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Experimental Stand for Studying the Working Process in a Liquid-Vapor Jet Device with Replaceable Diffuser Parts

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Abstract. The article describes the prospects for experimental research of liquid-vapor jet devices with adaptable geometry of the flow part of the primary flow nozzle. To formulate the research objectives, a critical analysis of state-of-the-art studies was conducted among native and foreign scientists studying two-phase jet devices. As a result, of the literature survey, we saw that the working process of the two-phase jet devices, which include liquid-vapor jet devices, is quite complicated to study. So, the achieved results of theoretical studies require clarification and the conduction of additional experimental studies. The article provides a description and experimental research method on the liquid-vapor jet devices with a replaceable diffuser part of the primary flow nozzle. The program and the method contain the range of changing operational parameters while conducting experimental studies. The functional scheme of the experimental scheme and the devices to control and measure pressure in the critical points of the scheme are proposed.

Keywords: primary flow nozzle, pressure measurement, experimental research, jet flow, process innovation.

1 Introduction

Nowadays, creating energy-efficient and environmentally safe devices in all fields of the industry has become a significant problem. Also, the issue of modernization of the existing technological systems and bringing their ecological safety level to state-of-the-art European and world standards has become urgent [1].

In many existing technological systems, where secondary flow pressure is increased using the energy of working primary flow, vapor-jet ejectors are used [2–4]. They have been studied and used since the end of the 19th century. However, there has not yet been any breakthrough leading to improvement in their effectiveness, and it is unlikely that such a breakthrough will happen soon. This is due to the peculiarities of its working process, concerning limitations of pressure increase level in the vapor-jet ejector and the need to constantly generate a significant amount of working vapor, which leads to an increase in the sizes of steam-vapor devices. These drawbacks provide a multi-level vapor-jet device design with transitional capacitors. The efficiency of such a design rarely exceeds 8% [5–7].

The drawbacks mentioned above of steam-jet devices lead to searching for a new solution, one of which is using two-phase jet devices [8, 9]. One of the promising ways may be using the vapor-liquid jet device, the working principle of which is based on jet thermocompression [10–12].

The vapor-liquid jet device's efficiency depends mainly on the efficiency of the working flow going from the primary flow nozzle. In such a device, the generation of working vapor occurs inside it, namely in the diffuser part of the primary flow nozzle, where the process of relaxed vapor generation from incomplete heating of working liquid takes place.

The whole process efficiency directly affects the efficiency of the general vapor-liquid jet device working process. One of the ways to increase the efficiency of the vapor generation process in the primary flow nozzle is by profiling the walls of its diffuser part [13, 14].

2 Literature Review

Jet devices have been used since the end of the 19th century. However, the absence of a united theory helping to describe their working process slowed down their development and expanded their application scope. The author of the article[15] was the first to try to describe the working process of gas ejectors and formulate an ejection equation for it. Further research was aimed at attempts to use different working environments in jet devices in both primary and secondary flow [16–18]. This fact was conditioned by their use in various fields of industry. Nonetheless, the major problem of jet devices is their low efficiency.

The main breakthrough was using two-phase jet devices, including liquid-vapor jet devices, working using principles of jet thermocompression. It is much more efficient than the existing vapor jet analogs but needs further study. Currently, the most reliable mathematic model describing its working process is the authors' model [19, 20], which was designed for the compression’s operating working mode and was improved by the author [21] for the vacuum mode of work. Such mathematic models allow getting relatively high efficiency of working jet outflow from active flow nozzle, up to 97%. However, they do not consider the shape of the diffuser part of the primary flow nozzle, where flow deviation from the walls of the nozzle can occur at different working modes and reverse flow.

Many research works were conducted in recent years that showed the importance and need for profiling the diffuser part of the primary flow nozzle. The authors of the works [22–24] conducted a significant part of the theoretical research, which requires further experimental re-examination.

Having analyzed all the above-mentioned experimental data, the authors set themselves a goal to conduct experimental research on the working primary flow nozzle of the liquid-vapor jet device with replaceable diffuser parts of the parabolic, elliptical, logarithmic shape, and shape.

