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A Comprehensive Review of Liquid Ring Vacuum Pumps and Compressors for Improving Global Efficiency and Energy Saving

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***Abstract* — Liquid ring vacuum pumps and compressors are mechanical positive displacement turbomachines that can operate in the mode of both vacuum compressor and vacuum pump. They are widely used in the fields of filtration, cryogenic, reaction, gas injection, condensation, evaporation, and drying. Despite their low performance, they have many advantages such as low costs, simplicity, reliability, improve suction characteristics, and in many cases, can provide a more efficient option. Improving efficiency is the key to decrease energy consumption and costs. The article analyzed and evaluated the previous investigations regarding these machines with a focus on challenges of improving efficiency, advances in numerical simulation, and experiments to afford beneficial insight on future research and next steps. The study revealed that the thermal interaction and the cavitation phenomenon are among the most important problems that require further research.**

***Index Terms* — liquid ring vacuum pumps and compressors, global efficiency, numerical simulation, experimental research, energy saving.**

I. INTRODUCTION

Liquid ring vacuum pumps and compressors (LRVPs) are special and different types of positive displacement pumps and compressors, the reason for this is the difference in their working principle. They provide several functions such as compression, creation of a vacuum, and pumping of fluids [1]. An ejector can be used in systems working with LRVPs. The key advantages of these machines are high dependability, longevity, isothermal compression, sustainability, design simplicity, high productivity, low cost, and compliance with environmental standards [2]. LRVPs can easily handle condensable vapor using a range of fluids without sacrificing pump efficiency. They have only one rotating component, making them cost-effective and easy to repair and maintain. Thanks to its advantages, it is used in many applications and industries such as automobile, concrete, food, petroleum, water treatment, metallurgical, radio engineering, electrical, thermal power, grinding, distillation, production of fuel, extraction, filtration, de-airing of liquids and solids, and convective drying of materials [3–10]. Figure 1 presents the main components of the basic design of LRVPs. The accessory devices of the LRVPs system are a heat exchanger for cooling the recirculating seal liquid and a separator to separate the exhaust mixture of gas-liquid, pipelines, and liquid circulating pump as illustrated in Figure 2. The motivation of the current article is to offer a comprehensive review and beneficial insight about LRVPs to be the cleared review article published in the field of these types of machines. In the current article, a comprehensive review and analysis of previous investigations are presented to identify challenges related to LRVPs and to provide a database on which researchers can rely on the next steps to enhance global performance.

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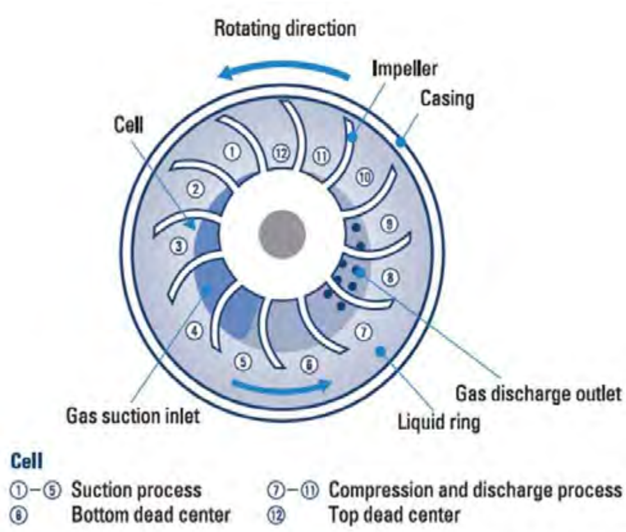

Fig. 1. Basic LRVPs.

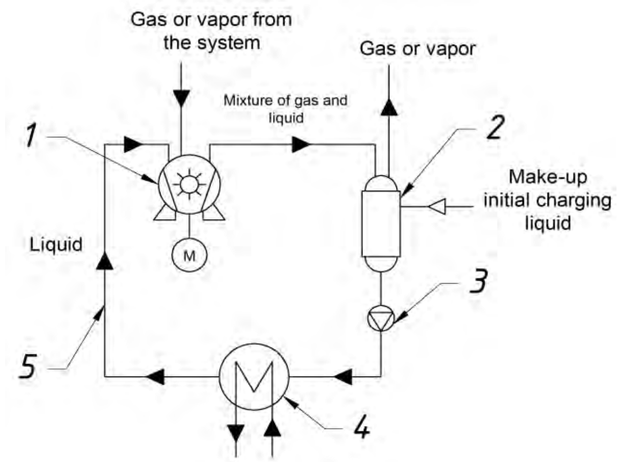

Fig. 2. A schematic diagram of major system components of LRVPs:
1 – LRVP; 2 – separator vessel; 3 – liquid circulating pump; 4 – water cooler; 5 – pipelines.

A. Working principle

Understanding of LRVP working principle will be important in the reduction of the losses and enhancement of the performance. At starting, the fluid begins to flow into the pump by the impeller. The impeller is off-center with veins bent toward the rotation, allowing centrifugal forces to form a rotating ring of liquid adapting to the shape of the casing. Due to the position of the impeller, a crescent-shaped space develops between the impeller hub and the liquid ring. The veins divide this space into several cells of different volumes, as the impeller rotates the cells in the suction side of the pump and become larger, increasing the volume, this causes the pressure in the cells to drop and draw the gas. As the gas travel to the opposite side, the cells decrease in volume, increasing pressure, causing the gas to compress and discharge out of the pump [7,11–13]. The gas-liquid mixture is pumped out through the discharge port of LRVPs as presented in Figures 1,2.

