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EFFICIENCY OF A VACUUM COOLING SYSTEM WITH LIQUID-VAPOR EJECTOR FOR BIODIESEL PRODUCTION

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ABSTRACT

This article deals with the issue of increasing an efficiency of the vacuum cooling systems during biodiesel production by using a new type of vacuum units, such as liquid-vapor ejector, which working process is based on the principle of jet thermal compression. The geometry of the flowing part has a significant impact on the efficiency of the mixing process in primary and secondary flows and the unit as a whole. The authors consider structural variations of liquid-vapor ejectors – with cylindrical and conical mixing chambers, followed by a cylindrical section, with a diffuser and without it. Numerical and experimental studies of liquid-vapor ejector with a various geometry of the flow part were put into practice and made it possible to obtain the dependence of the performance of the liquid-vapor ejector and the units on its basis, that allows to determine the optimal operating conditions of the system on the basis of this ejector. Analysis of the LVE exergetic efficiency and the unit as a whole made it possible to conclude that it is appropriate to use this type of ejector in the vacuum cooling systems of biodiesel production.

Keywords: Vacuum cooling system, Liquid-vapor ejector, Biodiesel production, CFD simulation, Exergetic efficiency

1. INTRODUCTION

At present, a lot of researches are being conducted all over the world that aimed at ensuring a fuel economy and the partial replacement of traditional fossil hydrocarbon energy sources, whose resources may be exhausted in the near future. Taking into account the constant increasing of oil prices, a local and world planet pollution with waste products has led to the biodiesel production an environmentally clean fuel based on renewable bioresources [1]. Biodiesel is a type of fuel, that derived from vegetable and animal fats and used (in pure or mixed form) to replace oil diesel fuel. The basis for its production is mostly rape oil (84%), however, according to the geographical location and natural climatic conditions, producers can use sunflower oil (13%), soybean (2%) [2].

European countries are absolute leaders in the production and using of biodiesel, where since 2010 the biodiesel industry from plant products accounted for 5,75% of used fuel, and by 2020 this figure will have reached 20%. A modern industry uses the vacuum systems, working on the basis of steam-jet ejectors, the main disadvantages of which are their multistage (3-5-step vapor-jet ejectors with intermediate capacitors) and, as a consequence, low efficiency (total efficiency of 2–10%) [3].

In this situation, the using of liquid-vapor ejector (LVE), operating on the principle of jet thermal compression becomes very relevant [4]. Modern software systems, that are based on the finite element method of analysis, allow to conduct a numerical simulation of the working process quite accurately [5]. After the experimental study and subsequent analysis of the exergy efficiency [6], it can be concluded that it is advisable to use this type of ejectors in vacuum cooling systems of biodiesel production plants.

2. VACUUM COOLING SYSTEM

The traditional biodiesel production plant is a multi-stage steam vacuum system, that consists of two boosters (two large steam-jet ejectors, connected in series), a main mixing condenser, a small transitory ejector with a mixing condenser for air pumping, and a liquid-ring vacuum pump of the final stage (Figure 1).

