Feasibility study and analysis of a plant for water extraction from the atmospheric air

The method is based on sorption and desorption of water vapor contained in the air with
its subsequent condensation. It is primarily intended for areas short of natural water sources
(including precipitation), or salt and brackish water suitable for desalination.

The other application area for this method is the production of pure water for domestic
and agricultural needs.

To operate the plant according to this method the input of both heat and electric energy
will be required, the first used for the desorption of moisture, and the latter for moving air
streams and for other operations.

As heat sources waste (or no-cost) heat generated during various industrial processes
(such as exhaust from diesel plant), as well as solar radiation and fuel combustion can be used.
In plants designed to operate on waste heat, the cost of required electric power will be minimum
amounting to about 10 kWh/m of water. When billed energy sources are to be used, in order to
save on them the consumption of electric power cant be increased to 30-40 kWh/m^3 of water.

1. Water production process

The water production process consists of a number of alternating sorption and
desorption operation. In each such cycle the water is released only at the desorption stage, i.e.
obtained by separate portions. The plant, though, can be designed so as to include several
sections, in which the process stages will be shifted in time, so that the total production will not
be intermittent, but continuous.

Also realizable are continuous operation plants, in which the sorbent will be constantly
introduced to the sorption and desorption zones. From the point of view of thermodynamics
such plants are much superior, and basic technological prerequisites for their construction
already exist. The first inevitable stage, though, is the development and adjustment of a plant
operating intermittently. For this reason first experimental prototypes, which we have
constructed, operate periodically.

It should be noted, that the adsorption time depends on the properties of the ambient air,
type of sorbent, and to some extent on the plant's design (thickness of the sorbing layer, time of
sorbent contact with the air, etc.). The desorption time is primarily determined by the intensity
of heat input to the sorbent, which depends on a great number of factors, among which
economical, and can greatly differ for various designs.

The adsorption process involves generation of heat equal to the condensation heat plus

so called "wetting heat". In the considered case, the sorption heat will be about 700 kcal per
1 kg of absorbed moisture. The liberation of this heat results in some increase of temperature of
the throughput air and the sorbent relative to the ambient temperature. In our case this increase
will not exceed 10-15°C. In the process of saturation the temperatures of sorbent and of passing
air decrease, and when the sorbent is fully saturated even out with the temperature of ambient
air. Moisture can be desorbed in a wide range of temperatures. When temperatures are too low,
water vapor released by the sorbent cannot be condensed simply by sinking heat to the
environment, but special arrangements of thermal transformation make it possible to save up to
60% as compared with the existing methods.

A principal advantage of the suggested method is the possibility to condense vapor
released at the desorption stage. At high ambient temperatures (t>30°C) it will be impossible to
extract water from the air after it has passed the adsorbent, because the concentration of vapor
in the mixture will be too small. Our plants can condense water vapor at any ambient
temperature. This is achieved due to vapor concentration at the desorption stage, which is
secured by special design and arrangement solutions. The condensation heat is released to the
environment through condenser cooled by the ambient air or by an intermediate heat transfer
medium. In the latter case the condensation heat can be advantageously utilized. The air which
cools the condenser is delivered by a low-pressure axial fan, or by natural draught. The
condensation heat can be much better utilized in big industrial plants, where special thermal
transformation arrangements can be employed.

The amount of air passed through the plant in the process of adsorption depends on its
parameters, the characteristics of selected adsorbent and the plant's design. The lower the air
temperature and higher the moister content, the smaller amount of air will be needed to produce
1 liter of water.

It is apparent that at lower moisture contents in the air the plant's efficiency will
decrease. We have studied climates of the Earth from the point of view of the possibility to
extract moisture from the air. The analysis indicates that in all hot arid zones of the Earth the
moisture content of atmospheric air considerably exceeds 5 g/kg, and under such conditions the
employment of the suggested method will be definitely advantageous. At constantly low
moisture contents, combination of various types ofsorbents should be employed, and the
economic expedience of using the suggested method and apparatus should be analyzed for each
particular case.

