VACUUM METHODS OF WATER ICE FORMATION

B. T. MARINYUK, A. E. ERMOLAEV, D. V. SUSLIKOV

Moscow State University for Environment Engineering
21/4, Staraya Basmannaya, 107884 Moscow, Russia
Fax: 7 495 267 0784, e-mail: marinyuk@msuie.ru

ABSTRACT

Study of water ice formation under vacuum conditions was undertaken. Two forms of water ice were considered: cylindrical slabs and water ice suspension (slurry). The results of special analytical description were suggested. The flow-sheet of an experimental plant and vacuum methods of water ice formations were discussed. The experimental results were compared with analytical solutions.

1. INTRODUCTION

Refrigeration engineering is developing under strict rules of ecology standards set up by international scientific community, which is concerned by the series of negative climate trends concentrated around of ozone depletion and warming effect in environment. One of the ways to face this negative process is to stimulate the application of environmentally friendly substances as working fluids of refrigeration machines and minimizing consumption of energy at such plants. These suggestions can be implemented to a certain extent through application of water as working fluid. It is possible if rotary vacuum-compression machines are used for pumping vapour moisture. There are at least two main items of demands have to be put forward for such machines. As the volume of moisture vapour under vacuum conditions is great enough, this compressor should possess high volumetric capacity. The most acceptable one can be found among the rotative types.

The second item determines the possibility of creating proper residual vacuum pressure (1—30 mm Hg). Most of the usual types of the refrigeration compressors that are used now at food industry (3—50 kW) are unable to operate at the pressure of 1—25 mm Hg.

There are a few types of vacuum pumps which can be used for such purposes, but the most acceptable samples which answer both of two items are Roots type rotary vacuum pumps. Due to no contacts of blades, they are high speed machines with a number of revolutions of rotors 3000 rev/min and more.

Such a machine has no lubrication of rotors and is quite effective oil trap, which protect the evaporator from oil pollution. Roots type vacuum pump are easy in maintenance and well established in common industry. It's possible to design vacuum evaporative refrigeration installations operating with water as working fluid with Roots type vacuum pumps having a total cooling capacity up to 100 kW. It may cool liquids such as water down to 0 ºC as well as to freeze water into ice and turn it into slurry.

2. THE PRINCIPLE OF OPERATION

The installation consists of the main vacuum pump 2 which is Roots type rotary machine with a high volumetric speed, an auxiliary vacuum pump 4 of oil type, shell and tube condenser 3, cylindrical evaporator 1 and an auxiliary vessel-collector of water.

It operates in the following manner, fig. 1.

At the start air is pumped out of the system into atmosphere with the help of auxiliary vacuum pump. Then the main vacuum pump is getting into action. It produces the bulk of the job forcing H_2O vapour into condenser where it turned into liquid being cooled by external water. While pumping out vapour moisture out of the evaporator vessel the process of water boiling is going on and the temperature of it's reduced down to proper level +2 ºC…+3 ºC. Cold water is transferred to the auxiliary vessel-collector and the second stage of the process is begun.

After the first stage of cooling, cold water from the auxiliary vessel is introduced into the hermetically sealed evaporator cylinder1. The volume of this system is pumped out with an effective speed S m^3/s. Some portion of water introduced into the evaporator takes the form of thin lens with a layer thickness from 3 up 10 mm. While pumping out vapour moisture out of evaporator vessel the process of water boiling is going on and