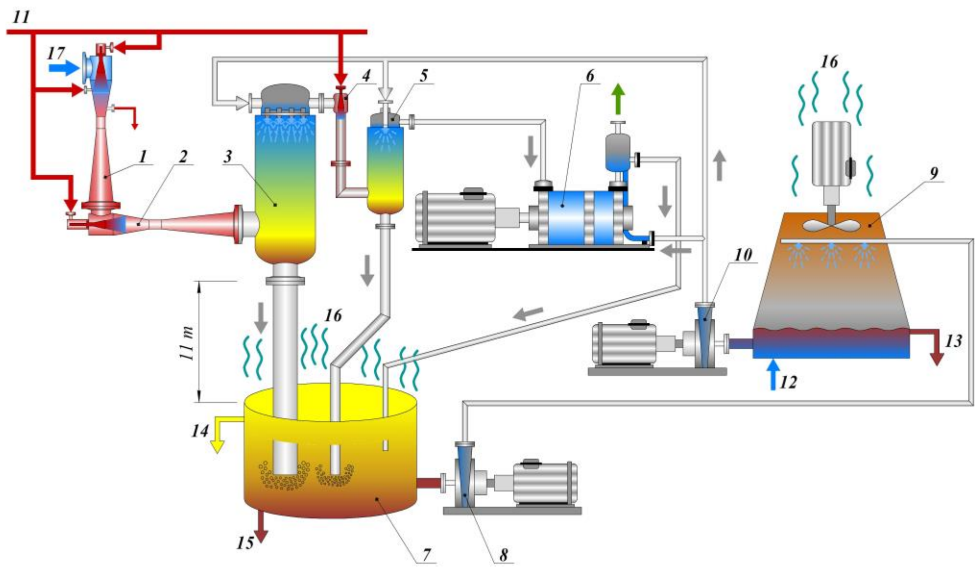

Figure 1: Basic vacuum cooling system: 1 – booster (1st stage), 2 – booster (2nd stage), 3 – main mixing (direct contact) condenser, 4 – steam jet ejector (3rd stage), 5 – interconnected mixing (direct contact) condenser, 6 – liquid ring vacuum pump (4th stage), 7 – seal tank, 8 – cooling water pump I, 9 – cooling tower, 10 – cooling water pump II, 11 – motive steam, 12 – fresh cooling tower water, 13 – bleed, 14 – overflow of contaminated liquid, 15 – draining, 16 – gas outlet, 17 – sparging steam from deodorizer

The capacity of the basic unit is 220 *kg/h* of water vapor + 8 *kg/h* of air + 5 *kg/h* of free fatty acids. Deodorization technology involves the extraction of fatty acids (odorants) by bubbling the hot water vapor through a ball of processed fuel at a pressure of 2 *kPa*. Maintaining this level of vacuum increases the volatility of odorants and it's vapors diffuse into water vapor bubbles.Condensation of bubbling steam and maintaining the pressure at a certain level is ensured by the supply of cooling water, which circulates in the cooling circuit through the cooling tower.

The working pressure of the boiler steam, that used by the steam ejectors as the working jet of the primary flow, is 0,9 *MPa*, the cooling water temperature at the inlet is 33°*C*.

The condensate of the working steam, that supplied to the motive nozzles of the steam ejectors is contaminated the components contained in the pumped flow together with the bubbling steam and does not return to the installation. For surface-type capacitors, that are used in the installation, it is necessary to pump condensate, as the condensation pressure is less than atmospheric.

Vacuum systems of this type use the combined advantages, when steam jet ejectors work in combination with liquid ring vacuum pumps. This means that the bubbled steam is compressed only by steam-jet ejectors (known as boosters) to the first possible stage of condensation. And after the first stage, behind the main mixing condenser, combinations of steam jet ejectors and liquid ring pumps are possible.

The proposed alternative circuit solution allows to minimize the consumption of boiler steam in the vacuum system (Figure 2). Pumping of the vapor gas mixture is provided by a liquid steam ejector operating as part of the vacuum unit.