To achieve the goal set, it is necessary to fulfill the following tasks:

– a creation of an experimental stand for studying a liquid-steam jet device with replaceable diffuser parts of the nozzle.

– experimental studies of the features of the working process of a liquid-steam jet device with replaceable diffuser parts of the nozzle to refine the mathematical model;

– experimental studies of the dependence of a liquid-steam jet's consumption and energy parameters, with replaceable diffuser parts of the expanding part of the nozzle on geometric and operating parameters;

– analysis of factors affecting the achievable performance indicators of a liquid-steam jet device with replaceable diffuser nozzle parts;

– refinement and further improvement of the mathematical model of the working process of a liquid-steam jet device, with replaceable diffuser parts of the expanding part of the nozzle;

– verification of the correctness of the obtained scientific results by comparing calculated and experimental data.

3 Research Methodology

3.1 Experimental case studies

According to the chosen object and the set goals, the program, and methods for the experimental research of liquid-vapor jet devices (LVJD) were developed using the proposed approach (Table 1).

Table 1 – Structure of the experimental case studies

Wall type	Parameters	
	p_{01}, bar	$1 - \varepsilon_{s0}$
straight walls	10–15	0.15–0.50
logarithmic shape	10–15	0.15–0.50
elliptical shape	10–15	0.15–0.50
parabolic shape	10–15	0.15–0.50
optimized shape	10–15	0.15–0.50

This table demonstrates the research stages of the flowing mechanism of boiling, unsaturated, and underheated liquid through the widening channels of the different geometrical shapes of a diffuser part.

During experimental research, a series of tests of the liquid-vapor ejector was carried out on the model, manufactured on a 3D printer with different geometric and operating parameters.

The variation range of the geometric parameters include the geometry (shape, length, area of the vertical shift) of the expanding prime flow nozzle part

Variable range of operational parameters:

– prime flow working fluid pressure at the inlet to the nozzle p_{01} = 10–15 bar;

– prime flow working fluid temperature at the inlet to the nozzle T_{01} = 140–190 °C;

– the value of the relative initial prime flow working fluid underheating at the inlet to the nozzle $(1 - \varepsilon_{s0})$ = = 0.15–0.50.

The experiments also include obtaining characteristics and dependencies of LVJD efficiency indexes and visualizing the flow by conducting tests using a 3D printed model of LVJD.

3.2 Experimental equipment

To measure pressure while conducting experimental research, high-accuracy sensors SITRANS P200, manufactured by Siemens, are used (Figure 1) [25].

SITRANS P200, P210, and P220 are compact sensors with a fixed measurement range for measuring absolute and excessive pressure. In this series, two different types of pressure sensors are used: two sensors with a stainless-steel sensor and one sensor with a ceramic sensor. Thus, measuring excessive, absolute and hydrostatic pressure is very easy. These sensors convert the measured pressure into a proportion signal of 4–20 mA / 0–10 V (Table 2).

Figure 1 – SITRANS P200 sensors [25]

Table 2 – Characteristics of the pressure sensor

Body	Stainless steel
Excessive pressure	1–60 bar
Output signals	4–20 mA / 0–10 V
Material of wetted parts	Stainless steel, plastic fitting, and PVC cable
Min. temperature	–15 °C
Max. temperature	125 °C

For data fixation and display, SIREC D400 is used [26] it is a high-end display recorder in 300 mm x 300 mm format with 12,1" Color- LCD-Display in XGA resolution (Figure 2).

