Vacuum-evaporative method of juice concentration

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Abstract. The article provides an overview of methods for concentrating juices and juice-containing liquids and proposes a vacuum method for concentrating juices, based on previous experiments on vacuum cooling of water. Vacuum-evaporative concentration of juices has a number of advantages that can be successfully implemented in production. The developments of water use as a refrigerant, as well as experiments on machines with an open cycle, provide the necessary and sufficient material for development in the field of concentrating juices. The use of low temperatures creates the evacuation effect.

1. Introduction

In 1915, a system for juicing was patented for the first time. Since that time, the methodology has been improved and changed; new ways to improve the quality and production of juices have appeared.

Juices are a valuable source of most of the vitamins and minerals necessary for the body, which are found in compounds. They are most easily absorbed by the human body which becomes important in the cold season. At this period the diet becomes scarce in minerals, vitamin complexes, dietary fiber, whey proteins. The perfection of processing methods determines the amount of stored useful elements, some methods of processing can reduce the content of the vitamins and minerals.

At the same time the properties of the juices (for example, beet juice) and their composition will depend on the original product. The final composition of fruit and vegetable juices is significantly different: the fruit juices have much more organic acids, amino acids, antioxidant minerals and dietary fiber, while the vegetable juices will be rich in proteins, fats, fiber and B vitamins.

All these elements are vital, and vitamins play a key role in metabolism and in all internal reactions of the human body.

2. Juice production technologies

Juice production may differ in processes and technologies, but in general, a technological line always includes several mandatory stages: washing, cleaning and preparation, which may include crushing raw materials, collecting the resulting juice, and subsequent procedures for bringing the juice to its consumer state, including cleaning, clarification, pasteurization (Figure 1).

Particular attention should be paid to the stage of concentration of the primary juice obtained by direct extraction. At the same time, the concentrated juice is not intended for direct consumption, but is
suitable for the recovery of juice and nectar-containing drinks, for the manufacture of jam, jelly and fillings; therefore this type of the product is rather difficult to find in retail. Juice concentration is carried out by one of several proven technologies.

The technology, which allows concentrating juices by evaporation, takes place under the influence of high temperatures, which would reduce the final quality of the product. At the exit, the resulting concentrate looks like a viscous mass, which is then frozen and sent to the juice producer.

![Figure 1. Technology of juice production in a simplified form](image)

Also recently, a method called membrane has been gaining popularity, during which juice passes through a finely dispersed membrane, passing only water molecules, and leaves larger concentrate compounds in the mixture.

Storing juices in a concentrated form does not involve high energy and financial costs, since the mixture obtained at the outlet has an extremely low water content, and as a result, a high density of the substance, which does not allow the process of microbiological spoilage to start. In this regard, tanks with a temperature of 5 to 10 °C are quite suitable for storing such a product, but if mixtures that improve the smell, taste or color of the product are added to the concentrated substance, as a rule, they try to keep the storage temperature below 0 °C.

Therefore, refrigeration methods are needed that keep energy, financial and technological costs to a minimum, which can be facilitated by a plant using water (juice) as a refrigerant based on the principle of vacuum evaporation.

3. Description of the Vacuum Concentration Unit
Currently, the development and study of the possible use of natural substances as refrigerating refrigerants are underway, among which water seems to be very promising.

The main advantage of using a vacuum evaporation machine is the use of water contained in the product (milk, juices) as a refrigerant, while cooling can be carried out from a high initial temperature of 40-50 degrees Celsius to a cryoscopic temperature.

The advantages of water lie in its properties and high prevalence: food, air conditioning, agriculture, various types of production. But a more important factor is that water is as environmentally friendly as possible and meets all parameters for environmental protection, it is chemically stable, non-toxic and fireproof, and capable of simultaneously performing both the role of a refrigerant and the role of a refrigerant.
However, there are a number of problems in the design of a vacuum water refrigeration unit. Water has an extremely low operating pressure, well below atmospheric pressure, which necessitates the use of systems with high flow rates and high vapor compression ratios. Machines with high volumetric capacities are the ideal choice.

The principle of operation of the vacuum refrigerator is based on the fact that during the boiling of the cooled liquid in the evaporator at a pressure below atmospheric pressure (10 mm Hg); intensive heat removal occurs with portions of vapors that condense in the water condenser.

The cooled liquid is placed in a vacuum vessel called an evaporator, from which vapors are pumped out by the auxiliary and main pumps.

First, an auxiliary pump operates, which performs preliminary rarefaction and pumping out non-condensable gases. When the pressure in the evaporator reaches the required value of 10 mm Hg, we start the main pump, which performs further pressure reduction to the required level of 5 mm Hg.

During operation of the main pump, the process of pumping out water vapors and vacuum boiling of the cooled liquid takes place.

During boiling, part of the liquid goes into the vapor phase. This reduces the temperature. The pumped water vapors are sent to the condenser, where the vapors condense and heat of condensation is removed with the help of cooling water.

Vacuum water refrigeration machines are capable of operating on the principle of Freon vapor compression machines, realizing the reverse thermodynamic cycle. Also, such machines can operate in open cycles, which further increases the efficiency of the circuit. However, due to the problems described above, it is required to design a machine that would allow operation in low pressure ranges, which makes it logical to use rotary vacuum pumps in installations. These developments are given in [1].

It is rational, in addition to open-cycle installations, to use vacuum-evaporating installations [2], tested in real conditions in a low-temperature laboratory using vacuum machines and contactless pump-compressors. It should be noted that these studies use a method that excludes the compression of water vapor in the flow path, allowing removing condensation in this unit, and redirecting the compression process to the exhaust pipe with a compression ratio of 10–12 units with averaged feed values (Figure 2).

