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Solar desiccant-evaporative cooling systems with ceramic packing (microporous multichannel structures)

In this paper, a method for the determination of the efficiency and limitations of the evaporative cooling process is presented. Ceramic is employed as a packing material in the evaporative equipment. It is shown that the experimental efficiency of the ceramic packing is 10-20% higher as compared to packings made of aluminum foil and multichannel polycarbonate plates because of the absence of common liquid film on the packing surface, and due to the absolute wettability of the ceramic packing. Heat and mass transfer equipment for desiccant-evaporative cooling systems (direct and indirect evaporative coolers, cooling tower) utilizing ceramic structures has been developed.

Nomenclature:

A	Air
W	water
ABR	Absorber
DBR	desorber-regenerator
CTW	cooling tower
CPM	ceramic porous material
CS	cooling space
DECg	direct evaporative cooler
IECg (IEC-Rg)	indirect evaporative cooler
HEX	heat exchanger
HMTE	heat and mass transfer equipment
E	Efficiency
F	Area (m^2)
G	mass flow rate ($kg\ s^{-1}$)
H	enthalpy ($kg\ kJ^{-1}$)
c_w	constant pressure specific heat ($kJ\ kg^{-1}\ K^{-1}$)
L	relative flow rate (-)
P	pressure (bar)
Q	heat flow rate ($W\ m^{-2}$)
Q	water sprinkling density ($m^3\ m^{-2} h^{-1}$)
SCS	Solar cooling systems
SACS	Solar air conditioning systems
SCw	water solar collector
SCg-l (R)	solar collector-regenerator (gas-liquid solar collector)
T, t	temperature (C)
V	velocity ($m\ s^{-1}$)
W	water
X	moisture content ($g\ kg^{-1}$)

Greek letters

α	heat-transfer coefficient	(W m^{-2} K^{-1})
Δ	Increment	
β	mass transfer coefficient	(kg m^{-2} s^{-1})
Λ	characteristic number	(-)
Φ	relative humidity	(%)

Subscripts

A	Air
Id	ideal
P	Primary
S	Secondary
Wb	wet bulb
Ult	Ultimate
W	water
1	Entrance
2	Exit

Introduction. Evaporative cooling is efficient for dry and hot climate conditions (when the humidity ratio of the ambient air x_a<12…14 g kg^{-1}). The development of the indirect evaporative coolers is of particular interest because the air flow is cooled without contact with water, meaning that the humidity ratio of the handled air is unchanged. The application of a heat-driven absorption cycle, which consists of the preliminary dehumidification of the air followed by its further use for evaporative cooling, is the basis for the development of alternative solar refrigeration and air conditioning systems (RACS).

The wide practical application of desiccant-evaporative cooling methods in modern solar cooling and heating systems requires solutions of the following problems: selection of working fluids (desiccants) that provide high absorption capacity and show minimum adverse effect on structural materials; elaboration of effective heating circuits for desiccant regeneration, which is essential to the development of high quality solar collectors, which can provide the required temperature level for regeneration; the decrease of the energy inputs for transport of the working fluids (flows of air, water, and desiccant). The development of desiccant-evaporative systems can remove climatic limitations for the application of evaporative methods of cooling and significantly enhance energy and ecology characteristics of alternative RACSs.

The number of studies investigating the capabilities of the open-cycle absorption as applied to cooling and air conditioning increases because such systems are easy to design and to use, with high reliability and durability (Doroshenko and Glauberman, 2012; Xie et al., 2012 [4]).

One of the most important considerations for such systems is the process of coupled heat and mass transfer in the packing of the appropriate device: absorber, desorber (for the systems with desiccant regeneration in desorber), direct evaporative cooler (DEC), indirect evaporative cooler (IEC), and cooling tower (CTW). As Zhao et al. (2008 [17]) stated, the packing can vary in structure (structured and random) and material (metal, plastic, paper, cotton, ceramics, etc.). The problem of film distribution on the packing surface (the problem of maximum wettability) is of great importance because the dry part of the packing is eliminated from the heat and mass exchange process, resulting in a decrease of device efficiency. Nozzles and other devices can be used to ensure uniform distribution of liquid and total wetting of the packing.

To avoid these problems, porous materials (ceramics) were proposed as materials for packing elements for evaporative cooling. Recently, a number of theoretical and experimental investigations have been performed to study the application of porous materials for cooling (Gomez et al., 2005 [7]; He and Hoyano, 2010 [8]; Ibrahim et al. [9], 2003; Martínez et al. [11], 2011; Pires et al. [12], 2011; Riffat and Zhu, [13] 2004).

The main objective of this research is the development of constituent devices, based on ceramic modules, for innovative, high-performance solar-driven desiccant-evaporative systems with direct desiccant regeneration in the solar collector-regenerator. Such systems are intended for commercial application in different domestic and industrial cooling, refrigeration, and air conditioning systems.

1.Experimental study of the heat and mass transfer processes in evaporative coolers. A test rig was built for experimental investigations of the evaporative coolers' operational characteristics. A schematic diagram and photograph of the test rig are shown in Fig 1. The test rig provides the opportunity of studying the working processes in CTW and DEC, as well as in IEC. The ambient air after heat and humidity handling (heating in the air heater 1 and moistening through the bypass line 7 by the air flow leaving the evaporative cooler) through ventilator 2 enters the working chamber 3, where the evaporative cooler module is installed. The variable speed motor of the ventilator allows for regulation of the air flow rate in the device. The temperature of the air is regulated in the channel electric heating coil 1, where it can reach 70 °C. The main part of the test rig, where the evaporative cooler module is located, is made with an inspection window (detachable cap) fabricated from thick-walled transparent plexiglass. Dimensions of the chamber are 460×400×180mm; throughput performance of the full air flow is up to 3500 $m^3 h^{-1}$. Air flow meter 6 and air flow regulators 8 and 9 are installed in the air line.

