Developing Special Turbine for Rational Utilization of Reservoir Energy of Hydrocarbon Deposits

Iuri Appolonievich Sazonov¹, Mikhail Albertovich Mokhov¹* and Khoren Arturovich Tumanyan²

¹Gubkin Russian State University of Oil and Gas; gasseparator@mail.ru, horen.tumanyan@mail.ru
²Oil and Gas Research Institute of the Russian Academy of Sciences.

Abstract

Background/Objectives: In the process of oil and gas production a considerable part of reservoir energy is lost. This problem can be solved by applying special turbines that operate with reservoir energy. Methods: The calculations and testing of the micromodels showed that the turbine vane can be designed as a permeable mesh. The uniqueness of the considered energy recovery method is represented by the application of a special turbine where the main flow of gas and liquids can move through the vane directly. The analytical and experimental methods of the investigations aim to study the process of gas and liquid movement through the permeable obstacle and thus reveal new opportunities for creating efficient and low-noise machines. Findings: Based on the results of the undertaken design activities an experimental prototype of the new hydraulic machine has been developed that is supposed to utilize the reservoir energy generated in the course of gas and oil extraction. The novelty of the developed technical solutions has been certified by the patents. Bench tests of the developed hydraulic machine equipped with a special turbine made it possible to confirm the new principles of the turbine operation control. It has been demonstrated that the force effects of the flow of gas (or liquid) on the permeable obstacle and on the turbine rotor can be controlled applying the operational principles of vortex diodes and vortex amplifier. The results of the investigations show that if the rotation of the permeable wall is taken into account it becomes possible to develop a new class of the unique hydraulic machines, including low-noise turbines, pumps and compressors. The results of the undertaken scientific and design studies are supposed to be used for developing efficient separation equipment and power generation turbines. Applications/Improvements: The developed equipment is supposed to be applied for oil and gas extraction in the offshore fields and also for other purposes due to their low weight and compact dimensions.

Keywords: Hydrocarbon Deposit, Reservoir Energy, Technical Solution, Testing, Turbine.

1. Introduction

The costs of oil and gas extraction can be reduced by means of rational recovery of reservoir energy. When the conventional technological processes are employed considerable part of the energy is lost irretrievably. The solution to this problem is associated by many experts with the application of special turbines that operate with reservoir energy. This task is of particular importance for offshore oil and gas deposits. Technical solutions to such problems are usually seen in using vane hydraulic machines and vane turbines within the framework of developing energy efficient technological processes. Reservoir energy can be transformed into mechanical energy as oil and gas flow through the channels of the turbine. The obtained mechanical energy can be used for rotating the rotor in the dynamic type separator. Dynamic separators are more compact as compared to gravitational separators and this structural feature opens prospects for wider applications of dynamic separators in offshore oil and gas deposits.

Practical implementation of such turbines is complicated because the problem of ensuring reliable turbine control under the conditions of the changing operational modes of certain oil and gas wells has not been solved. Uncontrollable increase in the turning speed of the rotor of the turbine can destroy the machine. Thus, the objective of this study is to develop special equipment and the turbine for rational utilization of the reservoir energy in the process of oil and gas extraction.

*Author for correspondence
Current scientific and design studies show that the turbine designed for operation with dynamic separator can possess structures different from those of the vane turbine. The process of gas and liquid flow through the permeable obstacle occurs within this special turbine.

The flow of gas and liquids through permeable obstacles is characterized by the variety of modes and different practical applications. Thus, the permeable obstacles (grids and meshes) are used for developing heat-exchanging and separating units, for solving aerodynamic tasks in aviation and space engineering. Force effects produced by the flow of gas or liquid on permeable obstacles are usually studied under the conditions when the flow moves in a straight line. The results of the undertaken investigations show that when the rotational movement of the permeable wall is taken into account it becomes possible to create a new class of hydraulic machines featuring the unique properties. Thus, it may be supposed that the well-known theory of similitude widely applied to the development of vane hydraulic machines will not hold.