B. Energy consumption

Besides the advantages of these pumps, they are known for their high energy consumption and low efficiency [14]. Energy is a basic necessity for both the residential and industrial sectors [15]. The increase in the world's population and the construction of factories led to increased demand for energy around the world [16]. Energy consumption is expected to increase by 30% by the beginning of 2030 [17]. In the next 9 years (by 2030), the consumption of energy in the industrial sector is expected to reach 71,961 ZW (1.4% per year). Electric motors consume 46% of global power generation, according to the International Energy Agency. They consume almost 70% of the total electricity consumed by the industry. According to the European Commission report, the pumping system consumes nearly 22% of the energy supplied in the world, as illustrated in Figure 3 [17–20]. As a result, researchers and worldwide society must address this problem to solve the future energy shortage and find energy-saving possibilities.

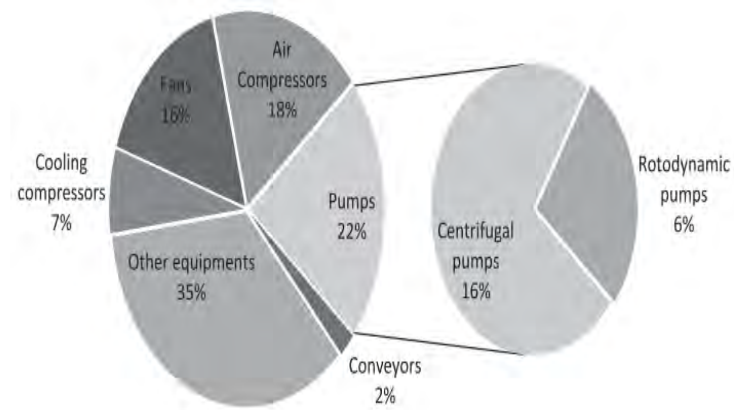

Fig. 3. Energy consumption for different applications [16].

C. Historical development

A summary of the historical development of vacuum pumps and their progress in the field of mechanical machines presents in this section. Reneri and Descartes suggested the first experiment to create a vacuum in 1631. In 1641, Gasparo Berti experimented with a water barometer, which is the first known attempt recorded for vacuum production. But this experiment was not convincing to the scientists. Vincenzio Viviani repeated the experiment conducted by Berti utilizing a mercury-filled glass tube inverted and placed in a mercury container in 1644. This experiment was planned by Evangelista Toricelli in 1643. These attempts to produce a vacuum, carried out by Toricellian convinced the scientists in that period. A few years after these initial experiments on vacuum the first vacuum pumps were created by Otto Von Guericke, and this is when the history of vacuum devices begins. In 1640 Otto Guericke began working on-air pumps, and Caspar Schott published the first article on his work in 1657. Von Guericke's works were spread in Europe by Schott's book, and the next amended pump was designed by Robert Boyle and constructed by Robert Hooke (Figure 4), during the period from 1658 to 1659 in England. The vacuum was measured firstly by Boyle utilizing a mercury manometer in a bell-jar (Figure 5), and the recorded pressure was 6 Torr. Over the years these pumps continued to evolve, but the basic design remained. In 1704 Hawksbee constructed a new pump with balanced pistons (Figure 6), the recorded vacuum pressure was 1.9 Torr in 2 minutes. Newman developed a vacuum pump and the pump recorded a pressure of 0.5 Torr and participated in the Great Exhibition in London and won an award in 1851 [21–24]. Figure 7 depicts the vacuum pressure ranges created by various types of pumps from 1660 to 1900. After 1990 there was a vital shift in the field of vacuum pumps and the attempts to produce a vacuum, especially in the period between 1990 and 1920, where great progress and development of vacuum technology accrued, especially in America and Germany. Figure 8 presents the vacuum pressures obtained over the period 1900 to 2000.

Fig. 4. Designed Piston vacuum pump from 1658 to 1659 by Robert Boyle and Robert Hooke.

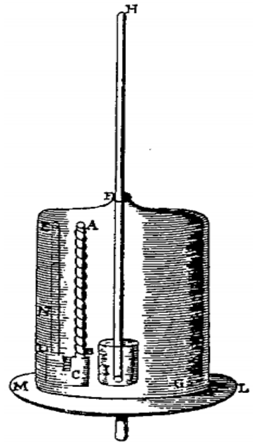

Fig. 5. Robert Boyle's Vacuum measurement device.

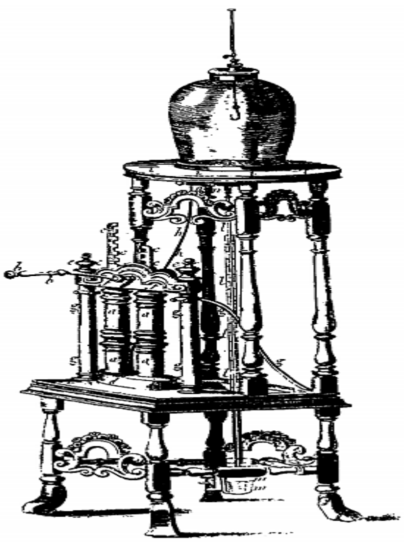

Fig. 6. Vacuum pump with double piston 1704.

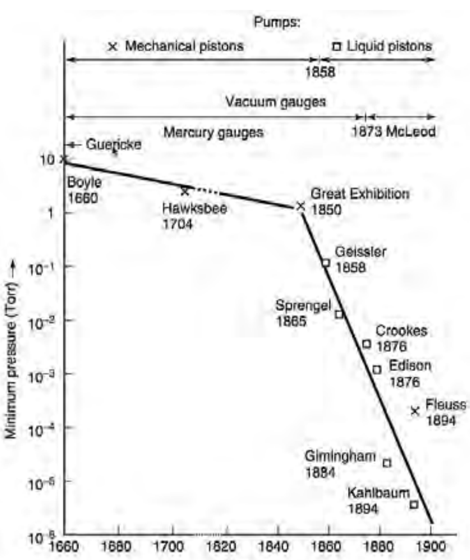

Fig. 7. Pressures of vacuum, achieved in the period from 1660 to 1900.