2. Principal sorbing materials

The following sorbing materials were experimentally studied:

• lithium and calcium chlorides in form of solid salts;
• various porous materials saturated with lithium chloride solution; special
   cardboard; charcoal; porous ceramic materials;
• solid granulated adsorbents, such as various types of silica gel,
   including
   specially modified by us, and zeolite.

Unfortunately we could not study sorbents manufactured by some well known
producers
in form of thin films applied on compact heat and mass transfer surfaces having regular
structure.

Each of the above sorbents has its specific advantages and limitations.

Lithium chloride has a maximum absorbing power, but its physical characteristic
alter in
the process of absorption, which in some cases may result in erratic operation of the plant.

Silica gel, as compared with lithium chloride, has a smaller specific absorbing
capacity,
having the advantage of stable physical properties, which makes it possible to design a
simple
and reliably operating plant.

Of considerable interest are regular structures with thin film of adsorbing materials
applied to their surfaces. They allow to significantly improve dynamic characteristics of
the
plant, at the same time greatly reducing its sizes and mass. The specific characteristics of
studied sorbents are indicated in the table below.

Table 1

Characteristics of studied sorbents

Parameters	Unit	Modified silica gel	LiCl+porous ceramic material	L1Cl+char coal	LiCl+special cardboard
Specific density	kg/m'	650	380	320	170
Porosity of the layer		0, 45	0,4	0,42	0,5
Heat capacity	KJ/kg.K	0, 92	0,9	0,9	1,2
Thermal conductivity	W/M.K.	0,2	0,26	0,28	—

Table 2

Average moisture capacity of studies sorbents

Type of material	Moisture capacity at stable temperature, t=30'"'C			Moisture capacity at stable moisture content, d = 12 g/kg		
	relative humidity,%			Relative humidity,%		
	30	45	60	80	45	25
LiCl+porous ceramic material	25	55	80	80	60	20
LiCl+charcoal	30	60	80	90	60	30
LiCl+special cardboard	30	60	90	90	70	35

As a filler in the first two experimental plants modified silica gel was used because of its
simple use and availability.

In order to achieve a minimum cost of the product water the final selection of sorbents
for commercially manufactured plants must be done taking into account the above distinctions.

CALCULATION NOTE
to the conceptual design
of a 30 I/day unit for water
extraction
from the atmospheric air

1. Principal parameters

Based on experimental data the following initial parameters were adopted:

- Sorbent - a composite material using lithium chloride (LiCI).
- Maximum amount of moisture absorbed from the air (%% to the mass of dehydrated sorbent) ^= 50%;
- Density of dehydrated sorbent:
    - o filled layer p = 400 kg/nr
    - o continuous film p = 500 kg/m

For a small capacity plant (up to 50-70 I/day) most advantageous is a 24 hr cycle (so
called "day-night" cycle), in which moisture absorption from the air (sorption) takes place during
the night, and moisture extraction from the sorbent (desorption) during the day.

For the considered plant of a 30 I/day capacity the "day-night" cycle was adopted, in
which during the night 30 kg of water can accumulate in the sorbent. The required mass of
sorbent shall be:

$$m=(M* 100)^=60 \text{ kg}$$

Further calculation was made for two alternatives:

a) sorbent filled in the plant as bulk layers;
b) sorbent applied as a continuous film on thin metal sheets forming a regular packing.

The appropriate alternative shall be selected based on the method of heat input to the
system and design reasons, and should be determined at the contractor design stage.
The cubic capacity of the sorbent housing chamber shall be determined from the formula:

$$V == m/(p*K) \ m$$

where m - mass of sorbent, kg
p - sorbent's density,
kg/m
k - chamber filling
factor

The calculation results are indicated in the Table below:

Parameter	Symbol	Unit	Calculation alternatives	
			a	b
Sorbent's density	p	kg/m^3	400	500
			0.8	0.5
Chamber filling factor	k			
3anoJiHeHHa				
Chamber cubic capacity	V	m	0.190	0.24
Approximate sizes of the chamber:				
- *parallelepiped*				
length		mm		
width		mm		
height		mm		
- *cylindrical*				
length		mm		
height		mm		
500	600			
500	400			
760	1000			
550	600			
800	850			