**Figure 2.** Scheme of a vacuum-evaporation plant for cooling liquids: 1 - evaporator in the form of a sealed container; 2 - vapor condenser; 3 - main pump; 4 - auxiliary pump; 5 - leak valve; 6 - filling device; 7 - condensate drain valve, 8 - anti-drift system
As shown by the results of the above studies of a vacuum-evaporating refrigeration machine, when operating with a water condenser, the energy consumption for cooling water to near-zero temperatures is on average 12–16% lower than that in vapor-compression refrigeration machines using Freons [4].

You can also rely on graphic and analytical conclusions, which are presented in the materials [1], [3], [4], as well as formulas as basic calculations for the parameters of juice cooling in the usable space of the installation.

Separately, it should be noted that vacuumized juice would work as a separate source of cold. If additional heat is supplied to it, juice can be used to remove heat from other cooled objects.

Almost any production has a low-potential heat source or cooling facility. By taking away heat from such an object, you can bring it to the juice. To do this, a loop with an intermediate coolant can be used.

The vacuum-evaporative juice concentrator allows the juice to be used as a refrigerant, that is, the pump-compressor makes the juice boil at a temperature significantly lower than the boiling point. That is, the juice boils and cools itself, performing two main functions at once: cooling and concentration [5-7].

Since the process of vacuumizing the juice for concentration is relatively long, the use of it as a separate source of cold can be rational.

Thus, the juice concentration unit will perform two tasks at the same time: concentrating itself and working as an additional refrigeration unit for cooling process liquids [8-10].

Vacuum-evaporative concentration technology has a number of advantages over those described above:
- has a simpler design compared to Freon coolers;
- does not use substances with high ODP and GWP to obtain cold, and there is no excess pressure inside the circuit;
- does not affect the quality of the concentrated juice, since there is no heating for evaporation;
- does not require low temperatures for operation, like freeze concentrators;
- juice is a cooler and cooled object, there are no losses during heat transfer through the wall of the heat exchanger;
- juice concentration is carried out in parallel with the main cooling process and is inextricably linked with it.

Preliminary calculations show that vacuum cooling of juice is almost the same as it is for water. When compiling the analytical description of vacuum cooling of water, there are the following assumptions:
- temperature field along the depth of the liquid layer is uniform;
- evaporator vessel wall temperature is equal to liquid temperature;
- heat of liquid steam generation is constant and does not depend on pressure;
- weight of the cooled liquid remains constant.

A mathematical model of the process of vacuum-evaporative cooling during concentration of juice can be obtained analytically from the following considerations.

The elementary amount of heat removed from liquid:
$$dQ_w = C_w \cdot m_w \cdot dT$$

$C_w$ - specific heat capacity of water; 
$m_w$ - mass of evaporated water; 
$dT$ - elementary temperature changes of water.

The elementary amount of heat removed from the evaporator:
$$dQ_M = C_M \cdot m_M \cdot dT$$

$C_M$ - specific heat capacity of the evaporator body; 
$m_M$ - weight of the evaporator body; 
$dT$ - elementary temperature changes of the evaporator body.

Main heat gain:
\[ dQ_W = K \cdot F \cdot (T_{OS} - T) \cdot d\tau \]

\( K \) - heat transfer coefficient;
\( F \) - heat exchange area;
\( T_{OS} \) - ambient temperature;
\( T \) - current temperature;
\( d\tau \) - elementary time changes.

Heat dissipated by vacuum effect:
\[ dQ_0 = (C_W \cdot m_0 + C_M \cdot m_M) \cdot dT + K \cdot F \cdot (T_{OS} - T) \cdot d\tau. \]

Differential heat balance equation:
\[ (C_W \cdot m_0 + C_M \cdot m_M) \cdot dT + K \cdot F \cdot (T_{OS} - T) \cdot d\tau = r \cdot P \cdot \mu \cdot S_{EF} \cdot R \cdot T^{-1} \cdot d\tau \]

\( \mu \) - molecular weight;
\( S_{EF} \) - effective pumping rate;
\( R \) - universal gas constant.

The final equation of the juice cooling time:
\[ \tau = -(C_W \cdot m_0 + C_M \cdot m_M) \cdot R \cdot e^{273b} \cdot (2r \cdot \mu \cdot S_{EF} \cdot A \cdot b)^{-1} \cdot (-e^{-bT_k} (T_k + 14.28) + e^{-bT_0} (T_0 + 14.28)) \]

\( A \) - empirical constant;
\( b \) - empirical constant;
\( T_k \) - condensation temperature;
\( T_0 \) - boiling point.

Figure 3 shows comparisons with calculated and experimental data obtained by other authors.
The graph in red shows cooling using the main pump at 150 l/s with a filling of 50 liters of juice and a temperature of +30 °C.

**Figure 3.** The dependence of the temperature of the cooling time
The blue color shows the cooling graph with the main pump at 50 l/s when refueling with 20 liters of water and a temperature of +23 °C.

The purple color shows the cooling graph using the main pump at 150 l/s when refueling with 40 liters of water and a temperature of +30 °C.

4. Conclusion
As a result, it can be summarized that the vacuum-evaporative concentration of juices has a number of advantages that can be successfully implemented in production and in the developments of using water as a refrigerant. Experiments on machines with an open cycle provide the necessary and sufficient material for development in the field of concentrating juices using low temperatures and the effect of evacuation [11-15].

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