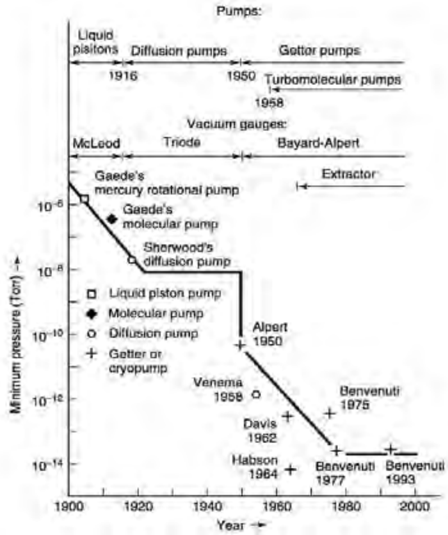

Fig. 8. Pressures of vacuum, achieved in the period from 1900 to 2000 [23].

D. Classifications and applications

LRVPs are pumps and compressors that transmit the energy required to compress the gases and vapors by the liquid ring and service liquid. They are classified into several types according to different criteria, such as ranges of pressure and type of application. In the systems that require creating a vacuum using these pumps, the vacuum pressure on the suction side is usually lower than the atmospheric pressure, and on the discharge side, the pressure is higher than the atmospheric pressure. The vacuum pressure is divided into different ranges based on DIN 28400, as illustrated in Table I.

TABLE I
VACUUM PRESSURE RANGES AND APPLICATIONS

Vacuum pressures range	Applications
Rough vacuum (100000 - 100 Pa)	Food processing, Drying, degassing
Medium vacuum (100 - 0.1 Pa)	Vacuum distillation, Steel degassing, Vacuum induction melting, freeze-drying
High vacuum (0.1 - 0.00001 Pa)	Electron beam and plasma and processes, packaging materials, coating, architecture glass, magnetic, optical, and other data storage media,
Ultra-high vacuum (< 0.00001 Pa)	Space simulation, Nuclear fusion, molecular beam epitaxy, surface science

In many processes of technology, the rough range of pressure is used. In some applications, a two-stage vacuum process is used for high productivity. The different kinds of these pumps and compressors that are utilized for the creation of a vacuum, pumping, and compression of the suitable different liquids and gases in various industries are presented in Figure 9.

E. Cooling system

When using LRVPs in various applications, during their operation, heat is generated due to the friction between the liquid and the housing of the pump. Therefore, the cooling process is considered necessary, especially in hot climatic conditions to maintain the normal operation. Two possible ways to cool recirculating hot liquid, pumped out from LRVPs [13,25]. The first method is to cool the hot liquid with external cooling water entering the heat exchanger, as in Figure 2. Recirculating and cooling of water reduce consumption by several liters per hour and increase energy efficiency in LRVPs units. The second method is cooling by an air cooler, as shown in Figure 10.

II. PROBLEMS OF LRVPS AND CHALLENGES OF INCREASING EFFICIENCY

LRVPs are one of the most common pieces of equipment in processing plants. It is important to understand the working principle and identify the problems of plants operating based on these machines, to deal with the inevitable daily challenges. Several factors affect the performance of the vacuum system, such as process conditions, differences in specifications of equipment and other accessories, malfunction of equipment, temperature, leakage rate, hydraulic losses, cavitation, suction load, and in particular, the vacuum pump plays a major role in the efficiency of a system. Figure 11 summarizes the most common problems associated with the operation of LRVPs. During the past 20 years, much more information has become available on LRVPs. A brief synopsis of previous investigations related to LRVPs, which are focused on the enhancement of efficiency, are analyzed and discussed in this paper, as listed in Table II.

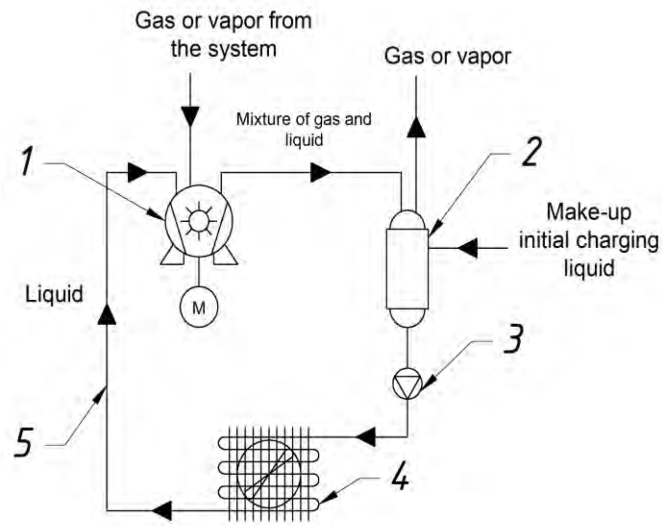

Fig. 10. LRVPs unit with air cooler of circulation working liquid: 1 – LRVP; 2 – Separator vessel; 3 – Liquid circulating pump; 4 – Air cooler; 5 – Pipelines.