2. Energy consumption analysis

The bulk of energy consumption in the plant, analyzed in this section, is related to the
process of desorption.
The energy used to move the air streams during this process is relatively small, and not
considered in this section, as it depends on specific sizes of air ducts, and can be calculated only
at the shop design stage. To achieve desorption (moisture emission from the sorbent) a certain
amount of heat must be introduced to the plant, which can be determined using the formula:

$$Q = (q*M)/k \text{ kcal/day},$$

where:

q = 700 kcal/kg - specific heat of desorption

M - 30 kg/day - plant's capacity per day

k»0.75 - efficiency of the plant, taking into account heat losses (for heating-up, to the
environment, etc.)

Thus the required amount of heat will be:

$$Q = 30,000 \text{ kcal/day}$$

The most suitable source of heat for small capacity plants is solar energy, although
employment of other sources (such as natural gas or liquid fuels) is equally possible.
Further calculations were done for three alternatives:

Alternative I. The total amount of required heat Q is provided by solar batteries.
This allows a most simple design of the plant and batteries, but the area required for the
batteries will be the greatest. The total amount of desorbed vapor will be condensed by the
ambient air. The area of solar batteries can be determined from the formula:

$$F = Q/(E*a)\text{m}^2$$

where:

E == 10 hrs - assumed period of solar insulation per
day.

a - 350 kcaHm^hr) - specific heat production of a solar battery.

Hence:

$$F = 8.5 \text{ m}^2$$

It should be noted that in this alternative, as in those that will follow, the solar
batteries
energy is used not for heating up the intermediary heat carrier, but for direct heating of
the
working gas-and-vapor mixture. This results in a considerably lower cost of such
batteries.

Alternative II. The sorbent containing chamber is separated into two sections.
The first section receives heat form solar batteries, and a portion of vapor desorbed in
Section I (so called "secondary vapor") will be directed not to the air condenser, but to
Section
II, where it will give away the condensation heat, used for additional extraction of water
from
the sorbent in Section II. So, a two-stage utilization of the energy provided by the solar
battery is
achieved. In such case, the required amount of heat Q will consist of two parts:

$$q = qc + qb \qquad (3)$$

where:

Qc - heat, provided by solar batteries - Stage I;

qb - heat of secondary vapor condensation - Sage II

About 90% of vapor generated in Section I can be used as a secondary vapor. The
amount
of secondary vapor will be:

$$qb = 0.9*Qc*r/q \text{ kcal/day} \qquad (4)$$

where:
r = 550 kcal/kg is average specific heat of water evaporation, at:
q = 700 kcal/kg - specific desorption heat of the secondary vapor.

Solving (3) and (4) simultaneously we obtain

$$Qc=Q/1.7=17600$$

kcal/day

The required area of solar batteries according to (2)

will be:

$$F=17600/(10*350)=5m^2$$

Alternative III. The sorbent containing chamber is subdivided into three sections. Section I receives heat from solar batteries. A portion of vapor desorbed in Section 1 arrives to the thermal transformer (thermal pump) where it will be mechanically compressed.,
and its thermal potential brought up to the to the level of heat potential of the solar battery.
From the thermal transformer high potential vapor arrives to Section II, where the desorption process will be carried out in the same way as in Section I. A portion of secondary
vapor, which was desorbed in Section II, arrives to the same thermal transformer, and after
leaving it will be again directed for desorption to Section II. To increase the potential of secondary vapor some mechanical (or electrical) energy must be expended in the thermal transformer. Theoretically, the value of this work (under assumed temperatures) will be:

$$AT==46 \text{ kcal/kg}$$

At final stages of the desorption process the potential of secondary vapor arriving from
Section I or Section II will be rather low, and it appears ineffective to send it to the thermal
transformer, as much greater compression work will be required. The low potential secondary
vapor with temperature of about 80°C will be directed as a heating medium to Section III, serving in this case as a second stage of heat utilization. The amount of desorption heat Q required under Alternative III includes three components:

$$q=qc+qt+qb,$$

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where:
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Qc - heat provided by the solar battery - Stage I.
qt - heat of high potential secondary vapor leaving the thermal transformer
qb - heat of low potential secondary vapor - Stage 2.