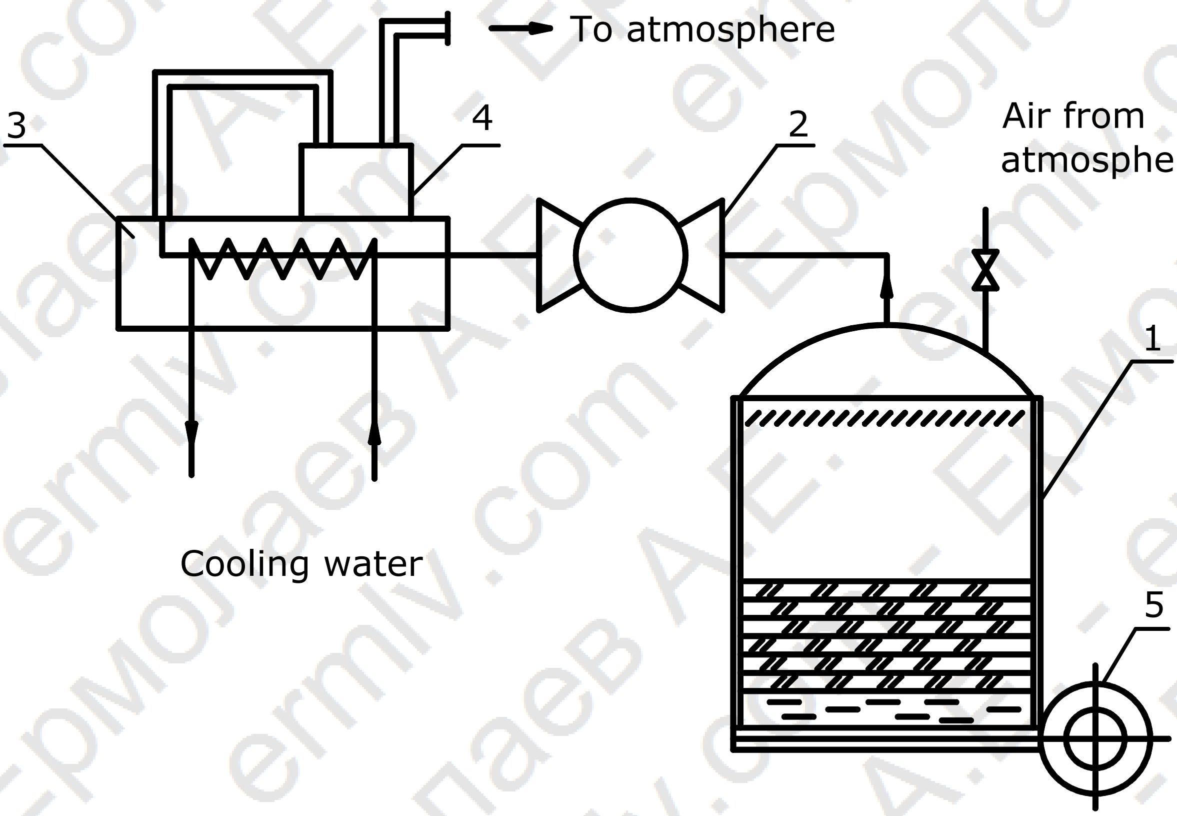

Fig.1. The flowsheet of the vacuum-sublimation installation.
1 — evaporator vessel, 2 — the main vacuum pump,
3 — shell and tube water condenser, 4 — an auxiliary vacuum pump,
5 — vacuum shift

temperature of water layer is reduced down to 0 ºC. The greater the volumetric speed of the main vacuum pump, the more cooling effect is generated as a result freezing of water is beginning on the upper part of the water layer. The thickness of the freezing zone is raised with time and after a final period of time the whole portion of water is turned into cylindrical slab of ice. After this second portion of water is introduced, the process is repeated.
The drawback of existed ice generators operated with HFC compressors is such that heat transfer between boiling agent and water is going on through an ice layer which increases with time. Heat transfer resistance of ice layer is increasing with time and usually is the main reason of heat transfer losses in system. Vacuum ice layer formation gives an alternative to it. The cooling surface in vacuum process is removed from inside of ice layer to the outside of it and is going on with it as the process is developed. Such a method gives opportunity to exclude the negative influence of ice layer heat transfer resistance and increase of heat effectiveness of the installation.

3. THEORETICAL ANALYSIS OF VACUUM ICE LAYER FORMATION

The portion of water in the evaporator vessel shaped like a disc (3—10) mm in thickness is cooled by pumping out of moisture vapour with an effective speed S m^3/s related to a unit of a cross square of the cylinder, S^* m^3/(s·m^2), it is constant during the process. The temperature of water at the start of the process is

0 ºC. Ambient heat flux transferred to the water and its crystal form of ice is negligible (the evaporator has heat insulation layer). The latent heat of evaporation and sublimation of water ice are constant.
Thermophisical properties of water molecular mass *M*, specific heat coefficient Cp, latent heat of evaporation and sublimation L^* of water ice are known and constant.
The illustration picture is shown on fig. 2 where ξ is the depth of freezing layer. It also can be considered as coordinate of phase front changing, which coincide with coordinate X.
As the bordering condition for a system pictured on fig. 2 (vacuum side) it is possible to write down an expression

$$\lambda \left.\frac{\partial T}{\partial x}\right|_{X=0} = S*\rho''L = L*md\tau \tag{1}$$

where ρ'' — the density of the saturated vapour;
λ — heat conductivity of ice;
m — mass of water vapour pumped out of the vessel per unit of time τ.