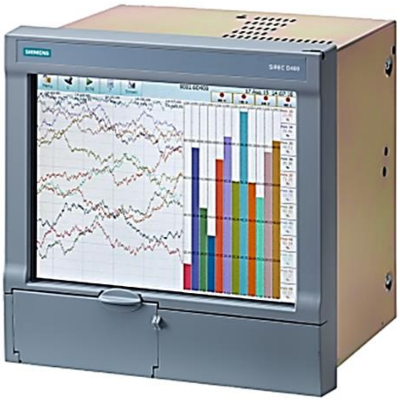

Figure 2 – Display recorder SIREC D400 [26]

The benefits of its use are as follows (Table 3): fast scanning rate of 20 / 100 / 200 / 500 ms; internal data buffer from 1 GB up to 4 GB; high accuracy: 0.1%; transmitter power supply 24Vdc; comprehensive math functions; interfaces – Ethernet, RS 485, USB, slot for CD card; data logging via USB interface or by SD card; fast operation through a touch screen; configuration on the device or through the SIREC D manager or server software; NEMA 3/IP65 type front face protection, NEMA 4X/IP66 available as an option; firmware options individual selectable through a flexible credit system.

Because the measured environment temperature exceeds the working temperature ranges of sensors, we use gas coolers. We use cooling element made by ATEK Sensor Technologies (Figure 3) [27].

Table 3 – Characteristics of display recorder

Analog channels	16–48
Digital channels	up to 48
Format	300 mm x 300 mm
Display	12.1" color TFT
Data storage	SD card / USB memory key
Screens	22 (free designable customized)

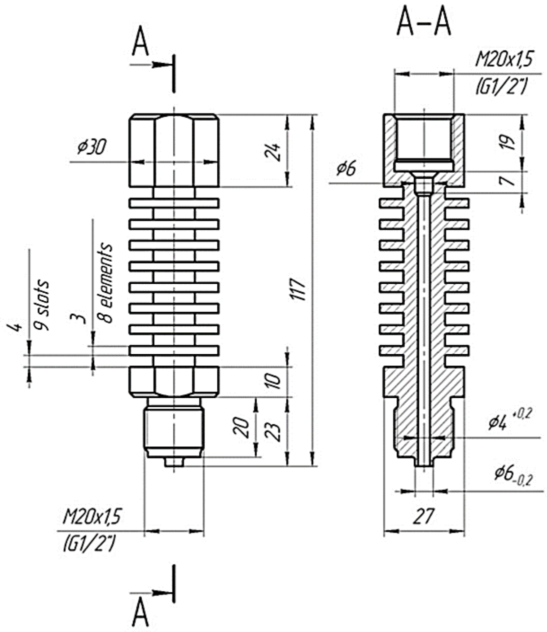

Figure 3 – Cooling element by ATEK Sensor Technologies [27]

Designed to protect pressure gauges and pressure sensors measuring the pressure of steam, hot liquid and other measured media having a high operating temperature from the direct action of the medium. When using an adapter cooler, the temperature of the medium is lowered to the operating temperature of the converter due to heat dissipation.

Technical specification is as follows: case material 304 stainless steel; max. working pressure 580 bar; max. operating temperature 200 °C; length 117 mm; outer diameter 30 mm; Connection of the G 1/2 / M20x1.5 sensor; process connection G 1/2 / M20x1.5.

4 Results and Discussion

4.1 Experimental stand

The experimental setup for the study of a liquid-steam jet device (Figure 4) consists directly of a jet device with replaceable diffuser parts of the primary flow nozzle 1, two heating tanks 2 and 18 for heating the working fluid and auxiliary communications, pipelines, and fittings.

Running water is used as working fluids for the primary and secondary flows of the jet device. When testing a liquid-steam jet device in vacuum mode, the working fluid of the primary flow is taken from tanks 8 and 14, where it is filled from a common network located directly in the test box room and is fed into the heating tank 2 using pumps 9 and 10. Shut-off valves 4 and 12 are used to stop the supply of working fluid to the heating tank after it is filled.

