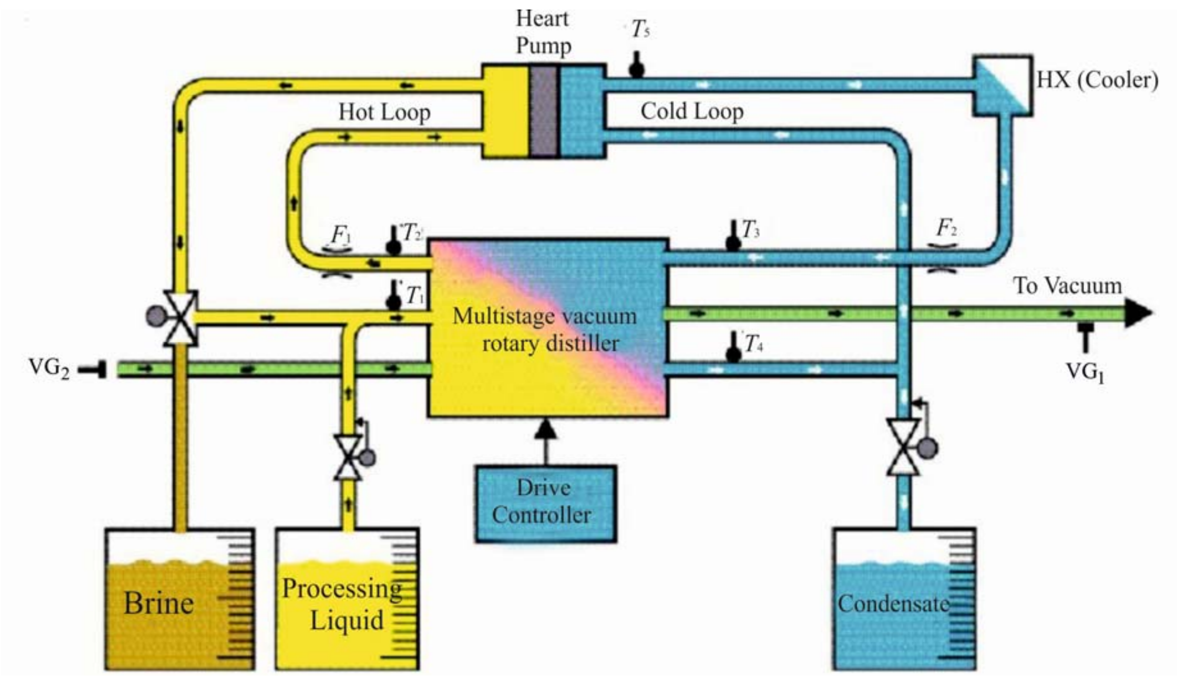

Fig. 8. Functional diagram of a cascade system

The process continues until the hot circuit is filled with concentrated brine and the evaporation temperature rises. At this point, the heat pump is turned off and the pressure is restored to atmospheric. This usually occurs when more than 90 % of the water is removed from the feed solution and collected in the product tank. The brine is then pumped out of the system into the brine tank and the distiller is turned off.

Two variants of the distiller were made: with three and with five stages.

Fig. 11 shows a diagram of a three-stage distiller. The five-stage device has a similar design, the main difference of which is only the number of steps.

The distiller has a sealed housing 1, in which the rotor 2 is mounted on bearings. The rotation of the rotor is provided by a drive through a sealed magnetic coupling. The rotor is divided by partitions into a number of distillation stages and a final condenser. Process (outlet) solution 3 is fed through channel 4, where it is distributed according to the degrees of distillation. The solution is fed through channel 5 to the system heater, from which (in an overheated state) through channel 6 it returns to the device, where the overheating of the liquid is removed by self-boiling. The vapor of the last stage of evaporation is condensed in the final condenser at contact with the distillate cooled on the cold side of the heat pump and in the additional heat exchanger. The cooled distillate enters the device through channel 7, is heated and removed again for cooling by the built-in pump through channel 8. Excess condensate (distillate, product) is discharged by the Pitot tube into the storage tank through channel 10. Evacuation of the device is through channel 11.