The water pump 13 with regulated flow rate provides water circulation through the evaporative cooler module. The water flow rate is measured by RS-type flow meter 10. The water through the discharge line enters distribution chamber 4, from which it comes for packing sprinkling. The constructive embodiment of all HMTE is unified (CTW, DEC, IEC). They all are constructed as cross-flow devices in which vertical multichannel plates from ceramic porous material (CPM) are utilized as a main element of the packing. Water chamber 11 consists of five pockets. This provides differential measurement of water flow rate and the latching of its lengthwise surging by air flow. All pipelines are thermally isolated. Temperature and relative humidity of the air are measured before and after the working chamber (mercurial thermometers and RTD sensors - 17 and 18). K-type thermocouples are used for temperature measurement during the cycle, along with a multichannel measuring converter.

The test rig provides the experimental investigations of designed evaporative coolers with the packing built of equidistantly located CPM plates with ribbing, which create multichannel regular packing. Previously, the experimental research of evaporative cooling in lengthways-corrugated elements made of aluminum foil paper and multichannel polymeric structures was fulfilled at the Odessa State Academy of Refrigeration (OSAR) (Doroshenko, 1992 [2]; Doroshenko and Gorin, 2005 [5]). The value of the equivalent diameter of the channels was varied in the range of 15…20 mm; the area of the packing constructive specific surface was varied in the range of 170…200 $m^2 m^{-3}$. Obtained recommendations along with the results of the studies of Doroshenko (1992) [2] and Doroshenko et al. (2005) [3], were used in the manufacturing of the evaporative cooler modules made of CPM. The working range of air velocity in the channels of the packing was varied in the range of 1.0…7.0 $m s^{-1}$. The value of the ratio of air and water was $l = G_a / G_w \approx 1.0$ for the evaporative coolers of water, and the water sprinkling density was q_w = 5…18 $m^3 m^{-2} h^{-1}$.

Measurement accuracy of the main data is determined by the accuracy of the devices, and it was calculated for each experiment (for the heat balance the accuracy was about 12%). The following results were obtained experimentally. The increase of water flow rate G_w from "dry" regime to the value of the water sprinkling density q_w = 10 $m^3 m^{-2} h^{-1}$ did not result in an appreciable increase of pressure drop as air passes through the "wet" part of the IEC packing (Fig. 2).

It was explained by a practical absence of liquid film on the surface of the packing. The common phenomenon of flooding (evacuation of liquid from the packing of the device by air flow and the decreasing of the device capacity up to zero) for the cross-flow scheme is fully absent up to the value of v_a < 8-10 $m s^{-1}$; phenomenon of lengthways drifting of liquid, resulting in its unfavorable distribution in the volume of the packing and removal from the layer, is also fully absent – which can be explained by absence of liquid film on the surface of the packing as well. The transition to a cross-flow scheme provides the decrease of Δp, and consequently the decrease of rated power inputs compared to counter-flow mode, and also provides the possibility of further increase of the capacity. Besides, when several devices are located in one cooling unit, the cross-flow linear mode is an optimal solution for the arrangement of the devices.

The liquid retardation in the layer of the packing substantively provides high value of the heat and mass transfer surface, and thus it results in acceptable efficiency of the evaporative cooling process. The accumulation of the liquid in the volume of the ceramic packing takes place practically instantly and in such a way that the total surface for heat and mass transfer is formed. A circulating method was used in the study to determine the liquid retardation in the layer of the packing, based on the principle of conservation of the liquid mass in a closed circuit (Doroshenko and Glauberman, 2012 [4]).

The liquid is pumped to the device from the calibrated tank (12-20) and it drains into it. The difference between the levels of the liquid before activation of the de-