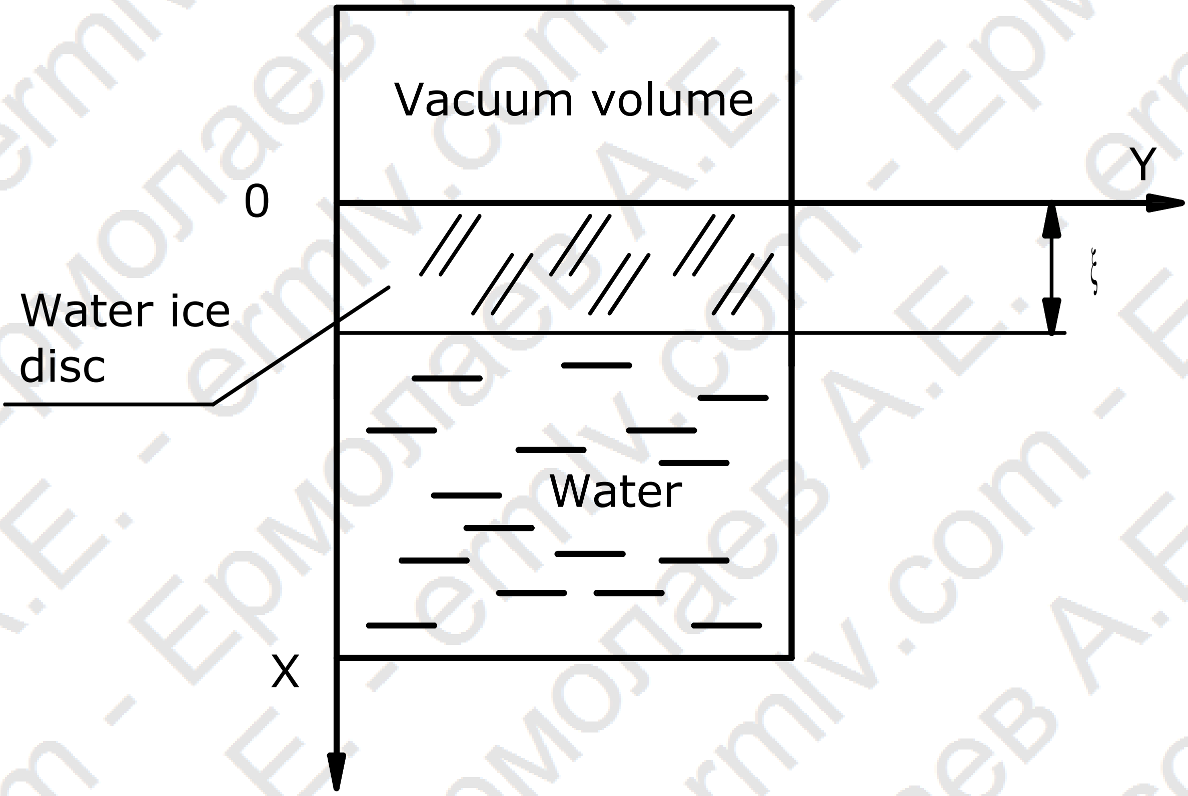

Fig.2. The illustration picture of the process

On the water-ice border of the system (fig. 2) the following expression is valid

$$\lambda \left.\frac{\partial T}{\partial x}\right|_{X=\xi} = L*\frac{d\xi}{d\tau}\rho_{ice} \tag{2}$$

where ρ_{ice} — is the density of water ice.
Linear distribution of temperature within the freezing layer of ice looks like this

$$T = T_0 + \frac{T_f - T_0}{\xi} \cdot X \tag{3}$$

where T_0 is variable temperature at the surface of the freezing layer of ice faced to the vacuum volume

The procedure used to solve these equations is quite traditional, so it's omitted and secured expression is

$$\frac{S^* L^* P\mu}{RT_0} = \frac{\rho \xi L}{2\tau} \tag{4}$$

where L — is latent heat of water freezing;