At the same time, it has to be noted that the development of the technological processes aimed at recovering the reservoir energy is rather slow. One of the reasons that hamper the development is associated with the fact that the issue of securing reliable control of the turbine under different operational modes in particular oil and gas wells has not been resolved. It has been established that the uncontrollable increase in the rotor turning velocity in the turbine can result in damages to and destruction of the machine. The turbine operation automated control system can be developed based on applying the elements of jet techniques. Jet equipment is known for its reliability and efficiency, which is mostly explained by the absence of any movable parts. Within the framework of studying the subject under consideration special attention will be paid to the jet elements that ensure the possibility to change the direction of oil and gas flow at the outlet of the nozzle. Among many options two groups of equipment will be selected, namely, the Coanda effect based units, and the units with vortex chambers.

2. Concept Headings

The research and investigation work was founded on the concept as follows: if the flow of gas (or liquid) produces the force effect on the immovable permeable obstacle then it is possible to consider a separate class of hydraulic machines where the effects of the interaction between the gas flow and the permeable wall will be used for running the turbine or separator. It can be assumed that in the area where the speed of the flow is high, the permeable wall can possess some properties characteristic for the conventional vane with impermeable wall. And in the areas where the speed of the flow is low the presence of the permeable wall can be undistinguished due to the low values of the hydraulic resistance quotient. Such properties of the permeable walls will make it possible to create high-speed hydraulic machines possessing special features and equipped with quite light but durable rotors. Particularly, it becomes possible to consider the new opportunities for creating the low-noise machines of dynamic type where the process of operation will differ considerably from the operations of the vane machines.

The objective of the research, scientific and design investigations is to develop the experimental prototype of the new turbine and the new hydraulic machine, to establish technical basis for developing the efficient technological process of oil and gas extraction featuring rational recovery of reservoir energy.

The study is aimed at developing the experimental prototype of a special turbine running due to the interaction occurring between gas (or liquid) flow and the hard permeable wall. The technical solution will be developed that would make it possible to protect the turbine from the uncontrollable increase in the rotor rotation speed. Bench testing of the special turbine and of the hydraulic machine will be carried out.

3. Results

Within the framework of the undertaken scientific and design activities the new special turbine has been constructed that operates based on the interaction that occurs between the flow of gas (or liquid) and the hard permeable wall. The bench testing of the experimental prototypes of the turbine and of the hydraulic machine has been performed. The developed hydraulic machine presented in Figures 1–3 consists of three nozzles 1-3, turbine rotor 4, separating disk 5, separating drum 6, shaft 7, stator 8, outlet channels 9 and 10.

The structure of the hydraulic machine can feature one or two nozzles or even more than two. The turbine rotor 4 is designed as a permeable honeycomb structure that consists of mutually connected outward and inward lobes, according to the patent. In between the inward
Iuri Appolonievich Sazonov, Mikhail Albertovich Mokhov and Khoren Arturovich Tumanyan

and outward lobes in the turbine rotor 4 there are flow channels hydraulically connected with the nozzles 1–3.

In this turbine structure the force effects produced by the flow of gas (or liquid) on the permeable obstacle and on the turbine rotor can be controlled applying the operational principles of vortex diodes and vortex amplifiers. As the rotational speed of the rotor increases, the jet of the gas deviates from the initial direction (Figures 2 and 3) and the force effects on the turbine rotor become lower which in turn prevents the uncontrollable increase of the turbine rotor velocity.

In the stator 8 there is, at the very least, one separation drum 6 installed between the turbine rotor 4 and the outlet channels 9 and 10. Figure 1 shows the option of the hydraulic machine that includes two separation drums 6 installed on one shaft 7 together with the turbine rotor 4. Thereat, the separation drum 6 is designed as a permeable honeycomb structure that consists of mutually connected outward separating lobes and inward separating lobes. In the separation drum 6, there are flow channels hydraulically connected with the flow channels in the turbine rotor 4 and with the outlet channels 7 and 10. At least one outlet channel 9 is located closer to the axis of rotation of the shaft 7.

