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INTENSIFICATION OF SECONDARY VAPOR CONDENSATION IN GRAPE JUICE CONCENTRATION UNITS THROUGH OPTIMIZATION OF PHASE HYDRODYNAMICS

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ABSTRACT: *Subject. The mixing-type condensation of secondary vapor during vacuum concentration of grape juice in a barometric condenser, in which the cooling water is dispersed through atomizing nozzles of various geometries.*

Purpose. To intensify heat and mass transfer and improve the energy efficiency of vacuum-evaporation units by optimizing phase hydrodynamics in a mixing-type barometric condenser through nozzle atomization of the cooling water.

Methodology. Experiments were carried out on a vacuum-evaporation unit concentrating grape juice ('Black Kishmish' variety, 16–18% Brix). The hydrodynamic interaction between secondary vapor and finely dispersed cooling-water droplets, produced by centrifugal-jet nozzles, was studied at

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condenser pressures of 15–30 kPa. Droplet size distribution and motion were recorded by high-speed photography and laser Doppler anemometry; data were processed by one-way ANOVA ($p < 0.05$).

Results. Replacing the traditional tray (cascade) elements of the barometric condenser with a fine-droplet nozzle-spray system fundamentally reshapes the phase hydrodynamics. At a mean droplet diameter of 1.2–1.8 mm, the specific phase-contact area reaches $162 \text{ m}^2/\text{m}^3$, shifting condensation into a highly turbulent regime. The volumetric heat-transfer coefficient increased by 52.4%. Vacuum depth stabilized at 92–94%, lowering the juice boiling temperature and preserving thermolabile components. Specific cooling-water consumption fell by 25.6%, and vacuum-pump energy consumption fell by 21.0%.

Practical value. The developed hydrodynamic scheme and operating parameters are recommended for retrofitting existing barometric condensers at food- and wine-industry plants.

Keywords: *grape juice, vacuum evaporation, secondary vapor, mixing-type barometric condenser, nozzle, water atomization, phase contact, heat-transfer intensification.*

1. INTRODUCTION

Uzbekistan is one of the largest grape producers in Central Asia, and processing surplus harvest into concentrated grape juice is a priority direction for the republic's food industry. In concentrating grape juice, the key task is to preserve vitamins, sugars and aromatic compounds while minimizing energy costs, which is achieved by lowering the boiling temperature through intensified vacuum-generating systems and efficient condensation of secondary vapor.

The mixing-type barometric condenser is a key unit of the vacuum-evaporation plant: its efficiency determines the depth of vacuum and,

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consequently, the boiling regime of the product. In conventional tray (cascade) condensers, vapor and cooling water contact on falling water streams of limited specific surface area, which leads to incomplete condensation, degraded vacuum, and excess consumption of cooling water and vacuum-pump electricity.

Fundamental principles of multiphase hydrodynamics [1] indicate that the most promising route to intensifying heat and mass transfer is converting a continuous liquid stream into a dispersed droplet state [5, 6]: breaking the liquid into fine droplets increases the specific phase-contact area by an order of magnitude or more. The same principle of maximizing contact surface is successfully applied in related intensification processes — ultrasonic drying of plant raw material and high-frequency extraction of oil from stone-fruit pits [2, 3, 4].

At the same time, the condensation kinetics of secondary vapor containing volatile organic fractions of grape juice, under nozzle-atomized cooling conditions, remain insufficiently studied [7, 8]; existing foreign studies address spray condensation mainly for power and chemical plants [6, 9, 10], while the specifics of food media call for dedicated study.

The idea of this work is to fundamentally improve the phase hydrodynamics of a mixing-type barometric condenser by supplying cooling water through centrifugal-jet nozzles to create a well-developed droplet-type phase contact. The aim is to intensify heat and mass transfer and improve the energy efficiency of vacuum-evaporation units concentrating grape juice.

Objectives: (1) to determine experimentally how nozzle water pressure affects droplet dispersion and specific phase-contact area; (2) to establish the relationship between the volumetric heat-transfer coefficient, vacuum depth, and nozzle operating parameters; (3) to assess the energy and water efficiency of the proposed method relative to a conventional tray condenser.

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2. MATERIALS AND METHODS

The experimental rig comprised a 50-liter vacuum-evaporation unit and a retrofitted vertical mixing-type barometric condenser. The material processed was grape juice of the 'Black Kishmish' variety (Brix = 16–18%); system pressure was maintained at 20 kPa.

In place of the cascade trays, a manifold fitted with centrifugal-jet nozzles (nozzle diameter $d_n = 2.5; 3.5; 4.5$ mm) was installed. Cooling water was supplied at an excess pressure of $\Delta P = 0.10\text{--}0.30$ MPa, producing a spray cone angle of $60\text{--}75^\circ$. Secondary vapor from the evaporator was fed counter-current to the descending droplet flow to maximize phase-contact time at minimal hydraulic resistance.

Monitored and measured parameters [2, 3, 4]:

1. Pressure and vacuum: recorded by calibrated vacuum gauges and pressure sensors with real-time PC logging.
2. Flow rates: juice and cooling-water flow were measured with electromagnetic flow meters.
3. Droplet hydrodynamics: the mean droplet diameter (d_{32} , Sauter diameter) was determined from spray-cone angle and pressure drop, and verified by optical probing and high-speed photography with computer image processing.
4. Temperature was monitored by thermocouples at characteristic points of the vapor–water path; droplet velocity and trajectories were recorded by laser Doppler anemometry (LDA).