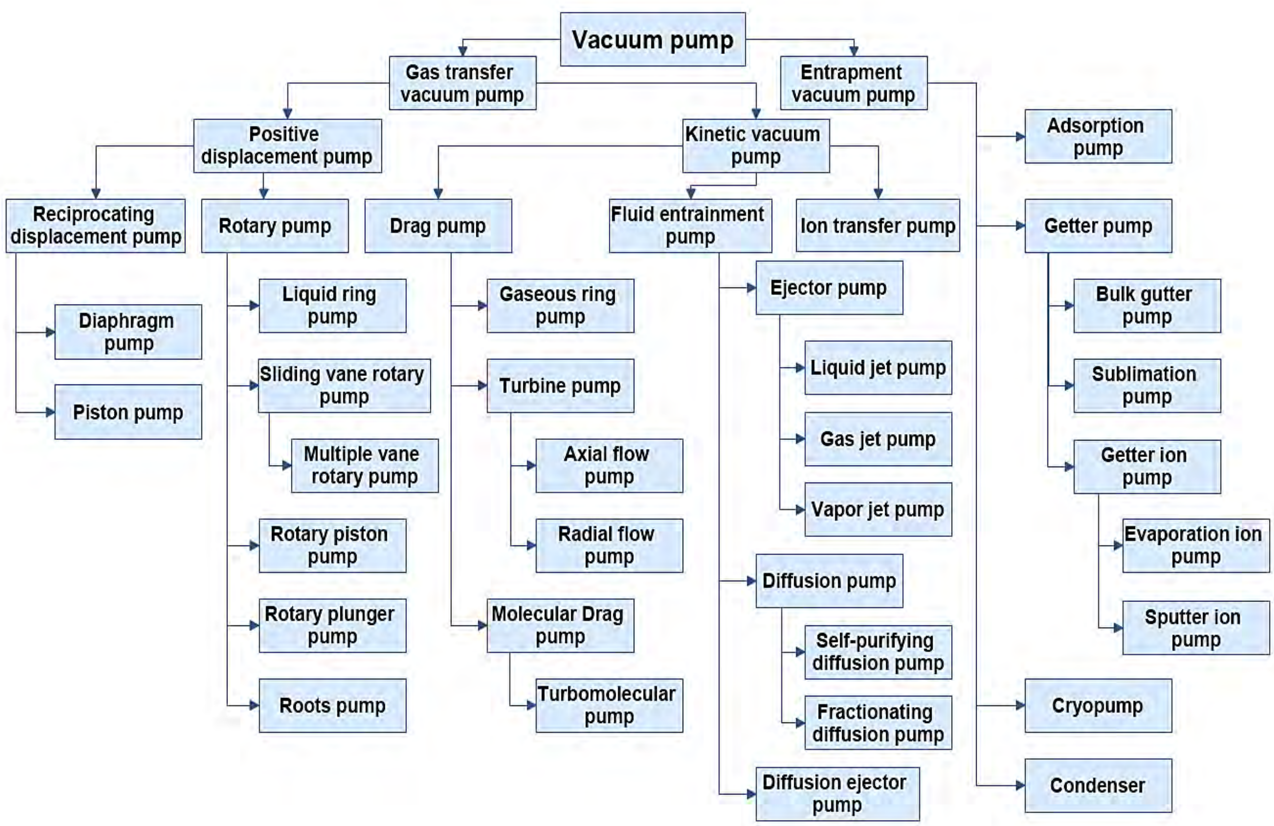

Fig. 9. Vacuum pumps classifications [1].

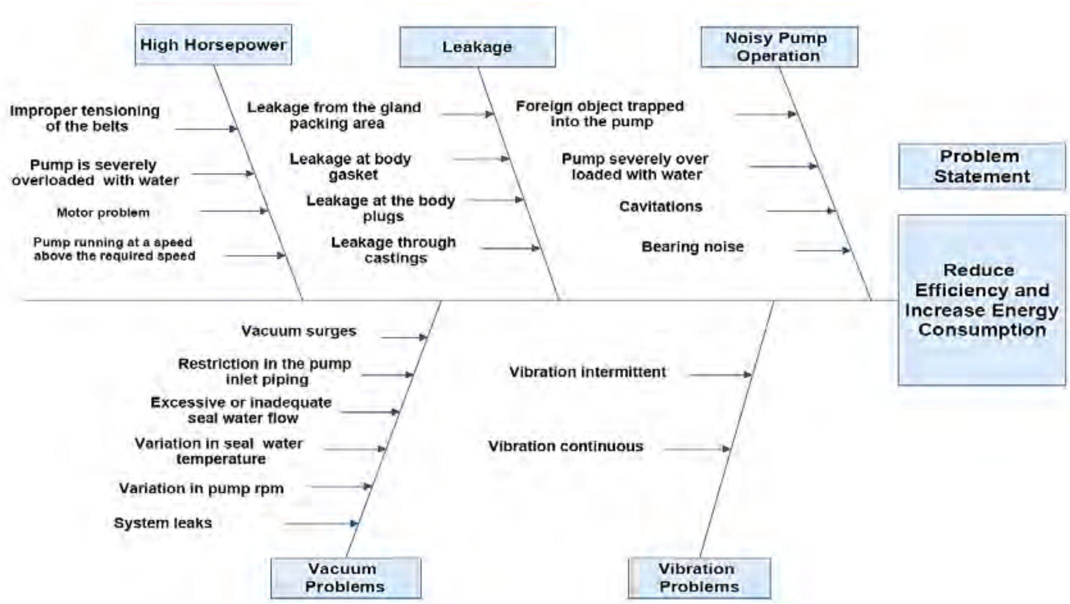

Fig. 11. Summary of LRVPs problems.