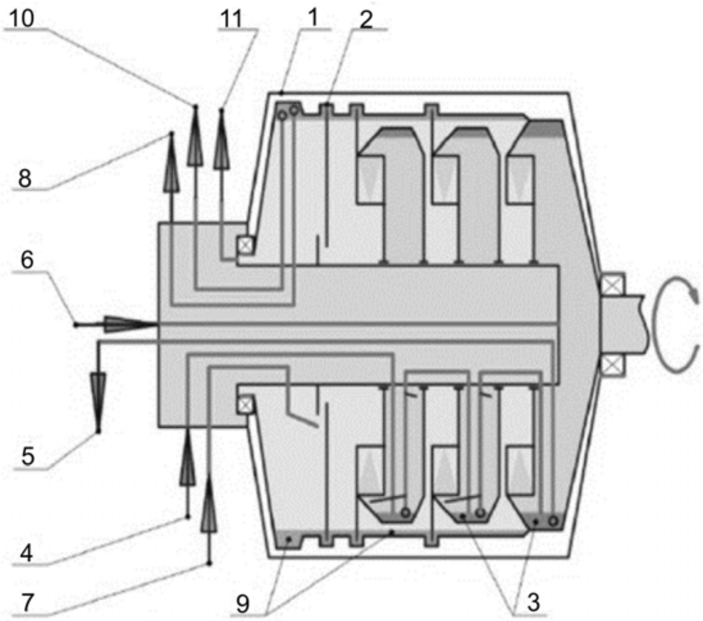

Fig. 9. The scheme of the centrifugal three-stage distiller:
1 - case; 2 - rotor; 3 - outlet solution 4 - inlet of the initial solution;
5 - outlet channel; 6 - supply channel; 7 - cooled condensate inlet; 8 - heated condensate outlet;
9 - condensate; 10 - the output of the distillate product; 11 - gas outlet

The advantages of CDS include:

1. High heat transfer coefficients (up to 104 W/(m^2 • K)) provide small temperature differences on the stages of the distiller.

2. The ability to achieve the degree of water extraction from the solution up to 96 % without deposits on the heat transfer surface.

3. Distillate quality is better than in VCD.

4. No external pumps with separate drives.

5. No seals with friction on a hard surface.

6. Self-regulation of the solution and condensate levels in the rotor cavities of the distiller.

In [23 – 32], a large number of different studies of CMED characteristics in the concentration of various types of wastewater [33], distiller modeling, system reliability issues [34 – 36], etc. were carried out.

Comparison of characteristics of the considered distillers

The initial (evaporated) liquids were two solutions [22], the amount was chosen based on the calculation for a 30-day mission. The first solution 1 consisted of pretreated urine and pretreated moisture condensate. The second solution 2 included pre-treated hygienic wastewater (from shower, hand washing, brushing teeth, and wet shaving), as well as pretreated urine and pretreated moisture condensate. The summary characteristics based on the test results are shown in Table 1. For solution 1, the degree of water extraction for all systems was 93.5 %, and for solution 2 – 90 %.

The data in Table 1 show that each technology has proven itself well in the production of quality distillate. Overall, CDS was slightly better in terms of distillate quality, although all systems effectively removed over 99 % inorganic components and 98 % organic components. This efficiency minimizes the amount of post-treatment required to produce potable water.

Expert assessment of the test results: VCD system will be successful with a probability of 84 % – 90 % and a risk of 3 %; the CDS system 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 %.

In [33], the characteristics of three centrifugal distillation technologies were compared: a vacuum compression distiller (VCD), a centrifugal distiller with a Wiped-Film Rotating Disk (WFRD), and a thermal centrifugal distiller with thermoelectric heat pumps (CDS).