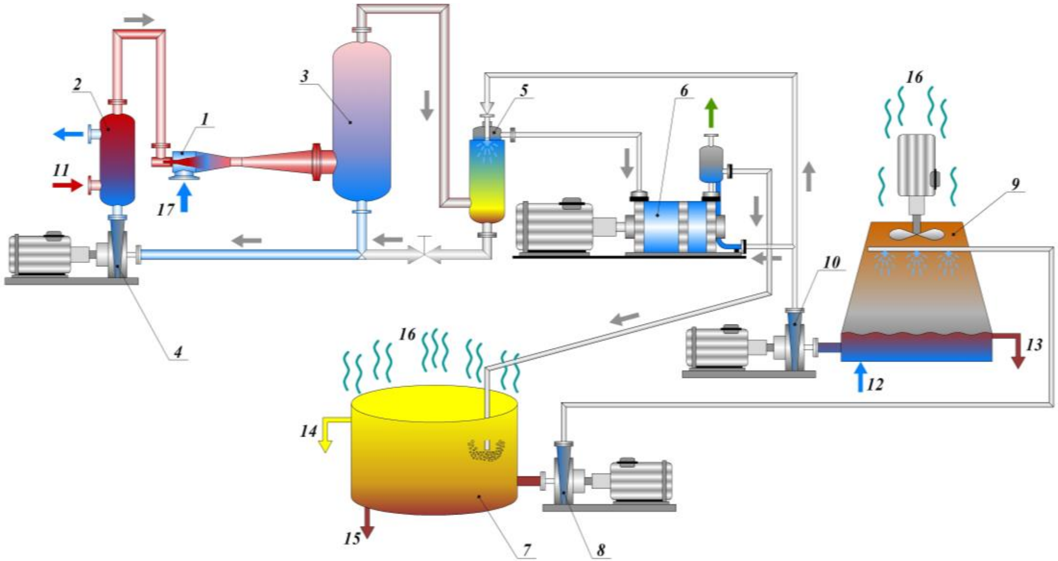

Figure 2: Vacuum cooling system with liquid-vapor ejector: 1 – liquid-vapor ejector, 2 – heat exchanger, 3 – separator, 4 – circulating pump, 5 – interconnected mixing (direct contact) condenser, 6 – liquid ring vacuum pump (4th stage), 7 – seal tank, 8 – cooling water pump I, 9 – cooling tower, 10 – cooling water pump II, 11 – motive steam, 12 – fresh cooling tower water, 13 – bleed, 14 – overflow of contaminated liquid, 15 – draining, 16 – gas outlet, 17 – sparging steam from deodoriser

For condensation the steam phase of the mixing flow after the separator and return the working fluid to the circulation block of vacuum unit, is provided a condenser unit, including a condenser, a liquid ring vacuum pump and a circulating water cooling system.

Using of the mechanical vacuum pump as a forvacuum device in this case is advisable from the standpoint of ensuring higher energy efficiency of the vacuum system.

3. NUMERICAL INVESTIGATION

3.1. Ejector design

The article considers LVE in four design versions – with cylindrical and conical mixing chambers, followed by a cylindrical section, with and without a diffuser (Figure 3).

The ANSYS CFX software package is used to simulate the flow part of the LVE and to assess the impact of its geometric parameters on the efficiency. The standard system of equations Navier-Stokes is accepted as a mathematical model. The k-ε model is used to account for turbulence. The kinetics of the vaporization process in the expanding part of the primary flow nozzle is described by the Rayleigh-Plesset equation [4].

Since the flow part of the LVE is plane-parallel and all of its part is used by the calculations. The generation of the computational grid, which consists of approximately 115000 cells, is carried out automatically and is condensed in places, where steam is reorganized structurally on length of flowing part (Figure 4).

To compare the results of numerical simulation by means of the ANSYS CFX software package, calculations were carried out using a method that is based on a mathematical model LVE that described as a system of equations for one-dimensional adiabatic motion in the quasi-equilibrium thermodynamic approximation for the distinguished boundaries of the current section of the flow. This method is developed by the authors and described in the work [4].