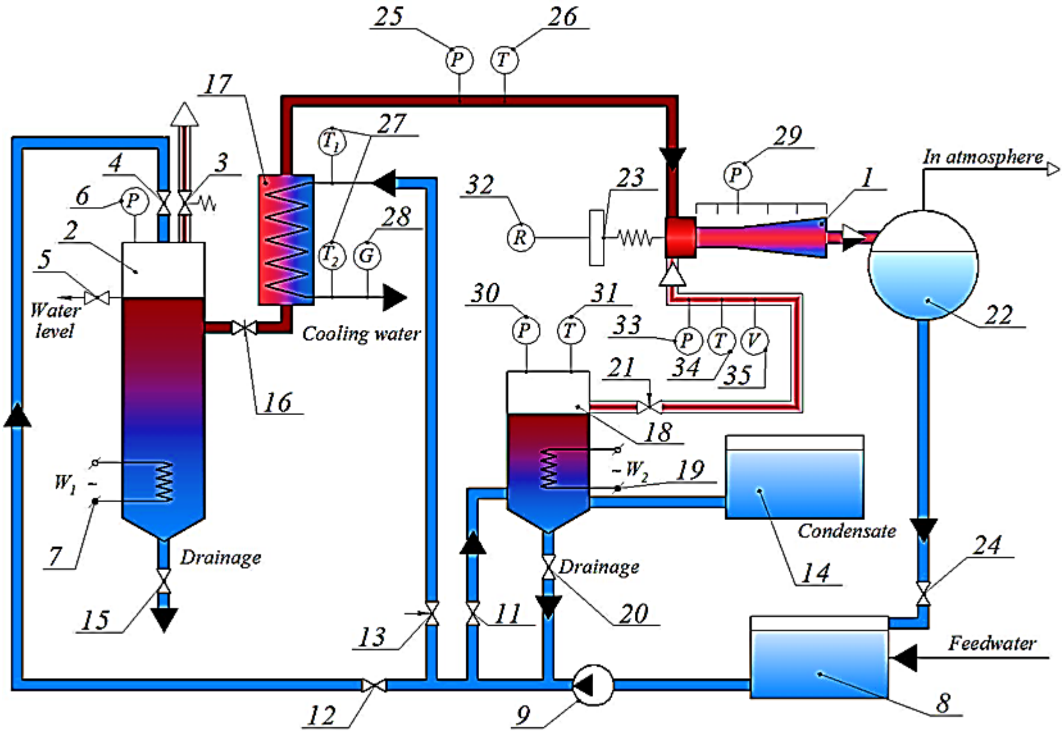

Figure 4 – Experimental stand to study the characteristics of a liquid-steam jet device of a vacuum unit: 1 – liquid-steam jet device, with a replaceable diffuser of the expanding part of the nozzle; 2, 18 – heating vessel; 3 – safety valve; 4, 5, 11, 12, 15, 20, 24 – shut-off valve; 6, 25, 29, 30 – model pressure gauge; 7, 19 – heating element block; 8, 14 – water vessel; 9, 10 – pump; 13, 16, 21 – adjusting valve; 17 – pipe-in-pipe heat exchanger; 22 – separator; 23 – digital scales; 26, 27, 31, 34 – digital multimeter; 28 – mass flow meter; 33 – model vacuum meter; 35 – volume flow meter

Level of the liquid in the heating tank is controlled by valve 5. Then the working fluid is heated by the heating element unit 7 to the required temperature value.

The pressure in the tank is controlled by a pressure gauge showing 6. The safety valve 3 is used for emergency pressure relief in case of exceeding the permissible value. Discharge into the drainage is carried out by means of a valve 15.

After heating and reaching the required pressure value, the working fluid, which is in a state of saturation, is fed through a pipe-in-pipe heat exchanger 17 to the nozzle of the jet device. The liquid flow is regulated by the valve 16. The cooling water for the pipe-in-pipe heat exchanger is taken from tanks 8 and 14, where it comes from the common network. Water circulation through the heat exchanger is carried out using pumps 9 and 10.

