Design features of a high-vacuum steam jet pump and some results of its tests

I V Petrova¹, V I Ermolov¹, A K Rebrov²

¹Novosibirsk State Technical University, Novosibirsk, Russia
²Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia

E-mail: i_v_petrova@mail.ru

Abstract. This paper presents an original design of a high-vacuum steam jet pump in which a heater made of a heating cable is immersed in a working fluid located in a stainless steel boiler. At the same time, the boiler itself is vacuum isolated from the pump housing. There is also a heater made of a heating cable in a stainless steel shell, made in the form of a spiral and immersed in a working fluid. Such an arrangement of the heater is possible only when a liquid with a homogeneous chemical composition and a low saturated vapor pressure is used as a working fluid in high-vacuum pumps.

1. Introduction

Due to their simplicity and versatility, vacuum diffusion pumps are widely used in various fields of science and technology for pumping gases and gas mixtures with various physical properties. However, a sufficiently large amount of the return flow of the working fluid into the pumped volume does not always satisfy consumers, because it negatively affects the results of technological processes and complicates the operation of pumps due to the need to use low-temperature traps, the use of which, in turn, is not always desirable for the following reasons:

- traps significantly reduce the conductivity of the supply lines;
- they have a limited work resource;
- when the temperature of low-temperature traps rises to room temperature, the latter themselves are sources of reverse flow.

The sources of the reverse flow are known, well studied and depend on the design of the pump, its operating mode and the thermophysical properties of the working fluid used in the pump (mineral oils, silicones, polyphenyl esters, mercury, water, etc.).

In mass-produced high-vacuum steam jet pumps, the heater located outside the pump body in diameter is usually equal to the radial size of the latter. With this arrangement of the heater, the total losses of the power supplied to the pump for steam preparation are almost 40%, including those into the environment, as well as during the transfer of heat from the heater through the bottom of the pump to the working fluid [1]. To obtain a high vacuum in such pumps, fractionating rings are installed in the bottom part to supply steam to the nozzles from the lower to the upper stages of the pump. The need for fractionation is due to the heterogeneity of vacuum liquids made on the basis of petroleum products.

Diffusion steam jet vacuum pumps are known [1]. The most significant disadvantages of these pumps are:
• The presence of a significant flow of working fluid vapors into the pumped volume, due to the specifics of expanding the steam jet of the nozzle to produce working fluid vapors;
• Externally, the heaters located in these pumps require increased power for steam preparation.

The closest in essential features to the pump developed by the authors of this work is a vacuum steam jet pump [2] containing a housing with inlet and outlet pipes, a heating boiler for working vapor-forming liquid located in the lower part of the housing, a multi-stage steam pipe with nozzles located along the axis of the housing.

Disadvantages of the solution:
• The detachable housing is used only for the installation of a very complex steam pipeline, the design of which is almost impossible to implement for pumps DU-160, DU-250, etc.;
• The atmospheric air layer between the boiler and the pump housing does not reduce the power consumption for steam preparation [3];
• The upper inclined part of the housing is not cooled, which means that it is a source of working fluid vapors in the pumped volume. The sealing jump formed by the structural elements does not provide a guaranteed optical opacity between the pumped volume and the steam jet of the first stage, and the channel formed by the wall of the upper part of the pump housing and the nozzle of the upper stage is an additional source of the reverse flow of steam into the pumped volume.

In [4], a diagram of a heater placed in a working fluid is presented, and the boiler with the working fluid is vacuum isolated from the pump body, which provides significant energy saving of the pump as a whole. However, the specific design of the heater is not attached.

The solution [5] is also known, in which the diffusion pump contains a heater made of a heating cable wound in the form of a spiral, placed in rectangular channels made on the inner side of the bottom of the boiler. Despite the direct contact of the heating cable with the vacuum liquid, heat exchange between the cable and the liquid is difficult due to the walls of the rectangular channel limiting the cable.

The purpose of this work is to create a diffusion vacuum pump, the design of which provides for the solution of the following tasks:
• to minimize the reverse flow of working fluid vapors into the pumped volume;
• to minimize heat losses when preparing steam in the boiler;
• to ensure rapid cooling of the working fluid located in the boiler when the heater is turned off.

2. The design of the diffusion vacuum pump.
The diffusion vacuum pump is shown in Fig. 1 and consists of a detachable F-F body (FIG. 2) made of AMg6 alloy. A stainless steel boiler (17) is vacuum-tightly installed in the lower part of the housing (10). The cylindrical part of the boiler has a thickness of 1.0 mm, the bottom is 2.0 mm. The forevacuum pressure was constantly maintained in the cavity between the boiler and the housing when the pump was operating through the tube (9). When assembling the pump, the following were installed in the boiler (17): a stainless steel tube for rapid cooling of the working fluid (18), a heater (19) made in the form of a spiral made of a KNMSNX cable, the ends of which were vacuum-tightly taken out through the flange of the lower part of the housing (10). Further, the following elements were axisymmetrically installed on the bottom of the pump: the base of the steam pipe (1), closed by a screen (2) made of stainless steel with a thickness of 0.5 mm, and a system of nozzles from the 4th to the 1st stages using various inserts. Inserts (3 and 4) were used to set the calculated values of the critical gaps of the nozzles of the 3rd and 2nd stages (15 and 14, respectively) of the steam pipeline (6). The diaphragm (5) served as a choke when steam was supplied to the 1st stage. Steam was supplied to the nozzle of the 1st stage (13) through 3 holes made in the steam pipeline. The critical size of the nozzle of the 1st stage (13) was formed by the inner part of the nozzle of the first stage. And the ratio of the diameter of the nozzle of the first stage to the diameter of the pump inlet was 1.4. All parts of the steam line were tightened with a stud (8) and are made of the same alloy as the pump body parts. It became possible to perform the ratio 1,4 when assembling the pump, since the radial size of the joint of the upper and lower parts of the pump housing (10, 11) satisfied this ratio, and the radial
size of the upper part of the pump housing was made so that the area of any section of the pump channel, starting from the inlet section, including the size of the annular gap in the plane of the nozzle of the 1st stage, was equal to the area of the inlet pipe opening (sections I-III-II, FIG. 1). A composite, vacuum-tightly installed insert (7) forms the flow part of the pump channel. When using aluminum alloys in the pump design, sectional cooling is used with the help of 3 channels connected in parallel. The channels are indicated in Fig. 1 as: C, D and E. Position 12 is an umbrella designed to form a first stage supersonic jet, 16 is the ejector nozzle, 20 is the inlet branch pipe; 21 is the outlet branch pipe.