The permeable honeycomb structure of the separation drum 6 in the developed machine is constructed of mesh material where the threads of this material form the outward and the inward separating lobes. The mesh cells of this material are united into the flow separation channels between the outward and inward separation lobes.

The circular flow channel between the separation disc 5 and the stator 8 ensures hydraulic connection between the flow separation channels in the separation drum 6 and the flow channel in the turbine rotor 4.

Nozzles 1–3, outlet channels 9 and 10 can be located at different distances from the axis of rotation of the shaft 7 taking into account the specifics of the application of the hydraulic machine.

The hydraulic machine operates as described below. The nozzles 1–3 located in the stator 8 ensure the formation of the flow (or several flows) of the operating body in the direction of the turbine rotor 4. The operating body can be represented by liquid, liquid-gas mixture or gas. For example, each of the nozzles 1-3 can be connected to a separate oil well (or to the gas well); thereat, the operational parameters of the flow in each nozzle can be different in terms of the mass flow rate as well as in terms of the pressure at the input of the nozzle. The flow of the operating body affects the outward lobes of the turbine rotor 4, and
sets the turbine rotor 4 to rotating motion. Thus, kinetic energy of the flow of the operating body is transformed into mechanical energy revealed through the rotations of the turbine rotor 4. The operating body through the flow channels also comes into the internal void of the turbine rotor 4, inasmuch as this rotor is designed as a permeable honey-comb structure. The flow of the operating body in this part of the rotor interacts with the inward lobes which results in more efficient transformation of the energy because, as the velocity of the operating body decreases, the flow can shift closer to the axis of rotation of the turbine rotor 4. The turbine rotor 4 is connected to the separation drum 6 for the purposes of transferring the energy further. Thereat, mechanical energy is transmitted from the turbine rotor 4 to the separation drum 6. The surplus energy can be redirected to other machines. Thus, additional machines to the shaft 7 can be connected that are not shown in the figure (they can be represented, for instance, by extra separator, pump, compressor or electric power generator).

The turbine rotor 4 and the separation drum 6 in the course of their rotation create the conditions for the process of separation. In the process of separation affected by the centrifugal forces the fractions with higher density move to the peripheral areas of the separation drum 6. Fractions with lower density move to the center of the separation drum 6. At least one outlet channel 9 is located closer to the axis of rotation of the shaft 7 which makes it possible to discharge from the stator the fractions with higher density separately from the fractions with lower density. Thereat, the high and constant circumferential speed of the operating body within the stator 8 is ensured. As the length of the separation drum 6 increases it also becomes possible to increase the period during which the operating body (gas-liquid mixture, for instance) stays in the stator 8 affected by centrifugal forces, thus improving the efficiency of the separation process, inasmuch it is a well-known fact that the efficiency of the separation process increases as the time within which the operating body (gas-fluid liquid) is affected by centrifugal forces becomes longer. Thereat, given the above structural features of the separation drum 6, the values of the centrifugal forces that affect the gas or the liquid are maintained constant along the whole travelling path of the operating body in the stator 8. In this case, mechanical energy is used for maintaining the high and constant rotational speed of the gas-liquid mixture (operating body) and the energy is spent on the separation process and on overcoming the friction forces that occur during the movements of the operating body within the stator 8 in the direction from the turbine rotor 4 to the outlet channels 9 and 10. In the course of separation affected by centrifugal forces the fractions with higher density are moved to the peripheral areas of the separation drum 6 and further on to the outlet channel 10 located farther from the axis of rotation of the shaft 7. The fractions with lower density are moved to the center of the separation drum 6 and then the fractions with yet lower density (for example, gas) are forced to the outlet channel 9.

In the course of operation, the properties of the gas-liquid mixture are known to be changed due to the altered percentage content of gas in the gas-liquid mixture and due to the altered flow rate of the liquid phase which in turn is associated with pressure fluctuations. Such instable mode of the gas-liquid flow is usually accompanied by the recirculation of the gas-liquid mixture in the central parts of the turbine rotor 4 and of the separation drum 6. The separating disk 5 prevents the gas-liquid mixture from coming from the central part of the turbine rotor 4 to the central part of the separation drum 6. Due to this kind of segregation the conditions of the process of separation in the separating drum 6 improve. Thereat, in the central part of the separation drum 6 only the fractions with lower density gather and the fractions with higher density are prevented from coming there. The fractions with higher density are retained at the peripheral areas of the separation drum 6 affected by centrifugal forces.