TABLE II
SUMMARY OF THE PREVIOUS STUDIES OF LIQUID RING VACUUM PUMPS AND COMPRESSORS

Investigators	Refs	Aim of research	Methodology	Significant results
Yifan Zhang et al.	[25]	Improving the energy efficiency of LRVP using xanthan gum (XG) solution working fluid.	Theoretical and experimental	- Using XG as a working fluid with pressure at the inlet of 60 kPa, the LRVP efficiency was 34.4% and may be enhanced to 43.2% at the best concentration of 4500 ppm, and energy saving of 21.4%. - The variation in the energy conservation rate is appropriate during the operation of the pump.
Renhui Zhang et al.	[26]	Gas-liquid two-phase flow investigation in LRVP using three models of turbulence flow (RNG k-ε, SST k-ω, and LES).	Numerical and experimental	- The used models are difficult to recognize in the liquid ring, while LES model appeared with large bubbles close to the interface of gas-liquid. - The cost of calculation for LES model is high compared to the others, the two models RNG k-ε and SST k-ω have a superior ability to analyze and predict than LES taking into account the phase of gas-liquid distribution and pressure in LRVP.
Renhui Zhang and Guangqiang Guo	[27]	Researching of unsteady gas-liquid flow characteristics in LRVP.	Experimental	- The bearing house and pump casing are a quadratic curve through the start-up time, - The maximum amplitude of vibration of the pump casing is affected by the unstable interface of gas-liquid. - With an increase in the rotational speed of the impeller, bubbles pass through the liquid ring more, causing more intense operation of the pump. - For transient flow, the vibration frequency of the pump casing increases as the flow rate decreases and the rotation speed increases.
Giegerich et al.	[28]	Study performance of LRVP, utilizing mercury as a working fluid for the vacuum system of DEMO torus.	Experimental	- The use of mercury as a working fluid is an appropriate and applicable solution in the DEMO system and is considered the first step to improving the performance of LRVP in such a system.
Rodionov et al.	[29]	Design of LRVP to decrease the dynamic loads on the LRVP components to maintain a smooth operation and secure the stability of the liquid ring shape.	Numerical and experimental	- the consumption of power during the process of evacuation was brought down by 35% on average, 36% as a result of a reduction in a bladeless space area, and by up to 40% as a result of reduction of friction forces of fluid in the bladeless space.
Osipov et al.	[30]	Developing a mathematical model to study the effect of heat and mass transfer on LRVP performance.	Numerical and experimental	- The developed mathematical model is adequate and used in the design of complex systems working base on LRVP.
Irsha Pardeshi et al.	[31]	Developing a model to evaluate the ability of LRVP to swallow air and to produce lower pressure as a function of operating and design parameters.	Numerical and experimental	- The model used was 11% accurate over the experimental results. - When major geometric factors are altered, the model can also anticipate the change in capacity.
Huang et al.	[32]	Developing a performance monitoring system to capture the failure mechanism of LRVP.	Experimental	- The output levels of LRVP could be observed at any time, where maintenance costs could be minimized, the pump could be operated at the maximum performance level possible, and that pump efficiency could be effectively improved.

TABLE II
CONTINUED

Investigators	Refs	Aim of research	Methodology	Significant results
Renhui Zhang et al.	[33]	Numerical simulation of two-phase flow of gas-liquid in the LRVP with and without axial clearance using k-ε turbulence model.	Numerical and experimental	- In the axial clearance, the phase distribution of the two-phase flow of the gas-liquid is similar to that in the impeller region. In the suction zone, the gas-liquid interfaces are more disordered. Numerous of the droplets scatter beyond the suction zone, while others flow back to the low-pressure region along the suction port wall. - Because of the axial asymmetry of the flow channel, the phase distribution within the impeller volume is heterogeneous along the axial direction. The axial clearance has a significant impact on the distribution of gas and liquid phases within the pump, which has an impact on total pump efficiency. - The leakage flow occurs in the blade tip as a result of the action of the forward-curved blade. In the axial clearance area, leakage flow happens where wall jets pierce the suction side of the impeller blades. Leakage flow, axially, decreases the inlet vacuum and the performance. Finally, this investigation showed the flow structure of axial clearance in the LRVP, as well as the relationship between leakage and major flow.
Qiang Sheng Feng et al.	[34]	Calculating of the LRVP efficiency taking into account the temperature of sealing water.	Theoretical	- The LRVP overall energy consumption has been reduced by more than 25%. - The average monthly power consumption has been reduced by more than 12000 kWh. - Cavitation is avoided by lowering the water temperature.
Zheng Mao-xi et al.	[35]	CFD simulation of the air-ejector of LRVP to predict the global efficiency.	Numerical and experimental	- When the motive and suction pressures are kept constant, there is a critical outlet pressure that corresponds to the optimum working point of the air-ejector and can be used as a guide for determining the outlet pressure in ejector design. - When the motive and outlet pressures are both constant the entrainment ratio and air-ejector efficiency increase as the suction pressure rises, but the air ejector's vacuum capacity falls, and the application range shrinks. - The maximum vacuum of the LRVP can be used as the critical outlet pressure of the air-ejector in the LRVP and air-ejector unit to ensure the vacuum needed and a stable mass flow of suction fluid.
Naumov and Velikanov	[36]	An investigation of operational characteristics of WRVP.	Theoretical and experimental	- With a 10 % error, an increasing pumping speed causes the normalized isothermal efficiency to decrease.
Huang et al.	[37]	An investigation of gas-liquid two-phase flow in LRVP.	Numerical analysis and Eulerian multiphase approach.	- The numerical method used is feasible for investigation and provides good indicators for the optimal design.
Kakuda et al.	[38]	To present the application of the MPS scheme to incompressible viscous fluid flow in LRVP.	Numerical approach and experiment.	- The approach is applicable to solve the complicated flow phenomena in LRVP. - The theoretical and experimental results are satisfactory.
Róbert Olšiak et al.	[39]	Decrease the suction pressure of LRVP utilizing a supersonic gas ejector.	Experimental	- The air-flow rate calculated at the secondary suction port can be considered successful output in the case of an ejector used as a pre-stage. - The addition of the ejector had a positive effect on the overall efficiency of the vacuum system, as shown by the comparison of performance characteristics. - There is a great efficiency improvement at lower suction pressures (approximately fewer than 10 kPa abs.). - The added ejector also increased the vacuum pump usage in many applications, allowing the vacuum system to operate in a wider range of suction pressures without cavitation.
Huang et al.	[40]	Developing a mathematical model to investigate the performance of LRVP depending on the real working cycle.	Theoretical and experimental	- Considering the residual gas expansion process is an efficient way in LRVP to solve the problem of theoretical models deviating from real output during the operating cycle. - The expansion process is most likely adiabatic due to the short time of the process. - The performance parameters such as an actual capacity for suction and discharge, shaft strength, and global efficiency can be easily predicted using the proposed theoretical model without the limitations. - The axial width of the LRVP impeller must be considered for friction loss of liquid.
Velikanov et al.	[41]	Obtaining mathematical models of the stages of pumping liquid using liquid ring vacuum pumps in hydraulic systems.	Theoretical and experimental	- The liquid flow rate rapidly reaches its maximum value as time passes, and then falls as the pressure drop decreases. - The results obtained can be used in the development of automation systems for the control of the liquid pumping process.