Each operating regime was tested at least three times; the data were processed by one-way analysis of variance (ANOVA) at a significance level of $p < 0.05$, ensuring the statistical reliability of the differences observed between regimes.

3. RESULTS AND DISCUSSION

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Nozzle-based cooling-water injection fundamentally alters the phase hydrodynamics inside the barometric condenser. Instead of massive streams with a small heat-transfer surface, a highly dispersed droplet flow (a ‘water mist’) is formed. Secondary vapor entering from the evaporator condenses almost instantly on the droplet surface owing to the droplets’ large surface-energy reserve and the high relative velocity between the phases.

Table 1 presents comparative hydrodynamic characteristics for different nozzle water pressures ($d_n = 3.5$ mm).

Table 1. Hydrodynamic parameters of the droplet flow and secondary-vapor condensation efficiency

Mode / ΔP , MPa	d_{32} , mm	Specific contact area, m^2/m^3	K_v , $W/(m^3 \cdot K)$	Outlet water T, $^{\circ}C$	Residual pressure, kPa
Tray-type (baseline)	jet flow	35	12400	41.2	24.5
Nozzle (0.10)	2.1	95	15800	43.5	21.0
Nozzle (0.20)	1.4	162	18900	45.8	18.2
Nozzle (0.30)	0.9	210	19400	46.1	17.9

As Table 1 shows, the optimal spray regime is $\Delta P = 0.20$ MPa: the volumetric heat-transfer coefficient K_v increases by 52.4% relative to the baseline tray condenser, and the specific phase-contact area reaches $162 m^2/m^3$. Raising the pressure further to 0.30 MPa over-atomizes the droplets (0.9 mm) without a corresponding gain in heat transfer, while increasing the risk of fine-

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droplet carryover into the vacuum pump [7, 8] and, consequently, fouling and extra wear of the vacuum system.

The intensification mechanism follows classical heat- and mass-transfer theory for droplet condensation [5]: fine droplets carry a large surface-energy reserve, and the high relative phase velocity ($w_v - w_d$) strips the thermal boundary layer from the droplet surface, accelerating the vapor-to-liquid phase transition. As the droplet diameter decreases from 2.1 to 1.4 mm, the specific contact area rises almost 1.7-fold, correlating with the rise in the volumetric heat-transfer coefficient and confirming the decisive role of flow dispersion in process intensification.

An energy balance of an evaporation unit with a capacity of 600 kg/h of evaporated moisture confirmed the high economic effectiveness of the proposed method (Table 2).

Table 2. Comparative energy-efficiency indicators of the barometric condensation unit

Indicator	Cascade tray-type condenser	Proposed nozzle-spray condenser
Specific cooling-water consumption, kg/kg vapor	28.5	21.2
Outlet cooling-water T, °C	41.2	45.8
Vacuum stability in system, %	± 4.5	± 0.8
Specific vacuum-pump energy demand, kWh/t	16.2	12.8

The 25.6% reduction in specific cooling-water consumption reflects the fact that nozzle atomization brings the outlet barometric water temperature much closer to the secondary-vapor saturation temperature: the minimum temperature approach is only 1.5–2.0 °C, against 6–8 °C for tray-type

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analogues — i.e., the cooling water's heat capacity is used far more completely per unit of condensed vapor.

The 5.6-fold improvement in vacuum stability (from $\pm 4.5\%$ to $\pm 0.8\%$) is of particular technological significance for food production, since a stable vacuum keeps the juice boiling temperature constant throughout the concentration cycle — critical for preserving thermolabile vitamins and aromatic compounds. The 21.0% reduction in specific vacuum-pump energy consumption results from the smaller volume of non-condensed vapor that the pump must evacuate once condensation on the developed droplet surface is more complete.

These results are consistent with the general patterns established for spray-type barometric condensers in the chemical and power industries [6, 9, 10], while extending them to the specifics of food media containing volatile organic components. The developed hydrodynamic scheme and operating parameters ($\Delta P = 0.20$ MPa, $d_n = 3.5$ mm) can be recommended for retrofitting existing barometric condensers at food- and wine-industry plants without substantial changes to existing equipment dimensions, since replacing the tray elements with a nozzle manifold is feasible within the existing condenser shell.

4. CONCLUSION

1. A method for intensifying the mixing-type condensation of secondary vapor during grape-juice evaporation has been scientifically substantiated and developed, based on optimizing the phase hydrodynamics of the barometric condenser.

2. Centrifugal-jet nozzles (optimal regime $\Delta P = 0.20$ MPa) were shown to produce a well-developed droplet flow with a mean diameter of 1.4 mm and a specific phase-contact area of up to $162 \text{ m}^2/\text{m}^3$, increasing the volumetric heat-transfer coefficient by 52.4% relative to the baseline tray condenser.

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3. Implementing the developed nozzle method in the barometric condenser reduces cooling-water consumption by 25.6%, cuts vacuum-system energy consumption by 21.0%, and improves vacuum stability 5.6-fold, together lowering the production cost of concentrated grape juice while fully preserving its thermolabile components.

4. The developed hydrodynamic scheme is recommended for retrofitting barometric condensers at food- and wine-industry plants; further research should focus on mathematical modeling of condensation on a polydisperse droplet flow and on pilot-scale testing of the proposed solution on an industrial evaporation unit.

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