When the separation disc 5 is available the efficiency of transforming the energy becomes better with different properties of the operating body including cases when the flow modes of the gas-liquid mixture are not stabilized, because any recirculation of gas and liquid in the central parts of the turbine rotor 4 and the separation drum 6 is excluded, thus eliminating any potential energy losses associated with the recirculation of the gas-liquid mixture.

Figure 4 shows the option of the turbine rotor that underwent the bench testing. The permeable structure

![Figure 4. Option of turbine rotor.](image-url)
of the developed turbine rotor has been formed of mesh material. The cells of the mesh have been united into the flow channels.

Bench testing has been carried out for the developed turbine and hydraulic machine. For the purposes of describing some certain experiments the following conventional notation has been adopted according to the schematics in Figure 1: P1 – gas pressure at the inlet of nozzle 1; P2 – gas pressure at the inlet of nozzle 2; P3 – liquid pressure at the inlet of nozzle 3; P0 – pressure in the outlet channel 10; M – maximal torque of the shaft 7; M* – maximal torque of the shaft 7 when the gas is fed only through nozzle 2; n – frequency of rotations of the shaft 7; n* – frequency of rotations of the shaft 7 that corresponds to the change in the operational mode of the turbine 4.

The results of the bench testing are presented in Figures 5 and 6. In the course of this experiment P0=0.1 MPa; maximal torques M, M* have been measured for values n=0, n*=0 accordingly (Figure 5); n*=3100 rotations per minute, the frequency of the rotations of the shaft that corresponds to the change in the turbine operation mode (Figure 6).

Based on the results of the tests it is possible to draw preliminary conclusions that the well-known theory of similitude widely employed now for designing the vane type machines will not be suitable for the newly developed machines. As the rotational speed of the turbine rotor changes, the direction of the gas jet changes as well which entails the violation of the principles of geometric similitude and also the principles of gas dynamic similitude. The new turbine possesses some features of the vane-based operational process (the one characteristic for the vane machines) and also some features of the vortex-based operational process (the one characteristic for the vortex machines).

Operability of the developed turbine and hydraulic machine has been confirmed in case when the liquid was fed to nozzle 3. In the course of the experiment with the liquid the frequency of the rotations of the shaft used to change within the range of 1890-3420 rotations per minute. Thereat, the maximal pressure value P3 amounted to 14 MPa.

The undertaken scientific and design works prove that 3D printers can be regarded as quite a promising technology for developing new hydraulic machines and turbines equipped with permeable mesh rotors or with permeable mesh vanes. Figure 7 shows the option of the rotor for hydraulic machine where the permeable honeycomb structure of the rotor has been designed assisted by 3D printer.

![Figure 5](image1.png)

**Figure 5.** Bench testing results of the developed turbine and hydraulic machine: “1” – the gas was fed only to nozzle 1; “1+2” – the gas was fed to nozzle 1 and to nozzle 2; thereat, P2=0.160 MPa; “1+2*” – the gas was fed to nozzle 1 and to nozzle 2; thereat, P2=0.157 MPa.

![Figure 6](image2.png)

**Figure 6.** Bench testing results of the developed turbine and hydraulic machine: “1” – the gas was fed only to nozzle 1; “1+2” – the gas was fed to nozzle 1 and to nozzle 2; thereat, P2=0.155 MPa.

![Figure 7](image3.png)

**Figure 7.** Option of the rotor for the hydraulic machine where the permeable honeycomb structure of the rotor was designed applying 3D printer.