The pump works as follows. After creating a preliminary vacuum in the cavity of the pump housing and supplying the cooled water to the cooling channels of the diffusion pump, the working fluid is heated, the vapors of which, warming up the steam line, flow out in the form of low-density vapor jets from the nozzles of the 1-3 pump stages. Further, the vapor-gas mixture is separated when it flows out of each nozzle. The vapor of the working fluid condenses on the walls of the housing and returns to the boiler, and the pumped gas or a mixture of gases, having received an impulse in the direction of pumping, is compressed with respect to the inlet pressure. The final compression occurs in the 4th stage, which acts as a steam ejector, compressing the gas to the exhaust pressure. The gap formed by the vertical wall of the boiler and the screen of the base of the steam pipe acts as a hydraulic lock, ensuring the continuous operation of the diffusion pump.

Figure 1. Diffusion vacuum pump (section A-A)

Figure 2. Assembled diffusion vacuum pump, where 22 – coolant inlet; 23 – coolant outlet.

Since in this design, the nozzle diameter is 1.4 times larger than the inlet diameter, so that vapor from the nozzle cannot escape into the pumped out volume, but condenses on the wall of the pump housing (FIG. 3).
3. Heating element device.
The general appearance and device of the heating element is shown in FIG. 4, 5. The heating element consists of 2 rows of spirals fixed in 4 special guides made of stainless steel. The holes in the guides are made in such a way as to ensure an effective heat exchange between the heater cable and the working fluid in which the heater is flooded. Here we should immediately note that heaters of this type without complicating their design can only be used in non-fractionating pumps, which means that they can be used in high-vacuum pumps when working on individual products, for example, polyphenyl ethers, characterized by low vapor elasticity, as well as high thermal and thermal oxidation resistance. However, when using the proposed heater, the heat flow density is 4.2 times less in comparison with the bottom heater with the same inlet pipe diameters. The specific heat load per unit of the heat transfer surface in the proposed pump design is approximately 3.5 times less than in the NVDM-160 pump [6].

At the same time, the radial dimensions of the cable, the diameter of the heating core, the number of rows are selected in such a way as to minimize the heat flux density of such a heater, which will ensure reliable work during its long-term operation, and will also allow adjusting the heater power within wide limits to create supersonic jets with the necessary parameters for high-vacuum pumping. The holes in the guides are designed so as to provide an effective heat exchange between the heating cable and the working fluid in which the heater is recessed.

4. Conclusions
As a result of the tests of the pump developed by the authors, mass-spectral studies were carried out. The main attention in the experiments was paid to the study of the mass spectrum of residual gases in the chamber of the NMD-K magnetic discharge pump manufactured by LLC "Katod", Novosibirsk.
The volume of the pumped chamber is 0.01 m³. The pressure in the chamber was measured using a PferfferIKR – 270 vacuum gauge. The residual gases were analyzed using an ExtoorXT100 mass spectrometer. The spectrum of residual gases in the chamber pumped out by a high-vacuum steam jet pump of the proposed design does not differ from the background spectrum and is shown in FIG. 6. The obtained result indicates that the pump of the proposed design can be used as a pre-vacuum for magnetic discharge pumps instead of turbomolecular pumps used for this purpose today.

**Figure 6.** Residual gas spectrum

References

[1] Zeitlin A B 1965 *Steam jet vacuum pumps*. M. L.: Energiya 399.

[2] Tokarev V O, Malyarov V G and Novikov L V 2011 *Vakuumnyj parostrujnyj nasos [Vacuum steam jet pump]* Patent RF, no. 106311.

[3] Frolov E S, Minaichev V E, Alexandrova A T et. al. 1992. *Vacuum technology* – M.: Mechanical Engineering 391.

[4] Rebrov A K, Ermolov V I, Kuprienko P L and Nikolaev G.F. 1988 *Parostrujnyj vakuumnnyj nasos [Steam jet vacuum pump]* Patent RF, no. 2018722.

[5] Zhu Jianming, 2019 *High-vacuum oil diffusion pump with built-in heating device*, no. CN209800376U.

[6] JSC “Vacuummash” 2021. Available at: https://vacma.ru/catalog/vakuumnye-nasosy/vysokovakuumnye-nasosy/nvdm/nvdm-160/#char2.