P — is vapour pressure of water, its dependence from temperature can be expressed by the equation.

$$P = 35 \cdot T - 8940$$

Taking this into account the result is

$$\xi = \frac{2\tau S^* \mu L^*}{R\rho_{ice} L}\left(35 - \frac{8940}{T_f - \dfrac{\rho_{ice} L \xi^2}{2\lambda \tau}}\right) \tag{5}$$

To prove the validity of these results some experiments were made. Within a glass vacuum chamber we observed and measured the ice thickness with time. The results of the experiments are presented in fig. 3. As can be seen from the graph, the experimental points and theory lines are in a satisfactory compliance.

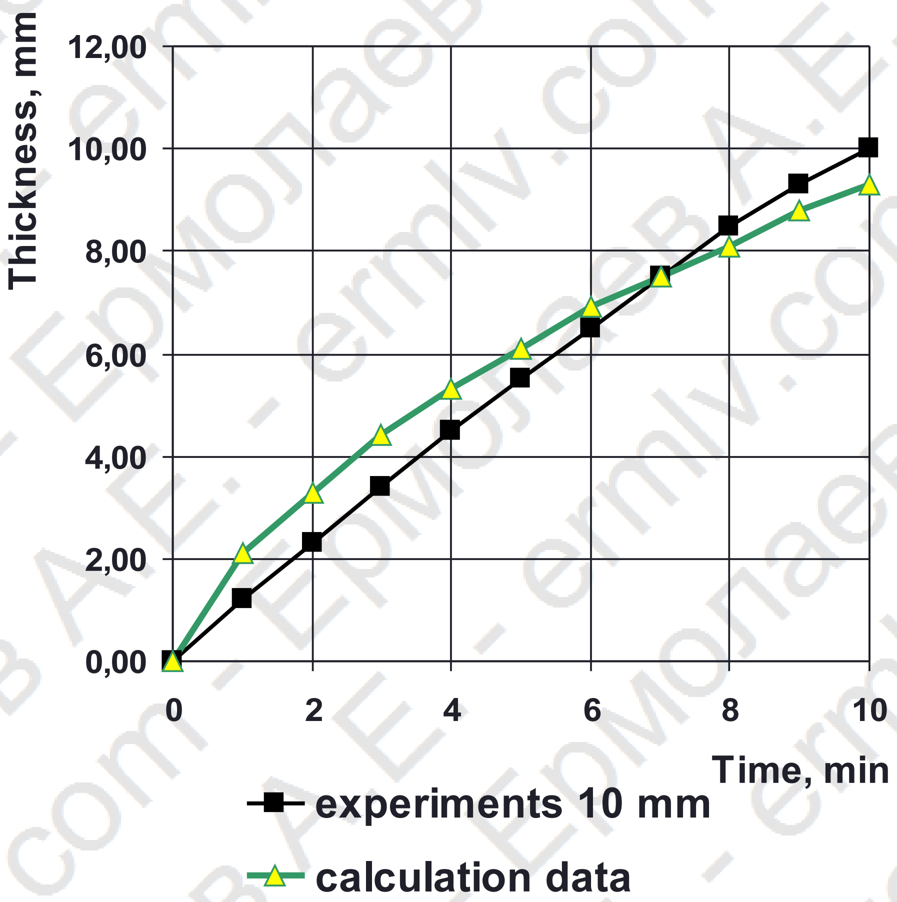

Fig.3. Comparison of theory results with experimental data

4. VACUUM WATER ICE SLURRY PROCESS

Generation of water ice slurry is a more complicated process by a few aspects: the size of water droplets introduced in to the vacuum chamber depends on a diameter of nozzle channel; flow water pressure drop through it. These are the first rate factors. Besides there are some other ones which seem to be of lesser importance but they follow the process: formation of ice at the end of the water nozzle; agglomeration of ice particles floating in water.

Theoretical consideration of the freezing of water droplets flying within vacuum chamber comes to the differential equation which can be solved analytically with the help of approach considered above for the cylindrical thin layer of the water subjected by vacuum pumping from one side. The difference is that spherical coordinates are used and water droplets are assumed to be ideal spheres flying within a vacuum chamber.