Two solutions were used as working fluids [22], the amount was selected from the calculation for a 30-day mission. The first solution 1 consisted of pre-treated urine and pre-treated moisture condensate. The second solution 2 included pre-treated hygienic wastewater (from showering, hand washing, brushing teeth and wet shaving), as well as pre-treated urine and pre-treated moisture condensate. The total characteristics according to the test results are shown in Table 1. For solution 1, the degree of water extraction for all systems was 93.5 %, and for solution 2 – 90 %.

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Expert evaluation of test results: VCD system will be successful with a probability of 84 % – 90 % and a risk of 3 %; the CDS system 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 1

Test results

Distiller	CDS		VCD		WFRD	
Solution	1	2	1	2	1	2
Productivity (kg/h)	3.7	4.88	1.63	1.87	16.1	16.8
Specific power consumption (Wh/kg)	109	110	188	163	85	86
Average power (W)	375	485	279	296	1252	1293

Data for WFRD showed an anomaly in the fact that the concentration of contaminants in the distillate is higher than for CDS and VCD. Analysis of the data shows that in the WFRD the streams of source liquid and distillate were partially mixed during operation.

The performance of CDS is about twice that of a VCD, and that of a WFRD is about 10 times that of a VCD. Therefore, although the input energy for WFRD and CDS is higher, the specific energy is less than for VCD. Values for VCD are also presented for the case when the heaters used to prevent condensation in the distiller housing are switched off.

Conclusions

Based on this review, it can be argued that the problem of providing astronauts with water during long flights is still very far from being solved. The VCD distillation system installed on the ISS is unsuitable in terms of reliability and stability. The TIMES and WFRD have a design unsuitable for working conditions in weightlessness. The CDS system shows the best results both in terms of energy efficiency and the quality of the distillate. However, the degree of water extraction is still insufficient.

Further research for future wastewater regeneration systems will be aimed at increasing the reliability and degree of water recovery.

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ОБГРУНТУВАННЯ МЕТОДУ ТЕРМІЧНОЇ ДИСТИЛЯЦІЯ З ТЕРМОЕЛЕКТРИЧНИМ ТЕПЛОВИМ НАСОСОМ ДЛЯ ТРИВАЛИХ КОСМІЧНИХ МІСІЙ

У статті описані основні методи термічної дистиляції, які можна використовувати для довготривалих космічних місій з людьми. Показано їх переваги та недоліки, наведено основні відомості щодо характеристик роботи систем, а саме: продуктивності по дистиляту, питомої витрати енергії на одиницю маси одержуваного дистиляту і якості дистиляту при випарюванні (концентруванні) водного розчину NaCl, урини й сумішей – урини з конденсатом, урини з конденсатом і гігієнічною водою. Вказано на обмеження, що не дозволяють їх використовувати для польотів та можливі шляхи їх вирішення. Бібл. 36, табл. 1, рис. 9.
Ключові слова: термоелектрика, тепловий насос, дистилятор.

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ОБОСНОВАНИЕ МЕТОДОМ ТЕРМИЧЕСКОЙ ДИСТИЛЛЯЦИИ С ТЕРМОЭЛЕКТРИЧЕСКОЙ ТЕПЛОВОЙ НАСОС ДЛЯ ДЛИТЕЛЬНЫХ КОСМИЧЕСКИХ МИССИЙ

В статье описаны основные методы термической дистилляции, которые можно использовать для длительных космических миссий с людьми. Показано их преимущества и недостатки, приведены основные сведения о характеристиках работы систем, а именно: производительность по дистиллята, удельного расхода энергии на единицу массы получаемого дистиллята и качества дистиллята при испарении (концентрировании) водного раствора NaCl, урины и смесей - урины с конденсатом, урины с конденсатом и гигиенической водой. Указано на ограничения, не позволяющие их использовать для полетов и возможные пути их решения. Библ. 36, рис. 9, табл. 1.
Ключевые слова: Термоэлектричество, тепловой насос, дистиллятор.

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