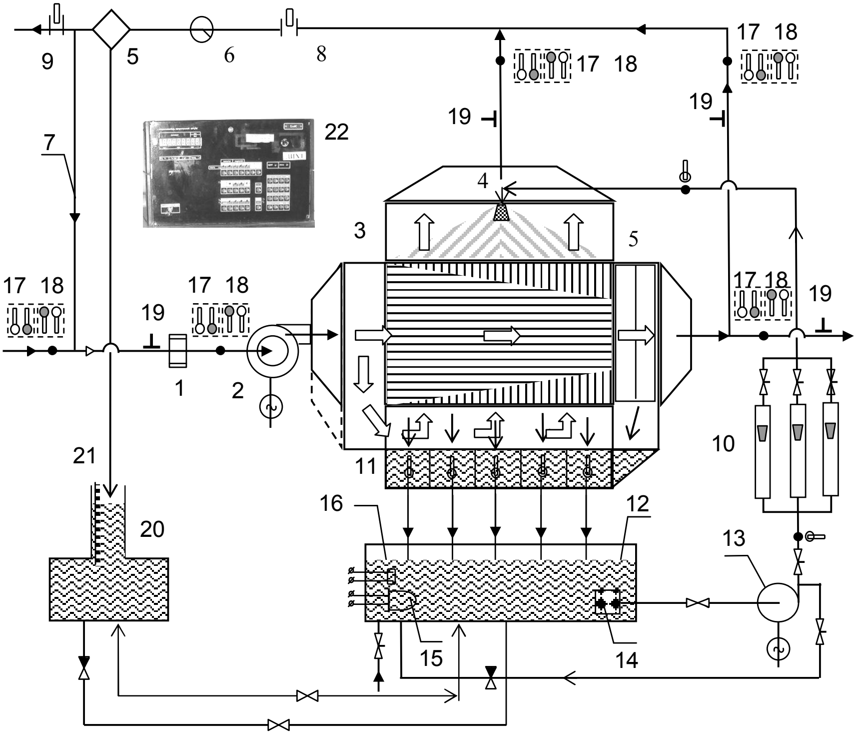

Fig. 1. Schematic diagram and photograph of the test rig to study the cross-flow heat and mass transfer devices for direct and indirect evaporative cooling of water and air. 1 – electric heater; 2 – ventilator; 3 – working chamber; 4 – liquid distributor; 5 – spray separator; 6 – air flow meter; 7 – return line; 8, 9 – air flow regulator; 10 – water flow meters; 11 – sectional meter of liquid flow rate; 12 – water tank; 13 – water pump; 14 – filter; 15 – water heater; 16 – water temperature regulator; 17, 18 – mercury thermometer and RTD sensor; 19 – pressure gauge; 20 – tank for the measurement of liquid retention; 21 – scale bar; 22 – control box.

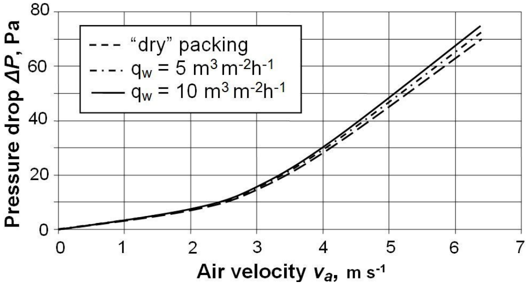

Fig. 2. Pressure drop in the "wet" channels of the ceramic IECg.

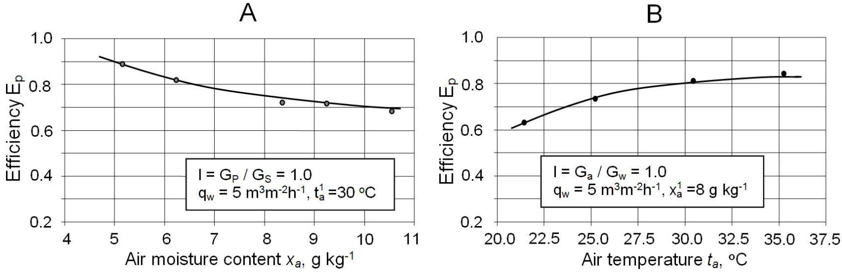

Fig.3. The influence of humidity ratio (A) and air temperature (B) on the efficiency of the IECg for the primary air flow.

vice and when the device is operated is proportional to the retention of the packing layer. During the operation, the level of the liquid was changed due to liquid evacuation and evaporation. Developed methodology allowed these ingredients to be taken into account to determine full liquid retardation.

For IEC during the experiment, the ratio of the primary and secondary air flows was $l_{IEC} = G_P/G_S = 1.0$. Thermal efficiency of the IEC for primary and secondary air flows is determined from:

$$E_p = \frac{t_p^1 - t_p^2}{t_p^1 - t^0}, \qquad E_s = \frac{t_s^1 - t_s^2}{t_s^1 - t^0}, \tag{1}$$

here t^0 is the air wet bulb temperature at the entrance of the device similar to *DEC*, but it is 1.5…2.0 °C higher because of thermal conductivity of the dividing wall and inner heat flux from primary to secondary air flow.

On average, the value of E_p is in the range of 0.6…0.9, which is substantially higher than the values of the process efficiency for the film-type packing composed from multichannel polycarbonate plates E_p = 0.55-0.75 (Doroshenko and Glauberman, 2012 [4]). This is determined by the value of liquid retardation. According to Fig. 3A, the efficiency of the process E_p decreases as the moisture content of the ambient air increases. The efficiency of the primary air flow process improves when the temperature of the air at the entrance of the device is increased (Fig. 3B). Thermal efficiency of the *IEC* for secondary air flow is 10-15% higher on average as compared

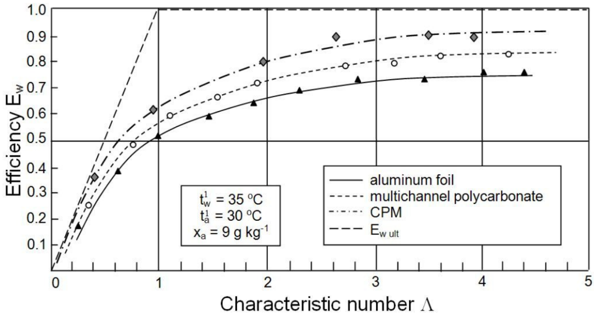

Fig. 4. Efficiency of the water cooling process in CTW.

to the efficiency for the primary air flow. Consequently, the working range of the value of l_{IEC} can be increased.