4. Discussion

Studying the peculiar features of the gas flowing through the permeable wall made it possible to create the experimental prototype of a special turbine. The permeable structure of the developed turbine rotor has been made of mesh material. The bench tests model the conditions when the turbine operates in combination with dynamic separator. Such equipment is designed for the purposes of developing the efficient technology for oil and gas extraction featuring rational utilization of reservoir energy.

The technical solution has been developed that prevents the uncontrollable increase in the rotational velocity of the turbine rotor. The bench tests proved the practicability of the special turbine and hydraulic machine. Within the framework of the study the jet elements have been considered that ensure the possibility to change the direction of the liquid flow at the outlet of the nozzle. Among multiple options two groups of equipment have been selected for the design; they were the units operating based on Coanda effect and the units equipped with vortex chambers. The force effect produced by the gas flow on the turbine rotor is controlled applying the operation principles that have something in common with the operating principles of vortex diodes and vortex amplifiers. The results of the bench tests confirm the possibility to limit and stabilize the rotational speed of the rotor including the cases when the rate of the gas flow directed into the turbine increases several times.

The obtained results can be used for developing high-speed machines possessing special properties. At the same time, special theory will have to be developed, insofar as within the new turbine some features of the vane operational process (characteristic for the vane machines) and some features of the vortex operational process (characteristic for the vortex machines) have been observed.

The operability of the developed turbine and hydraulic machine has been confirmed with the liquid fed into the nozzle. In terms of the functional applications the new mesh turbine can be regarded as a multi-phase turbine capable of operating under the conditions when several flows are fed to the turbine rotor simultaneously, including gas flow, liquid flow and gas-liquid flow. Thereat, apart from the density of the operating body, the mass flow rate and the flow velocity at the outlet of the nozzle can be changed.

In the course of the tests it was observed that the new turbine was a low-noise type of equipment and thus it seems advisable that these specific features of the machine should be studied in more detail. The area of the investigations can be much wider; thus, the operability of the pumps and fans equipped with the rotor made of the mesh material similar to the material used in the turbine described above have already been tested in laboratory environment.

5. Conclusion

The scientific investigations described above made it possible to develop the design of the new hydraulic machine for rational utilization of reservoir energy in the process of oil and gas extraction. A number of problems have been solved in terms of the practical applications of the technological processes associated with energy transformation under conditions of the interaction between gas (fluid) and the permeable wall. The unique characteristic of the considered method of energy transformation is that it employs special turbine where the flow of gas and liquid is allowed to pass through the vane or through the rotor directly. For the conditions of oil and gas extraction the machine has been designed that includes special turbine and dynamic separator that operate with the reservoir energy.

An option has been suggested for resolving the issue of ensuring the reliable control of the turbine under the changing operational modes in some particular oil and gas wells in order to prevent any uncontrollable increase in the rotational speed of the turbine motor and to protect the machine from destruction.

Based on the results of the scientific and design activities the experimental prototype of the new hydraulic machine has been developed. The novelty of the developed technical solutions has been patented. The bench tests of the created hydraulic machine equipped with the special turbine made it possible to confirm the new principles of the turbine operation control. It has been demonstrated that the force effects of the flow of gas (or liquid) on the permeable obstacle and on the turbine rotor can be controlled applying the principles of vortex diodes and vortex amplifiers. As the rotational speed of the turbine rotor increases the jet of the gas deviates from the initial direction; thereat, the force affecting the turbine rotor decreases which in turn prevents the uncontrollable increase in the speed of the turbine rotor. The results of the investigations show that if the rotational movement of the wall is taken into account it becomes possible to develop a new class of hydraulic machines possessing the
unique features, including low-noise turbines, pumps and compressors.

Principle application areas of the developed equipment are associated with the technological processes for extracting oil and gas in the offshore deposits. The results of the scientific and design studies are supposed to be used for developing efficient separating equipment. At the same time, given the low weight and compact dimensions of the developed equipment, new opportunities can be revealed for deploying the new turbines, including aviation and power generation technologies.