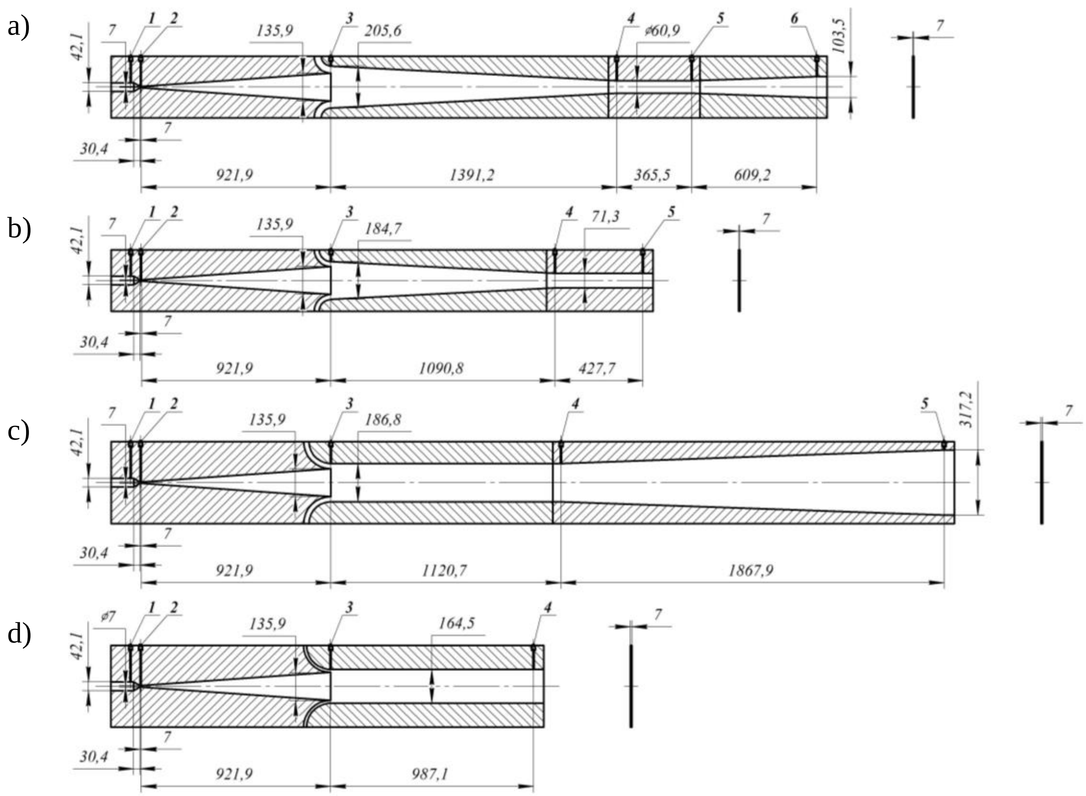

Figure 3: Liquid-vapor ejector design (dimensions in mm): a) with conical mixing chamber and diffuser, b) with conical mixing chamber without diffuser, c) with cylindrical mixing chamber and diffuser, d) with cylindrical mixing chamber without diffuser, 1…6 – pressure measuring

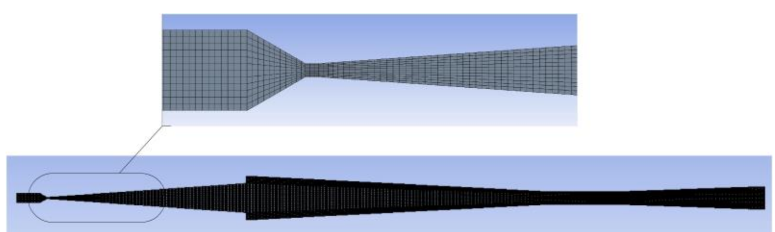

Figure 4: Computational grid (using the example of LVE with conical mixing chamber and diffuser)

3.2. Working fluid properties

Water is used as the working medium of the active flow, that at the inlet to the nozzle of the primary flow LVE has the following parameters: pressure P_{01} = 0,4 *MPa*, temperature t_{01} = 135º*C*, flow m_p = 0,4918 *kg/sec*.

A mixture of saturated water vapor (94,4 %), air (3,4 %) and fatty acids (2,2 %) is used as the working medium of the secondary flow, which has the following parameters at the inlet to the ejector receiving chamber: pressure P_{02} = 0,002 *MPa*, the flow rate of the working fluid in the secondary flow ms depends on the injection coefficient and LVE of various designs.

At the outlet of LVE we have a mixed two-phase flow of finely dispersed vapor-droplet structure with the following parameters: pressure p_t = 0,04 *MPa*, temperature t_t = 76º*C*, a consumption is equal $m_t = m_p + m_s$.

3.3. Boundary conditions

The boundary conditions for the primary and secondary flow at the input were assigned as inlet pressure, for the mixed flow at the outlet of LVE – outlet pressure (Figure 5).