The results of water cooling during the evaporative process in CTW are shown in Fig. 4 – the efficiency of the process (the water cooling degree) versus the characteristic number $\Lambda = l / l_{id}$, where $l = G_a / G_w$ (the value of l_{id} corresponds to the ideal design of the water cooler and is determined by t_w^1 and t_{wb}^1).

The value of the flow ratio was $l \approx 1.0$; the density of sprinkling was $q_w = 5…18$ $m^3m^{-2}h^{-1}$. It can be seen from Fig. 6 that the efficiency of packing made of CPM is 10–20% higher compared to previously received experimental results for packing constructed of aluminum foil and multichannel polycarbonate plates.

2. Design and development of the evaporative equipment for solar desiccant cooling systems. The main components of the cooling part of solar *RACS* with direct desiccant regeneration in a solar collector-regenerator are DEC or IEC, CTW, and an absorber. The application of CPM in the equipment of RACS cooling units is discussed in the present study.

The general requirements for heat and mass transfer equipment (HMTE) for solar desiccant systems are as follows: high efficiency of the running processes; low aerodynamic resistance for working fluid transportation (air and liquid flows); the wide range of operating loads for air and liquid, when the operation of the HMTE is reliable; the absence of working surface contaminations, or their destruction under long-term operation.

On the basis of many years experience accumulated in OSAR in development, production, and service of multifarious HMTE, particularly for evaporative cooling (Doroshenko et al., 2005 [3]; Lavrenchenko and Doroshenko, 1988 [10]), the authors have chosen film apparatus as the main universal construction of all HMTE, which provides separate motion of the gas and liquid at low aerodynamic resistance; and transversal-type for flows interaction, as it is the most acceptable when it is necessary to combine several HMTE and heat exchangers into one unit.

Before, the problems of flow stability of the gas-liquid system, liquid drops removal by gas flow and other problems were thoroughly studied in OSAR (Doroshenko and Glauberman, 2012 [4]). The main challenge in the practical application of a packing structure is the wettability of the packing element surfaces and the stability of the liquid film movement when the film directly interacts with gas flow. In a study conducted by Gomes et al. (2005), the authors employed porous ceramic structures as the main elements for IEC construction. The application of ceramic blocks with multichannel porous structures of the surface allowed to increase rated gas and liquid capacity, as well as the area of the wetted surface of the packing (Gomes et al., 2005 [7]).

A number of the HMTE developed for cooling units is shown in Figs. 5-7 (DEC of air and water, CTW, and IEC). The packing of the film transverse flow HMTE is made of the units, based on lamellate multichannel structures of CPM, which are filled with water; the air flows are moved between them. The plates are mounted vertically or horizontally, equidistantly from each other.

The device of DEC is shown in Fig. 5. The liquid penetrates into the air flow through the pores of the dividing wall (Fig. 5C.) The outer surface of the plate is wetted by the liquid, and the process of heat and mass exchange is realized in the partly deepened liquid of the wall channel. This allows for the avoidance of partial liquid distribution on the surface of the packing that is typical in traditional film HMTE when part of the unwetted surface is eliminated from the heat and mass transfer process. In the same manner, this excludes liquid drops removal by the air flow. According to the similar scheme, the evaporative cooler of water CTW with outside heat load can be created (Fig. 6).

Schematic diagrams for flow movements and directions of heat and mass transfer in the proposed cooler systems are shown in Figs. 5B, 6B, and 7B. Q_α and Q_β are the heat flows rejected from the liquid surface by convection and evaporation (W); α and β are coefficients of heat and mass transfer, respectively, (W $m^{-2}K^{-1}$ and kg $m^{-2}s^{-1}$).

The schematic diagram of the IEC is shown in Fig. 7. At the entrance of the device, the ambient air flow is divided into primary *P* and secondary *S* air flows. Secondary air flow comes in direct contact with liquid, which penetrates through micropores in the ceramic plate (Fig. 7C) to the “wet” channels, where the process of evaporative cooling of the liquid, located in the cavities of the “wet” part of the cooler, takes place; in the “dry” channels, which alternate with “wet” channels, the primary air flow is in motion – it is cooled at a constant humidity ratio. “Dry” channels of the IEC are built of thin-walled metal plates (multichannel plates). Optimal values of the density of the ceramic packing layer (the distance between sheets in cells of packing and between cells in the packing layer, and overall dimension of the packing) for DEC and IEC of all modifications were determined previously, according to theoretical and experimental study of the heat and mass transfer in HMTE of the film type (Doroshenko and Glauberman, 2012 [4]). The values of equivalent diameters of the packing channels are 15…20mm. The equivalent diameters values of multichannel plates and interchannel space (channel between cells of packing, where the process of heat and mass transfer takes place) for *IEC* are equal, but they can differ from against assumed proportions of the contacting flows.

An absorber (air dryer) can be made in one of three variants: with technological cooling tower (CTWt) and outside heat exchanger for the cooling of desiccant entering the absorber; with CTWt and inbuilt heat exchanger in the body structure of the absorber; with inner evaporative cooling of the absorber. The latter solution results in an increase in density of the whole solar system unit, as well as an increase in isothermality of the absorption process of up to 20-25%, and therefore the increase of absorption process efficiency (Doroshenko and Glauberman, 2012 [4]). Inner evaporative cooling of the absorber eliminates the additional CTW.