For a special case of a water droplet 2 mm in diameter, the correlation between a thickness of freezing layer ξ and a time of the process in a graphic form is shown in fig. 4. The water flow rate is 20 kg/h and vacuum speed of pumping related to the unit of sphere droplet surface 8.9 m^3/m^2s.

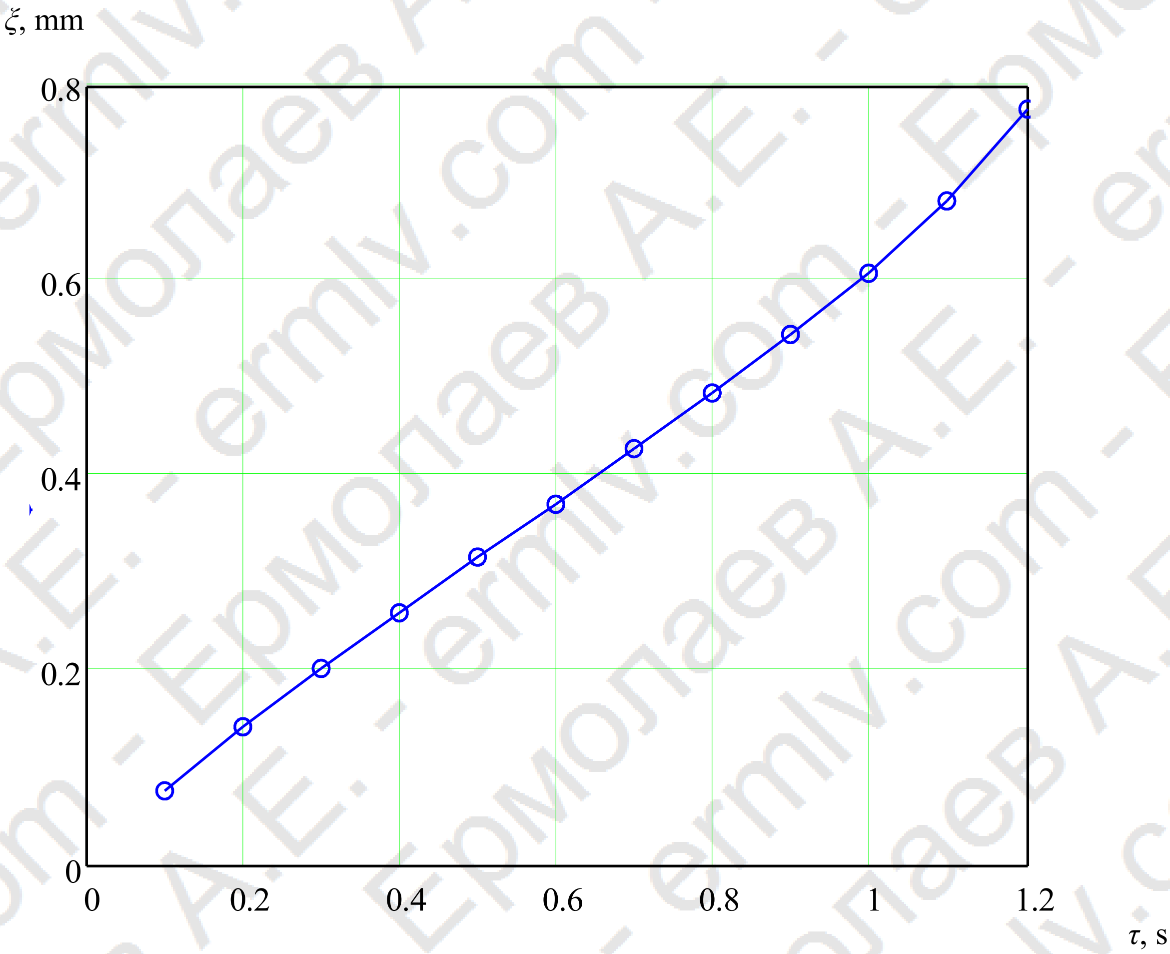

Fig.4. Freezing layer of ice sphere as a function of time
(for initial diameter of water droplet is D = 0.002 m; initial temperature of water is 0 ºC)

5. CONCLUSIONS

Our analytical and experimental work demonstrated the possibility water ice generations with the help of vacuum technology .This ice machines with water as refrigerant have some advantages in comparison with traditional HFC systems: they need no chemical and vessel pressure regulation; besides the process ice generation is more simple as the number of equipment is less.