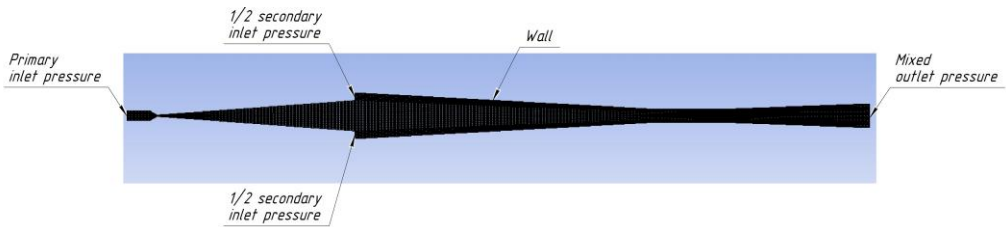

Figure 5: Boundary conditions (using the example of LVE with conical mixing chamber and diffuser)

The temperature limit value for all flows was assigned as 120º*C*. The boundary pressure of the primary flow at the LVE inlet is equal 5 *bar*, of the secondary flow at the inlet to the suction chamber 0,01 *bar*, the pressure of the mixed flow at the outlet of the ejector 0,5 *bar*. The ambient pressure is assumed to be equal to atmospheric pressure under normal conditions, that corresponds to 101325 *Pa*.

4. EXPERIMENTAL INVESTIGATION

The authors experimentally investigated the liquid vapor ejector of different design according to Figure 3. The parameters of the working fluid at the inlet to the motive nozzle were as follows: pressure P_{01} = 0,3–0,6 MPa, temperature t_{01} = 120–150º*C*. Parameters of the working fluid in the secondary flow at the inlet to the suction chamber: pressure P_{02} = 0,03–0,055 *MPa*, temperature t_{02} = 40–90º*C*. The parameters of the mixed flow at the outlet of LVE were as follows: pressure P_4 = 0,04–0,1 *MPa*, temperature t_4 = 70–100º*C*.

Experimental studies were carried out on the stand experimental model according to the developed program and the test procedure [5].

5. RESULTS AND DISCUSSION

5.1. Distribution of pressure and velocity

On figure 6 presents the results of numerical and experimental studies LVE different design describe changes of operating parameters in the axial direction, such as pressure and rate of primary, secondary and mixed flows during the working process in the flow part of LVE.

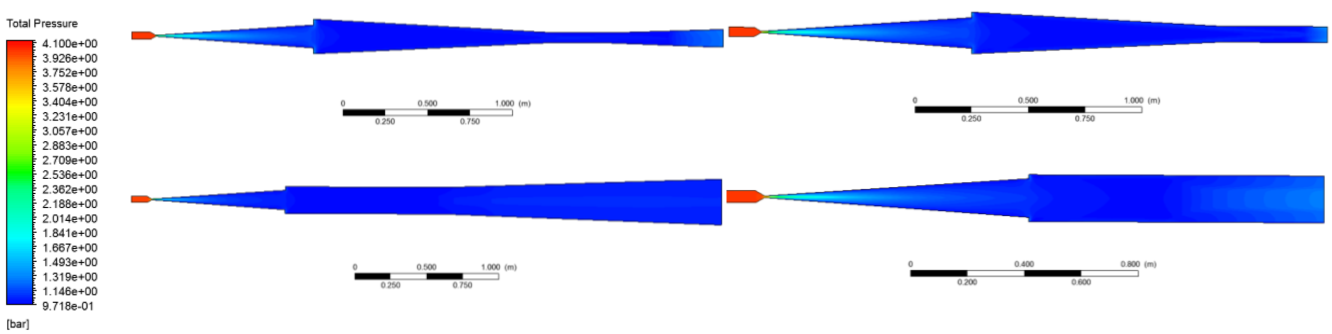

Figure 6: Distribution of pressure. Numerical (lines) and experimental (points) results (designations according to Figure 3)
---- conical mixing chamber and diffuser, ---- conical mixing chamber without diffuser, ---- cylindrical mixing chamber and diffuser, ---- cylindrical mixing chamber without diffuser