3. The perspectives of solar liquid desiccant cooling systems. Analysis of the results. The ASHRAE Standard (2005) [1] for comfort conditions in the summer period specifies temperature of 25^{o}C with a 10g$\cdot$kg^{-1} humidity ratio. Comfort zone (CZ) around recommended data is considered in this study according to State Standard 12.1.005-88 and State Standard 30494 for the summer period.

On the basis of obtained results on the efficiency of solar collector-regenerator (SC-R), and considering previously received data about efficiency of the absorber and *IEC* (Doroshenko and Glauberman, 2012 [4]), the analysis of the perspectives of solar desiccant-evaporative air conditioning systems is made. The formula for the system is *ABR-IEC*, with desiccant regeneration in *SC-R*. The working fluid used as the desiccant is a water solution of LiBr, which has become the most popular for such systems (Xie et al., 2012 [16]); however, its application is limited by its corrosion activity to metals and other materials and its relatively high cost. The problem was considered for several initial parameters of the ambient air: three variants of absolute humidity of 10, 15, and 20 g kg^{-1} (at temperature 35^{o}C), and three variants of temperature of 30, 35, and 40^{o}C (at absolute humidity of 15 g kg^{-1}). Solar desiccant-evaporative cooling systems can provide comfort parameters for CZ according to Fig. 8-9. The processes in Fig. 8 and Fig. 8B are as follows: 1-2 – the process of dehumidification in the absorber; 2-4 – the process of primary flow cooling in IEC; 2-5 – secondary air flow in IEC; 2-3 – the process of evaporative cooling in DEC. The heat exchanger (HEX) in Fig. 8C provides the cooling of ABR from technological CTW. When the humidity of the ambient air is not very high, the degree of dehumidification in the absorber can be lowered by changing the flow rate and concentration of the desiccant, or by increasing the processed air flow rate. This provides for the maintenance of comfort parameters in the cooling space and offers additional energy economy. Such a solar air conditioning system ensures energy economy up to 30-35% compared to traditional vapor compression systems. If the temperature and humidity of inlet air is higher (climate is hot and humid), the solution of this problem lies in the incorporation of additional heat exchangers.

The choice between evaporative cooling of direct (DEC, process 2-3) or indirect (IEC, process 2-4) coolers turns to DEC because it increases the generation of product air flow, which enters the cooling space after thermal and humid conditioning. Primary air flow cooling in IEC has a considerable advantage when the moisture content is constant, and therefore the application of IEC is preferable in such cases;

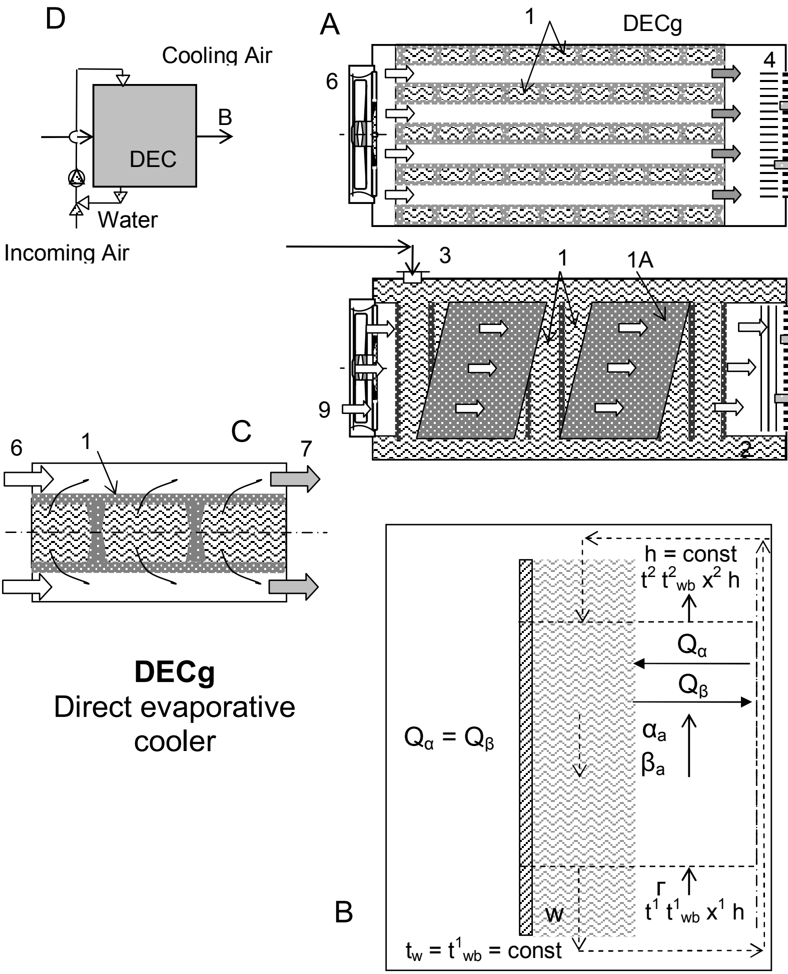

Fig. 5. Direct evaporative cooler of air DECg on the basis of plate ceramic micro-porous multichannel structures.
A – layout of air direct evaporated cooler DECg component, B – processes of coupled heat and mass transfer during evaporative cooling, C – contacting pattern of air and water flows, D – general diagram of DEC