The valves of the shut-off valves 11 and 12 are used to open or close the supply of cooling water to the pumps. Regulation of the cooling water supply is carried out by means of an adjustment valve 13. When the working fluid passes through a pipe-in-pipe heat exchanger 17, it is cooled, providing the required amount of underheating. Its pressure does not change at the same time. In the section from the heating tank to the nozzle, the following parameters are monitored: pressure before entering the nozzle of the jet device with a model pressure gauge 25, temperature before entering the nozzle of the jet device with a thermocouple with a digital multimeter 26, the temperature of cooling water at the inlet and outlet of the heat exchanger with two digital multimeters 27, the mass flow of cooling water when it passes through the heat exchanger with a mass flow meter 28.

The secondary flow is steam produced from water, which is taken from the heating tank 18, where it is preheated by a block of heating elements 19 to the required temperature. The pressure in the heating tank 18 is controlled by an exemplary pressure gauge 30.

The temperature in the heating tank 18 is controlled by a thermocouple with a digital multimeter 31. Discharge into the drainage is carried out by means of a valve 20.

The steam is then fed into the ejector. Its flow rate is regulated by the valve 21. In the section from the heating tank 18 to the nozzle of its supply to the ejector, the following parameters are monitored:

– the vacuum value before entering the ejector with an exemplary vacuum gauge 33, the temperature before entering the jet device with a thermocouple with a digital multimeter 34 and the volume flow with a volume flow counter 35. After passing through the ejector, the mixed flow enters the separator 22, where it is divided into vapor and liquid phases. The steam phase is discharged through the pipeline into the environment, and the liquid phase is drained through the pipelines into the tank 14, from which the pump;

– pumps it out to fill the heating tanks 2 and 18 or to cool the working fluid in the heat exchanger 17. The valve of the shut-off valve 24 is used to open or close the discharge of the liquid phase from the separator. When the flow passes through the ejector, the pressure and vacuum values are measured in five characteristic sections. Pressure measurement is carried out by exemplary pressure gauges and exemplary vacuum gauges 29.

4.2 Digital support system

The Mastech M-838 digital multimeter and the TR-01A thermocouple, which was used to adjust the temperature, may have an average value of systematic error less than 1.5% when measuring the absolute value of pressurization. The ultimate margin of error when measuring temperature with Chromel-Kopel thermocouples in a set with a multimeter of class 0.4, does not exceed 1 °C. The maximum error in measuring mass expenditures according to calibration testing is 3%. For pressure measurement high-accuracy devices are used, whose accuracy classes and margins of error are described in the next section of this article.

As a result of the research, the distribution of pressures and speeds of working fluids in the primary and secondary flow in the flow part of LVJD was obtained. The measurement's margin of error does not exceed 5% with confidence probability 0.95, which is permissible for technical experiments. And similar accuracy in measurements was reached in the works of previous researchers.

The speed in certain points is defined indirectly by measuring pressure, jet pulse and nozzle geometric parameters.

When a metastable superheated liquid flows out of the nozzle, the nature of the formation of the working steam jet and the features of its geometry are revealed at known and constant environmental parameters in the laboratory (pressure and temperature) and a given pressure value in the heating tank for heating the working fluid that is fed to the active nozzle:

– the values of the pressure and temperature of the working liquid at the inlet to the primary nozzle of the jet device, the pressure in the throat of the primary nozzle of the jet device, the reaction force of the jet in the pressure interval in the heating tank for heating the working fluid, which is fed into the primary nozzle of various underheating of the working fluid, will be measured;

– the temperature values at the inlet and outlet of the cooling water passing through the pipe-in-pipe heat exchanger will be measured, as well as the mass flow rate of the cooling water passing through the heat exchanger in the pressure range in the heating tank for heating the working fluid, which is fed into the primary nozzle and various underheating of the working liquid.

5 Conclusions

As a result of the research at the experimental stand, it can be obtained results that allow us to formulate the features of the working process of a liquid-vapor jet device working with replaceable diffuser parts of the nozzle, and to refine the mathematical model based on the results obtained.

As a result of the research, the distribution of pressures and speeds of working fluids in the primary and secondary flow in the flow part of LVJD was obtained. The measurement's margin of error does not exceed 5% with confidence probability 0.95, which is permissible for technical experiments. And similar accuracy in measurements was reached in the works of previous researchers.

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