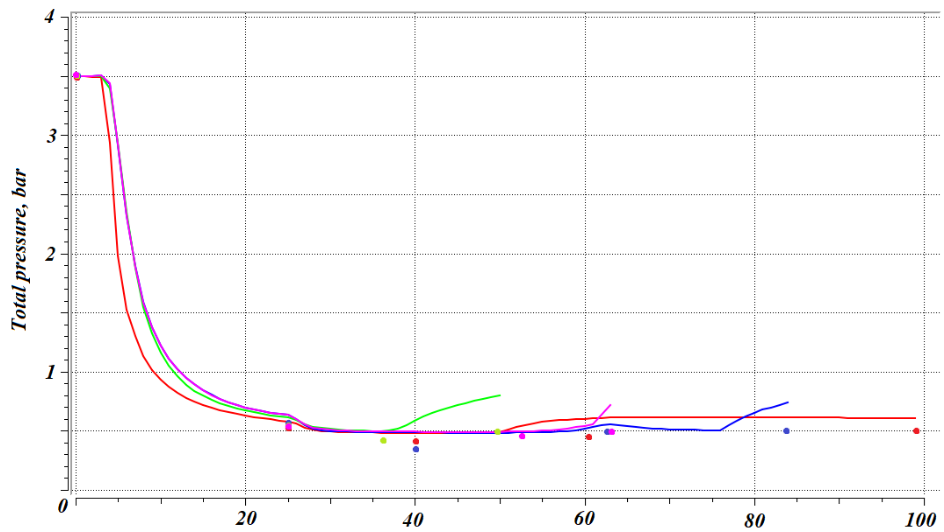

Figure 6: Distribution of pressure. Numerical (lines) and experimental (points) results (page 2)