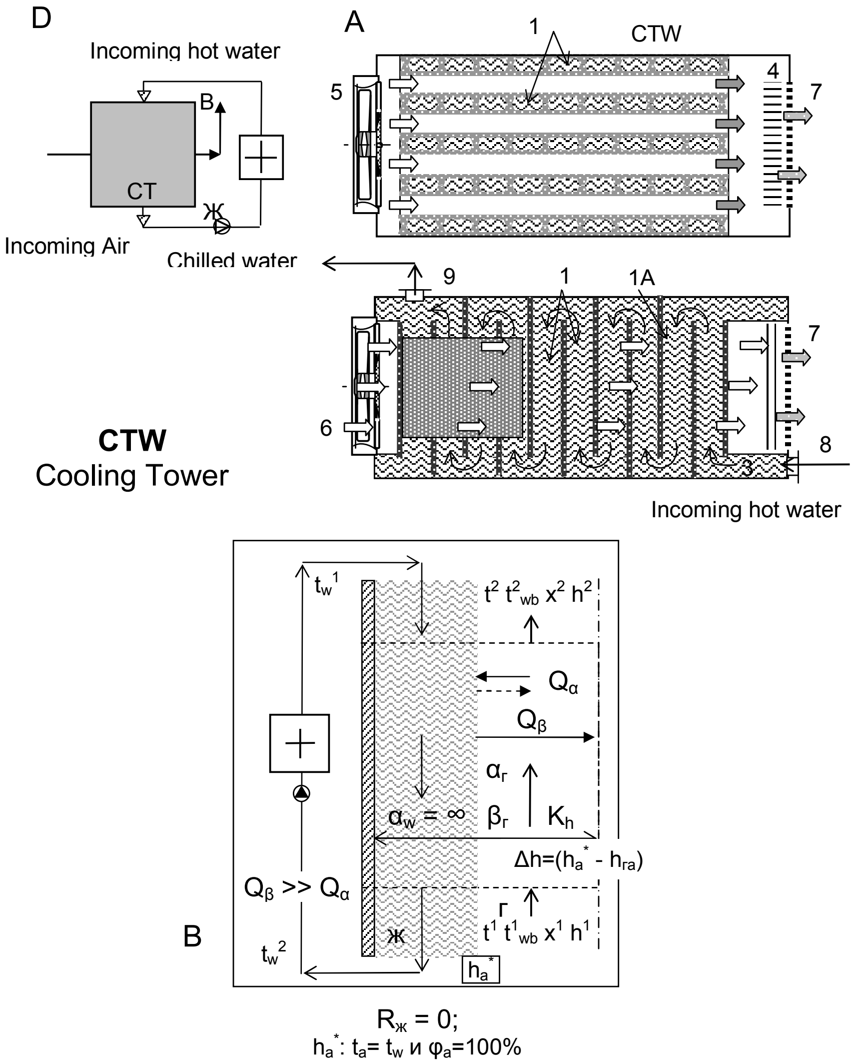

Fig. 6. Direct evaporative cooler of water DECw (Cooling Tower, CTW) on the basis of plate ceramic microporous multichannel structures.
Designations are according to Fig. 7. Additional: 7 – exhaust air; 8 – incoming hot water from supplier; 9 – chilled water

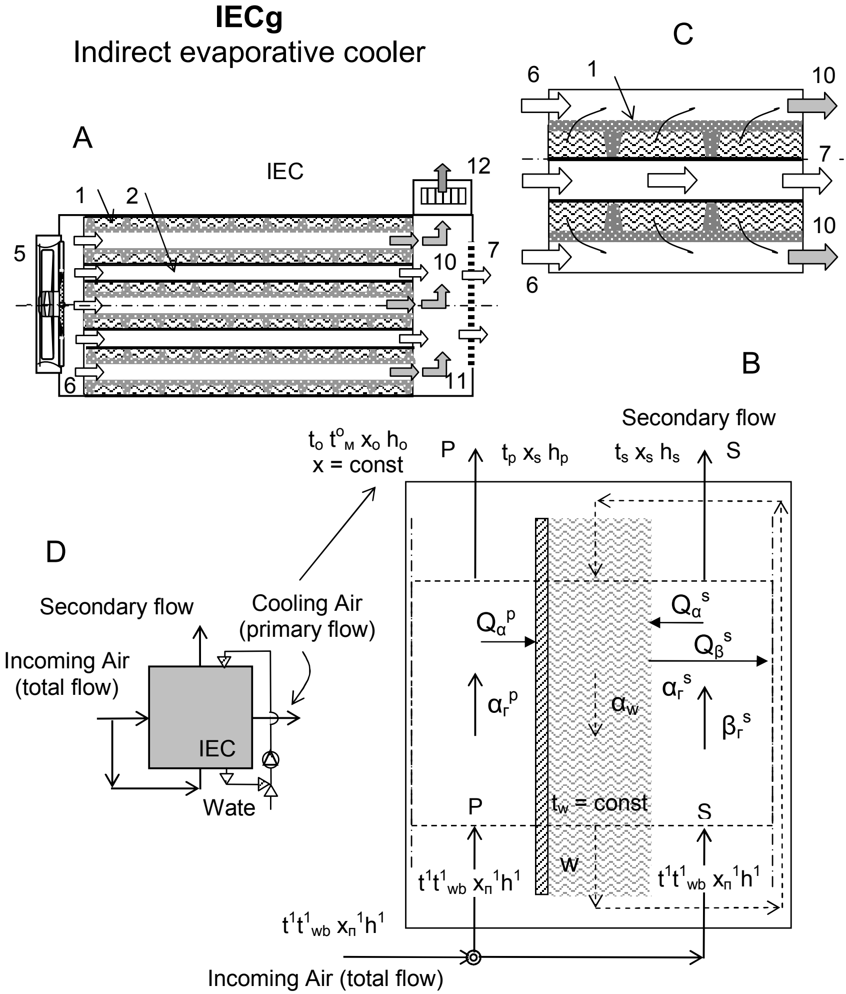

Fig. 7. Indirect evaporative cooler of air IECg on the basis of ceramic microporous multichannel structures.