The calculation (too bulky to be included into this paper) yielded the following results:

$$Qc = 9500 \text{ kcal/day}$$

The required area of solar batteries derived from (2);

$$F = 2.7 \text{ m}^2$$

Power consumption by thermal transformers (assuming the efficiency of thermal pump
0.8) will be:

$$A = 1 \text{ kWh/day}$$

The time of thermal transformer daily operation coincides with the insulation time

$E = 10hrs$

The capacity of the thermal pump drive:

$$N = 0.1 \text{ kW}$$

The specific alternative (I, II, or III) must be selected at the stage of working

design.

3. Costs of electric power

In Section 2 of this paper the amounts of heat and electric power required for the desorption process in the four alternatives of the plant's design were determined. The required
area of solar heaters was assessed, as these are one of most promising sources of thermal energy.
This source, though, is not the only one. To generate heat the electric power, liquid fuels and
natural gas can also be used. This Section presents a comparative cost analysis for various heat
sources.

Initial data:

Cost of natural gas $c_r = 0.082$ \$/m^3
Calorific value of natural gas $q_r = 8000$ kcal/kg
Calorific value of diesel fuel $q^\wedge = 9500$ kcal/kg
Cost of diesel fuel $c^\wedge = \$0.5/1$
Cost of electric power $c^\wedge = 0.09$ \$/kWh

The cost of electric power used as a heat source to drive the plant can be determined from
the formula:

$$C_r = Qc * c_r / 860$$

The total cost of diesel fuel can be determined from the

formula:

$$C, = Qc * c, / q,$$

The total cost of natural gas can be determined in a

similar way.

Qc is the total value of desorption heat for each

alternative.

The calculation results are indicated in the following

Tables.

Table 1

Design alternative (see Sec. 2)	Electric power		Heat power			
	Consumption KWn/day	Cost $/day	Consumption kcal/day	Cost in $/day, when using		
				Diesel fuel	Natural gas	Heating by electric power
I	-	-	30000	1,58	0.31	3.14
II	-	-	17600	0,92	0,18	1,84
III	1	0,09	9500	0,50	0,10	1,00
IV	0,18	0,016	12300	0,65	0,13	1,29

The total operating costs shall be:

Table 2

Design alternative	Cost, when using:							
	Diesel fuel		Natural gas		Heating by electric power		Solar heaters	
	$/day	cent/I	$/day	cent/I	$/day	cent/I	$/day	cent/I
I	1,58	5,27	0,31	1,03	3,14	10,47	-	-
II	0,92	3,07	0,18	0,6	1,84	6,13	-	-
III	0,59	1,97	0,19	0,63	1,09	3,64	0,09	0,3
TV	0,67	*2^*	*0^*	0,5	1,3?	^	q016	qo^

Table 2 proves that most efficient is the employment of solar batteries, and the least efficient
is heating by electric power, which can be used only under special conditions. But even in the most
unfavorable case, which is the use of electric heating in Alternative 1, the cost of 1 liter of water will
not exceed 11 cents.
Please note, that in case of Alternative 4, when solar heating is used, the cost of 1 m^3 of water
is only 0.54 $/$m^3$, which considering the existing prices of water, is quite competitive.

In the last period the theoretical and experimental works were carried out allowing improving

previous calculation results. There is a possibility practically minimize or completely avoid

expenses of thermal energy during extraction of water. It causes some increase of expenses of

the electric power, but allows essentially simplify the plant and, it is the main, the extraction of

water becomes economically profitable, even without use of solar heaters. Cost of water in this

case will not exceed USD 0.9/m . Our method requires the further experimental and industrial

approbation and the potential partners will be informed in details about its essence after

conclusion of the corresponding contract and patenting.

A. Tsymerman.