TABLE II

CONTINUED

Investigators	Refs	Aim of research	Methodology	Significant results
Manoj Radle and Biswadip Shome	[42]	Forecasting cavitation hazards and their impact on the performance of LRVPs to improve design and efficiency.	CFD numerical approach.	- The computational attempts are inexpensive for the steady-state MRF model, but the obtained findings are nonphysical, whereas, the expensive transient sliding mesh method provides realistic computational results.
Mali et al.	[43]	Development of the performance of LRVP impeller.	CFD numerical approach.	- Modification in the design will enhance the function of the impeller. - The cost of replacement and maintenance might be lowered by using detachable blades.
Ravi Kumar and Srinivas Reddy	[44]	Reduction of undesired noisy operation of LRVP because of cavitations and reduce angle blade.	CFD numerical approach.	- The impeller blades' wear and tear are minimized as the cavitation problem is addressed. - Because cavitation losses are decreased, the pump's efficiency improves.
Rodionov et al.	[45]	Improving the overall performance of LRVP using with adjustable discharge window	Theoretical and experimental	- The new design reduces energy spent by 25 % and increases work speed by 10%.
Huang et al.	[46]	Performance evaluation of LRC during the real operation cycle.	Theoretical and experimental	- Based on actual operation, the results showed that the developed model provides a theoretical foundation and method for analyzing LRC suction compression efficiency.

A large and growing body of literature has investigated about LRVPs in this section of the article. In recent years, there has been an increasing amount of literature on LRVPs as shown in Figure 12. Much of the current literature pays particular attention to improve global efficiency and analysis utilizing numerical methods and CFD software such as ANSYS, to demonstrate the fluid flow behavior in the working cavity of LRVPs. This great revolution in the increase of published research on LRVPs is attributed to the urgent need to develop overall performance when used in various applications. Comparing the utilized methods for analyzing the performance of LRVPs are presented in Table III.

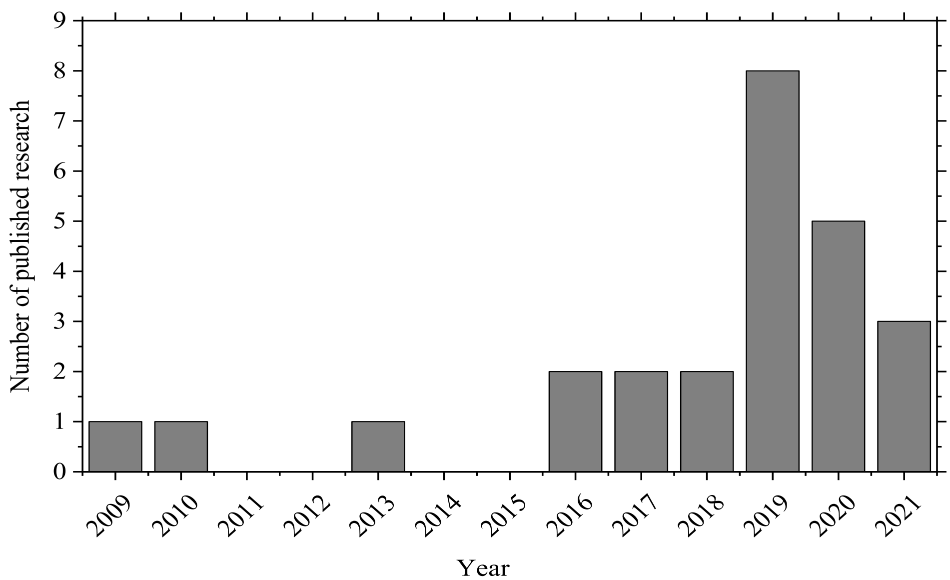

Fig. 12. Number of published papers per year related to LRVPs from 2009 to 2021.