Designations are according to Figs. 7 and 8. Additional: 1 – “wet” channels; 2 – “dry” channels; 10 – secondary air flow; 11 – separation chamber; 12 – withdrawing chamber for exhaust secondary air flow with moisture separator.

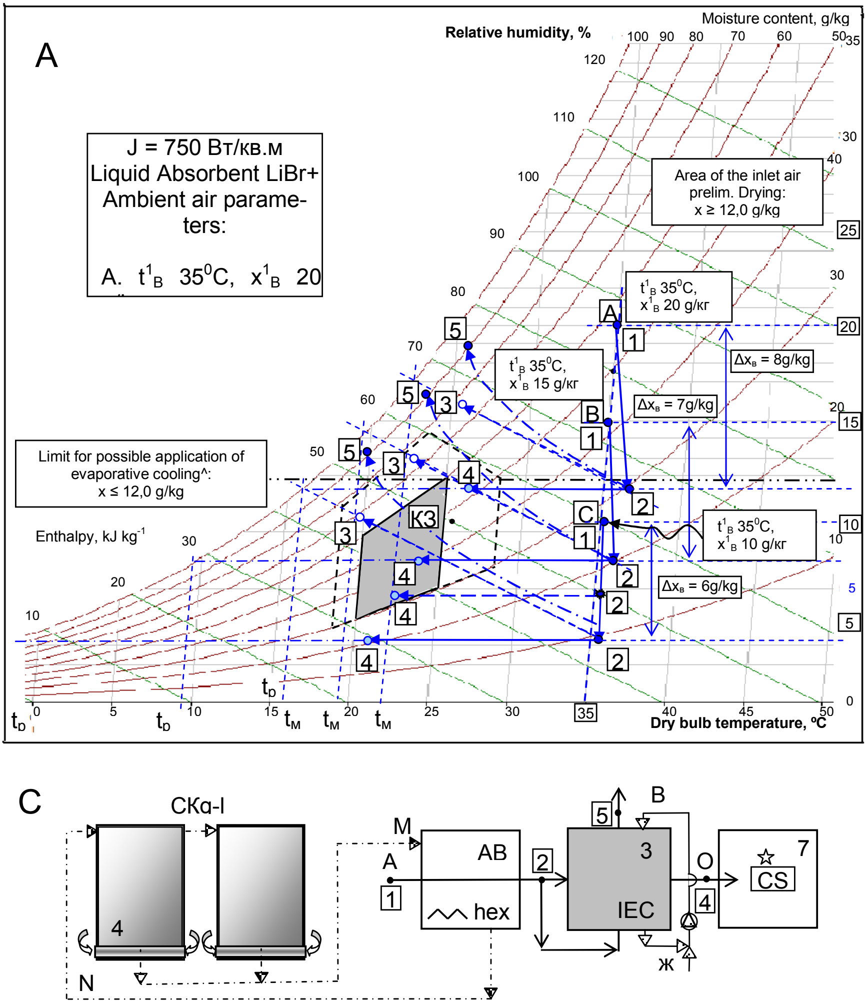

Fig. 8. Perspectives of the solar cooling system intended for air conditioning on the basis of open absorption cycle with direct solar regeneration of the desiccant (A) for the formulae of the system ABR-IECg. Solar cooling and air conditioning systems (Solar-EC)