6. Acknowledgement

The study has been developed with financial support from the Ministry of Education and Science of the Russian Federation (project unique identifier RFMEFI57714X0132)

7. References

1. Hofmann H. United States Patent No. 5117908. Method and equipment for obtaining energy from oil wells. Date of patent: 1992 Jan 2.
2. Turchetta JM. United States Patent No. 7043905. Gas energy conversion apparatus and method. Date of patent: 2006 May 16.
3. Adams R, Parker J. Reducing pressure - increasing efficiency. Sulzer Technical Review 1; 2011. p. 26–9.
4. Sarwar N. UK Gas pipeline to generate renewable energy through geo-pressure technology. Climatico. Independent analysis of climate policy [Internet]. 2009 Jan 10. [cited 2016 May 07]. Available from: http://www.climaticoanalysis.org/post/uk-gas-pipeline-to-generate-renewable-energy-through-geo-pressure-technology/.
5. Bondarenko VV, Sazonov YuA, Mokhov MA. Developing power unit of hybrid machines for extraction and processing of oil and gas in offshore fields. Oil Economy. 2015; 10:116–19.
6. Sazonov YuA, Mokhov MA. Patent No. 160288. Engine. Applications for utility model No. 2015131044/06, 27.07.2015; 2016 Mar 10, Bul. No.7
7. Brown FB, Erickson JW. United States Patent No. 4044943. Centrifugal separator and system. Date of patent: 1977 Jul 30.
8. Brown FB, Erickson JW. United States Patent No. 3960319. Centrifugal separator. Date of patent: 1976 Jan 06.
9. Zamtfort BS, Ivanov MYa. Near-sonic anisotropic cascade flow around symmetric profiles. Proceedings of TSAGI. 1972; 3(6):107–11.
10. Sazonov YuA. Basics of calculations and design of pump-ejector plants. Moscow, Oil and gas, Gubkin Russian State University of Oil and Gas, 2012. 305.
11. Allen D, Smith BL. Axisymmetric Coanda-assisted vectoring. experiments in fluids. 2009; 46(1):55–64.
12. Glezer A. Novel diagnostic techniques and actuator technology for turbulent shear flows. Georgia Institute of Technical Atlanta School of Mechanical Engineering [Internet]. 1996. [cited 2016 Sep 07]. Available from: http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA316341.
13. Circiu I, Dinea S. Review of applications on Coanda effect. History, theories, new trends. Review of the Air Force Academy; 2010.
14. Joyce JW. Design guide for fluidic laminar proportional amplifiers and laminar jet angular rate sensors. Harry Diamond Labs Adelphi MD; 1984.
15. Tesař V. Microbubble generation by fluidics. Part I: Development of the oscillator. Colloquium Fluid Dynamics. 2012.
16. Tesař V, Zhong S, Rasheed F. New fluidic-oscillator concept for flow-separation control. The American Institute of Aeronautics and Astronautics. 2012 ; 51(2):397–405.
17. Joyce JW. Fluidics: basic components and applications. Harry Diamond Labs Adelphi MD; 1983.
18. Weathers TM. NASA contributions to fluidic systems: A survey [Internet]. 1972. [cited 2016 Nov 07]. Available from: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19730002533.pdf.
19. Anderson WW. A dynamic model of vortex-type fluid amplifiers. PhD thesis, Massachusetts Institute of Technology; 1972.
20. Prabakaran J, Vaidyanathan S. Effect of orifice and pressure of counter flow vortex tube. Indian Journal of Science and Technology. 2010 Apr; 3(4).
21. Prahalad NT, Ramesh CS, Viswanathan K, Saravanan R. Vortex flow analysis of a large segmented solid rocket motor. Indian Journal of Science and Technology. 2012 Jan; 5(1).
22. Bauer AB. United States Patent No. 3712321. Low loss vortex fluid amplifier valve. Publication Date: 1973 Jan 23.
23. Doig R. United States Patent Application 20110203671. Apparatus and method for controlling the flow of fluid in a Vortex Amplifier. Publication Date: 2011 Aug 25.
24. Tesař V, Smyk E, Peszynski K. Fluidic oscillator with bistable turn-down amplifier. Colloquium Fluid Dynamics. 2014.