TABLE III

COMPARISON OF METHODS UTILIZED TO ANALYZE OF LRVPS

Method of analysis	References	Advantages	Disadvantages
Theoretical methods	[34,36,40-41]	- Relatively fast	- Assumptions - Depends on the geometry - Experimental data
Experimental studies	[27-33,35-36,38-41]	- Good visibility - Affords validated outcomes	- Requires a long time, - Expensive - Requires numerous experimental data
Numerical approaches	[29-31,33,35,37-38,42-46]	- Fast - Repeatable - Less costly - Accurate	- Processing limitations

III. Power and energy analysis of LRVPs

The specific power (N_{sp}) is the main indicator of the energy efficiency of LRVPs. The major governing equations for determination of the N_{sp} of these types of machines are presented in this section of the article. Let us represent the specific power on the LRVPs shaft in the following form:

$$N_{sp} = \frac{N_e}{S_{th} \cdot \lambda} \quad (1)$$

where, N_e is the total effective power of the LRVP, kW; S_{th} is the theoretical speed of action, m^3/s; λ is a coefficient takes into account the losses during the operation of vacuum pump.

N_e is required for evaluating N_{sp} and an investigating, how to make less power consumption of LRVPs. It is the sum of the power consumption for compression (N_{comp}) of vapor-gas mixture, the power lost (N_F) to overcome the friction of the working fluid, and (N_{fbs}) required for overpassing friction in the bearings and seals:

$$N_e = N_{comp} + N_F + N_{fbs} \quad (2)$$

The compression process in the pump proceeds with the conditional index (m_{ave}) of the polytropic compression, which is taken as an average value within the limits (1.03 - 1.06) taking into account possible measurement errors and accepted assumptions of LRVP. Accordingly, the process is described as:

$$p_s V_s^{\,m} = p_d V_d^{\,m} = \text{const}$$

or

$$\left(\frac{V_d}{V_s}\right) = \left(\frac{p_s}{p_d}\right)^{\frac{1}{m}} \Rightarrow \left(V_s\right) = \left(\frac{p_s}{p_d}\right)^{\frac{1}{m}} . V_d$$

Then, the work (W) of displacement and compression determined by means of the formula:

$$W = \int_{p_s}^{p_d} V_s \, dp = \int_{p_s}^{p_d} \left(\frac{p_s}{p_d}\right)^{\frac{1}{m_{ave}}} V_s dp \Rightarrow$$

$$W = \frac{m_{ave}}{m_{ave} - 1} . p_s V_s . \left[\left(\frac{p_d}{p_s}\right)^{\frac{m_{ave}-1}{m_{ave}}} - 1 \right] \quad (3)$$

where m_{ave} is calculated by the following relation:

$$m_{ave} = \frac{\log\left(\frac{p_d}{p_s}\right)}{\log\left(\frac{p_d}{p_s}\right) - \log\left(\frac{T_s}{T_{mix}}\right)} \quad (4)$$

where p_s is the suction pressure, Pa; p_d is the discharge pressure, Pa; T_{mix} is the temperature of the mixture of liquid and gas, K; T_s is the intake air temperature, K.

The power consumed in compression of the steam-gas mixture is calculated as [48]:

$$N_{comp} = p_s \cdot S \cdot \frac{m_{ave} - 1}{m_{ave}} \cdot \left[\left(\frac{p_d}{p_s}\right)^{\frac{m_{ave}-1}{m_{ave}}} - 1 \right] \cdot \alpha \quad (5)$$

where α = 1.0 - 1.5 – a coefficient represents the inverse expansion of the gas phase [48].

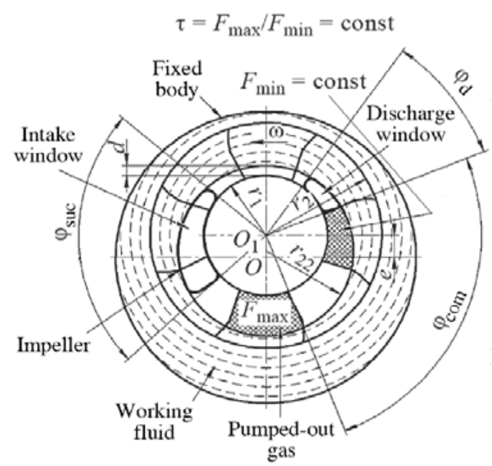

Fig. 13. The basic traditional design of LRVP [45].

S_{th} is calculated by the geometrical parameters scheme of geometric (Figure 13) of LRVP as in refs [47,48].

$$S_{th} = \pi \times (r_{22\varphi}^2 - r_1^2) \times b \times \psi \times n \quad (6)$$

Depending on the rotation angle of the impeller φ, the radius $r_{22\varphi}^2$ is determined as in the following formula:

$$r_{22\varphi} = r_2 . \sqrt{\frac{(r_1 + d)^2}{r_2^2} - \frac{2.k.\delta.\zeta}{\psi} + \frac{2.k.(2e + \Delta).\zeta}{r_2.\psi}} - e.(1 + \cos(\varphi)) \quad (7)$$

where e – eccentricity of the impeller, m; r_2 – the radius of the impeller wheel, m; r_1 – radius of impeller vane, m; ψ – a coefficient that represents the impact of the thickness of the blade; $\delta = \Delta / r_2$ – relative gap; φ – rotation angle of the impeller, rad; Δ – least gap between structure and impeller, m; $\xi = b/b_0$ – coefficient; b – structure width of LRVP, m; and b_0 – impeller width, m. k is the rate factor of bladed and blade-free spaces, and it's a function of the impeller rotation angle (φ) and considers the changes of the two-phase flow speed in the radial cross-section of the working cavity as a function of the operating regimes of LRVP, the working fluid physical properties, the gas phase thermodynamic parameters, in addition to operating characteristics of LRVP, it is calculated according to the results of mathematical modeling or experiments [40,49–53]. The energy lost due to friction of the working fluid can be calculated by the following corrected equation [40]:

$$N_F = 0.708 \times \frac{\rho}{2} \omega^3 \times r_2^5 \times \text{Re}^{-0.1732} \left(1 + f \frac{b}{r_2}\right) \quad (8)$$

$$\text{Re} = \frac{\omega . r_2^2}{\nu} \quad (9)$$

In the pump, the N_{fbs} do not exceed 1 - 2% of effective power N_e [47,48]. According to thermodynamics, the heat balance equation is as follows:

$$E = E_1 + E_2 + Q \quad (10)$$

where E is the energy supplied to a LRVP during operation, kW; E_1 is the energy dissipated from LRVP by the working fluid, kW; E_2 is the energy removed from LRVP by gas, kW; Q is the amount of heat removed from the LRVP as a result of heat exchange between the surface of the LRVP and the environment, kW. For the traditional design, experimental data showed [55,30] that the value E_2+Q is equal to 10% of the effective power N_e spent on the shaft during the compression process. Accordingly, with sufficient accuracy, it is expressed as:

$$N_e = E_1 + 10\% N_e$$

$$E_1 = m_{wf} . C_{\text{wf}} . \left(T_{\text{lr}} - T_{wf,in} \right)$$

Consequently, equation (1) takes the form:

$$T_{\text{lr}} = \frac{0.9 N_e + m_{\text{wf}} . C_{\text{wf}} . T_{\text{wf,in}}}{m_{\text{wf}} . C_{\text{wf}}} \quad (11)$$

where m_{wf} is the mass flow rate of working fluid through the liquid ring, kg/s; C_{wf} is an average specific heat of the working fluid, J/(kg.K); $T_{\text{wf,in}}$ is the liquid temperature at the inlet to the liquid ring, K; T_{lr} is the liquid ring temperature in the working cavity of the pump, K. The temperature of the mixture (eq. 4), at the LRVP outlet, can be estimated by the energy and mass balance equation:

$$T_{\text{mix}} = \frac{C_g . G_g . T_g + C_v . G_v . T_g + Q_{\text{comp}}}{C_v . (G_v + G_g)} \quad (12)$$

where C_g, C_v are the specific heat of suction gas and vapour, J/(kg.K), respectively; G_g, G_v are the mass of suction gas and vapour per unit volume, kg, respectively; Q_{comp} is the heat generated during the compression process and equals to spent compression power, kW.

Due to practical constraints, this section of the paper cannot provide comprehensive details on the analysis of power, energy, and other losses which depend on the proposed design and regime of operation. In this regard, more information about LRVPs can be obtained to build suitable mathematical models for novel design taking into account the characteristics of fluids movement, hydraulic losses, and other coefficients by investigators in refs [7,12,55,56].

IV. CONCLUSIONS AND FUTURE PERSPECTIVES

In this article, a detailed review of literature about the LRVPs, focusing on evolution in designs, advances in numerical simulation, and experiments to increase energy-saving and efficiency during the last past 20 years were analyzed and discussed. Investigators used technological and structural methods as well as CFD numerical approaches, and experiments to analyze and predict the performance of these machines. Also, there were few reports about the LRVPs compared to other types of pumps and compressors. From this review paper, we deduce the following important points:

1. These machines were improved, especially the impeller blades number, and the shape.
2. The developments did not meet the ambition in terms of efficiency, as the efficiency was physically limited to 50%, so further developments will be required to increase reliability.
3. Research should be carried out on the possibility of minimizing the various losses that occur during the operation.
4. The researchers also mentioned that thanks to the modern tools currently available, such as the method of computer modeling techniques (CFD), which allows the examination process to be repeated and corrected, therefore more tests can be addressed.
5. By analyzing previous studies conducted by researchers, it was found that some gaps and problems were not studied and solved by researchers.

Finally, we conclude that further theoretical, numerical, and experimental investigations into the problem of the cavitation phenomenon and the heat and mass transfer processes that occur during the operation of these machines will be required to improve the overall efficiency and thus increase energy savings when used in different applications.

Currently, at the Department of “Mechanics and Engineering Graphics” of the Tambov State Technical University, great attention is being to investigate the effect of heat and mass transfer processes on the effective and specific powers (global efficiency) of LRVPs, taking into account the drying process of materials.

It is recommended to study the influence of cavitation on the performance of LRVPs and find a realistic solution to this issue in the future to achieve the reliable design and the possibility of powering the LRVPs units depending on solar energy through the PV system.

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NOMENCLATURE

T	Temperature [°C]
N	Power [kW]
E	Energy [kW]
Q	Heat [kW]
C	Specific heat [J/(kg.K)]
G	Mass [kg]
m	Mass flow rate [kg/s], Polytropic index
P	Pressure [Pa]

S	Speed of action [m^3/s]
r	Radius [m]
Re	Reynold number
V_s or (S)	Volumetric capacity of suction [m^3/s]
f	Coefficient in friction power considering effect of impeller width, $f = 0.15$
n	Impeller rotational speed, [rpm] or [r/min]

Greek Letters

ω	Angular speed of impeller, $\omega = 2\pi n/60$, [Rad/s]
v	Kinematic viscosity, [m^2/s]
α,λ	Coefficients
ρ	Density [kg/m^3]

Subscripts

e	Effective
F	Friction
s	Suction
d	Discharge
th	Theoretical
fbs	Friction, bearings, seals
comp	Compression
g	Gas
v	Vapor
wf	Working fluid
in	Inlet
lr	Liquid ring
ave	Average
sp	Specific

Acronyms

LRVPs	Liquid ring vacuum pumps
LRVP	Liquid ring vacuum pump
WRVP	Water ring vacuum pump
LRC	Liquid ring compressor
CFD	Computational fluid dynamics
MRF	Moving Particle Semi-implicit

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