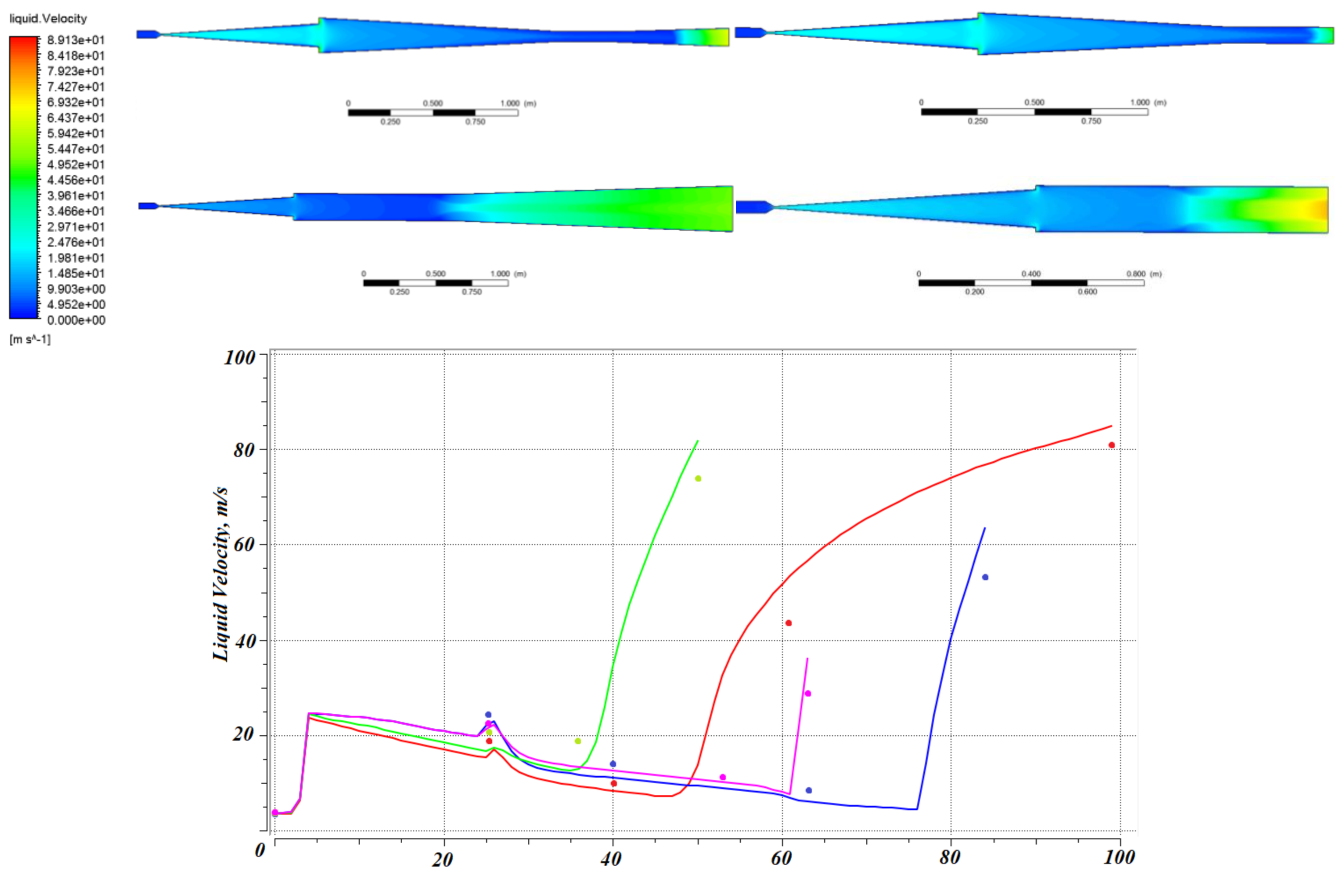

Figure 7: Distribution of velocity. Numerical (lines) and experimental (points) results (designations according to Figure 6)

From figures 6 and 7 it can be seen that in LVE with the diffuser we have more uniform pressure distribution in the mixing chamber of both conical and cylindrical shape. The rate of the mixed flow at the outlet of LVE with the diffuser is less than in the similar LIVE without the diffuser, which more favorably affects the completeness of the mixing process [7, 8].

5.2. Vapor mass fraction in total flow

On figure 8 shows the apportionment of the mass content of the liquid and vapor phase in the flow part of the LVE, during mixing. The results of numerical and experimental studies are presented.