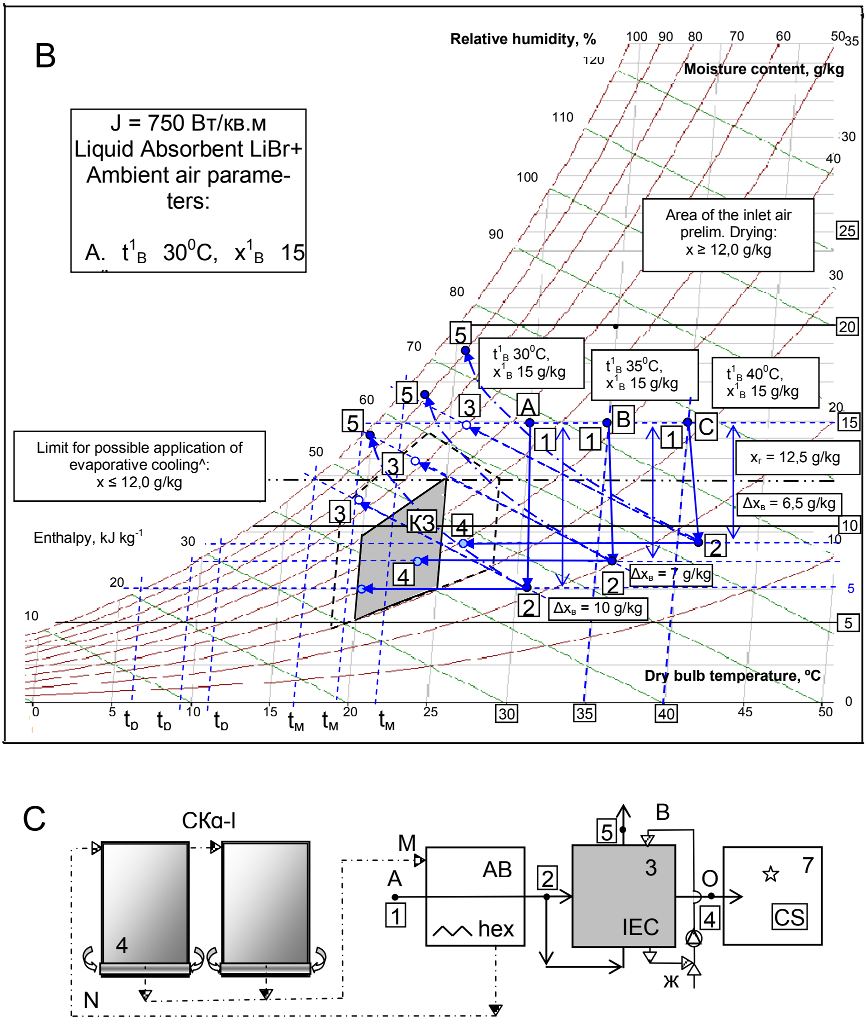

Fig. 9. Perspectives of the solar cooling system intended for air conditioning on the basis of open absorption cycle with direct solar regeneration of the desiccant (B) for the formulae of the system ABR-IECg. Solar cooling and air conditioning systems (Solar-EC)

for example, for deep cooling in solar refrigeration systems. In many cases it is optimal to use the potential of the recirculating air flow that leaves the cooling space.

The secondary air flow is cold (19-26 °C) and humid (90%) while leaving the IEC. It is possible to use it for cooling air after the absorber; this will enhance the overall performance of the system. Simultaneously, this will complicate the system and increase the power consumption for working fluids motion. Such a solution looks promising from the point of view of the recondensation risk and essential drop of the efficiency, and this risk is higher when the level of the cooling is lower (Doroshenko et al., 1998 [6]; Doroshenko et al., 2005 [3]).

Conclusions. The application of ceramics as a material for packing in evaporative coolers is discussed in the present study. Several evaporative cooling devices are designed on the basis of ceramic elements (cooling tower, direct and indirect evaporative coolers). It is shown experimentally that the efficiency of such equipment is 10-20% higher due to the complete wettability of the ceramic packing. Designed coolers can be easily incorporated into solar liquid desiccant systems intended for air conditioning.

On the basis of theoretical and experimental results, preliminary analysis of the perspectives of alternative solar liquid desiccant systems showed the potential for the use of such systems in refrigeration and air conditioning applications (irrespective of climatic conditions). Compared to traditional vapor compression systems, these new solutions facilitate the reducing power consumption by up to 30-35%, and significantly lessen negative impact on the environment.

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Глауберман М., Дорошенко А., Шестопалов К., Людницкий К., Жук К., Цапушель А.

Солнечные осушительно-испарительные холодильные системы с тепломассообменной аппаратурой на основе керамической насадки (микропористые многоканальные структуры)

АННОТАЦИЯ

В статье предложен метод определения эффективности процессов совместного тепломассообмена применительно к аппаратам прямого и непрямого испарительного охлаждения сред (газов и жидкостей) с конкретизацией пределов испарительного охлаждения. В качестве насадочных поверхностей тепломассообменных аппаратов используются многоканальные структуры из керамических элементов, что существенно увеличивает поверхность контакта между взаимодействующими потоками газа и жидкости, повышает устойчивость систем и снижает потери жидкости в связи с каплеуносом. Разработаны, на основе нового поколения испарительных охладителей, солнечные теплоиспользующие абсорбционные системы охлаждения и кондиционирования воздуха и выполнен, на основе полученных экспериментальных данных по эффективности процессов в аппаратах осушительного и охладительного контуров солнечных систем, сравнительный анализ возможностей таких систем с учетом климатических условий и режимных параметров.

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СОНЯЧНІ ОСУШУВАЛЬНО-ВИПАРНІ ХОЛОДИЛЬНІ СИСТЕМИ З ТЕПЛОМАСООБМІННОЮ АПАРАТУРОЮ НА ОСНОВІ КЕРАМІЧНОЇ НАСАДКИ (МІКРОПОРИСТІ БАГАТОКАНАЛЬНІ СТРУКТУРИ)

АНОТАЦІЯ

В статті запропонований метод визначення ефективності процесів спільного тепло-масообміну стосовно апаратів прямого і непрямого випарного охолодження середовищ (газів і рідин) з конкретизацією меж випарного охолодження. Як поверхні тепломасообмінних апаратів використовуються багатоканальні структури з керамічних елементів, що істотно збільшує поверхню контакту між взаємодіючими потоками газу і рідини, підвищує стійкість систем і знижує втрати рідини у зв'язку з краплеуносом. Розроблені, на основі нового покоління випарних охолоджувачів, сонячні абсорбційні системи охолодження і кондиціонування повітря і виконаний, на основі отриманих експериментальних даних по ефективності процесів в апаратах осушувального і охолоджувального контурів сонячних систем, порівняльний аналіз можливостей таких систем з урахуванням кліматичних умов і режимних параметрів.