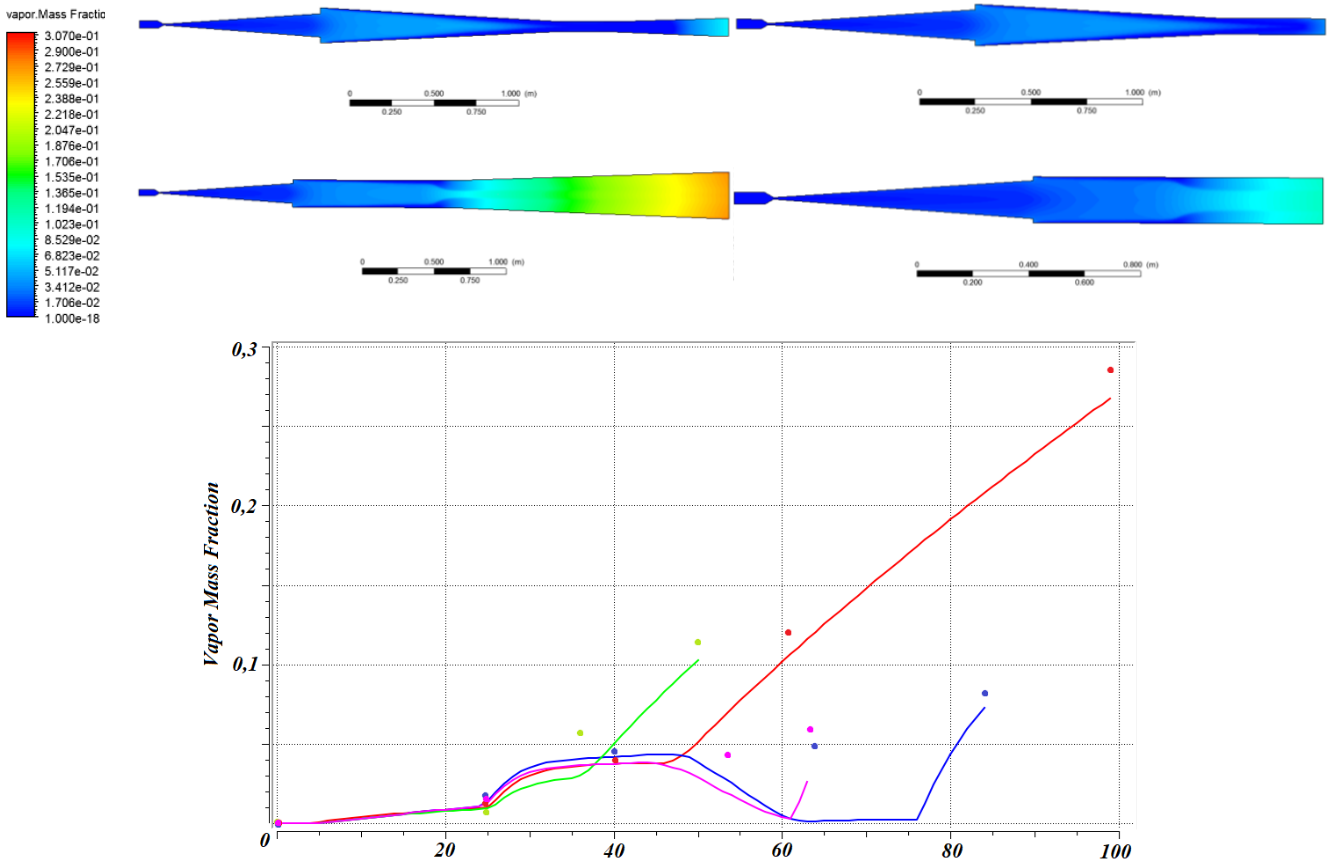

Figure 8: Vapor mass fraction in the flow part of the LVE. Numerical (lines) and experimental (points) results (designations according to Figure 6)

From figure 8 it can be seen that in LVE with diffuser and conical mixing chamber the mass vapor content is at the optimal level (x_4 = 0,1273), and, consequently, the degree of steam production is close to (ψ_4 = 1,171). In LVE with diffuser and cylindrical mixing chamber the degree of steam production in the mixed flow is higher (ψ_4 = 1,426). In LVE without a diffuser, the degree of steam production continues to increase and is at a level of ψ_4 = 2,273.

6. CONCLUSIONS

After analyzing the effect of LVE design parameters on the efficiency of the vacuum cooling system on the biodiesel production unit, the following conclusions can be drawn, that the use of LVE:

- makes it possible to simplify the design of the unit by switching from a three-stage steam jet ejector to a single-stage vacuum unit, based on LVE;

- allows to reduce the initial parameters of the working steam by switching to more moderate parameters of the working water in LVE primary flow (from 0,9 *MPa* and 225°*C* to 0,4 *MPa* and 135°*C*);

- allows to minimize the consumption of working steam due to the design features of the vacuum unit based on

LVE, where the working steam is consumed not as the primary flow of the steam-jet ejector, but only in a small amount for heating the working water of the primary flow in the heat exchanger-heater (reducing steam consumption from 1535 *kg/h* to about 216 *kg/h*, which is less than 7 times);

• conical or cylindrical mixing chamber without a diffuser makes it possible to obtain a flow of uneven structure at the outlet of the ejector due to high flow rates in the flow part, and, as a consequence, the incompleteness of the mixing processes in the chamber. This fact requires the placement behind the mixing chamber of an additional cylindrical section to align the final flow parameters at the outlet of the ejector;

• conical or cylindrical mixing chamber and a diffuser makes it possible to obtain a flow of a more uniform finely dispersed vapor-droplet structure at the outlet of the ejector with a degree of steam overproduction close to (ψ_4 = 1,171), although with lower energy efficiency (ε_1 = 19,2–23,5%) as compared with LVE without diffuser (ε_2 = 30,5–33,3%);

Therefore, due to the above, LVE with a conical mixing chamber with following cylindrical part and a diffuser (Figure 3,c) is optimal for this unit.

NOMENCLATURE

p	pressure (*MPa*, *bar*)	x	mass vapor content
t	temperature (º*C*)	ψ	degree of steam production
m	mass flow (*kg/sec*, *kg/h*)	ε	exergetic efficiency

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