*Universal Journal of Aerodynamics* **14 (2026), 1-14**
**www.papersciences.com** **EU Academy of Sciences (EUAS) e-Symposium**

# Innovative & Pioneering Aerodynamics Research of ESP Artificial Lift for Oil and Gas Well Development

**E.G. Ladopoulos**
**Interpaper Research Organization**
**Athens, GR - 106 72, Greece**
**eladopoulos@interpaper.org**

**Abstract**
A non-linear 3-D elastic waves real - time expert system is studied for the exploration of the on-shore and off-shore petroleum and gas reserves worldwide, according to the modern theory of "*Non-linear Real-Time Expert Seismology*". Such innovative & pioneering technology will work under Real Time Logic for searching off-shore petroleum reserves developed on the continental crust and on deeper water ranging from 300 to 3000 m, or even more. By the present research the 4-D seismic imaging is proposed, which incorporates many 3-D seismic surveys over the same reservoir at specified intervals of time. Thus, by studying multiple time-lapsed 3-D surveys, or three-dimensional subsurface images, portrays the changes in the reservoir over time. Also, a pioneering method is proposed for oil well development, by using the *"Non-linear ESP Artificial Lift Method by Multiple Pumps"*. According to the proposed modern technology the ESP (Electric Submersible Pump) Artificial Lift Method will be extended to non-linear form, by adding multiple pumps. Hence, the well will be able to handle very big flow rates which could be 500,000 bpd, or even up to 1,000,000 bpd. These multiple ESP pumps are used in a definite range of pumping rates. On the contrary, if the pumps are working outside the specified range, then system efficiencies rapidly deteriorate and several mechanical problems may occur. In such case there are two possible solutions: (1) the installation of a wellhead hydraulic choke or (2) by using a variable speed drive (VSD) unit. By using the first solution the wellhead hydraulic choke restricts the pumping rate and forces the ESP pump to operate within its recommended liquid rate range. By the current research NODAL analysis is further presented in order to study the negative effects of surface production hydraulic chokes on the energy efficiency of ESP systems, as compared to the application of VSD drives. Consequently, a calculation model is proposed to evaluate the harmful effects of wellhead hydraulic choking and to find the proper parameters of the necessary VSD unit. So, the beneficial effects by using a VSD drive are shown. Major petroleum companies must be therefore ready to face the new challenges of drilling of very big flow rates approaching 1,000,000 bpd for a single well.

**Key Word and Phrases**
Nodal Analysis, 4-D Real-time Expert Seismology, Non-linear ESP Artificial Lift Method by Multiple Pumps, Electric Submersible Pump (ESP), Wellhead Hydraulic Choke, Variable Speed Drive (VSD), Oil and Gas Well, Energy Efficiency.

## 1. Introduction

In general, artificial lift is a process used on petroleum wells to increase pressure within the reservoir and encourage petroleum to the surface. When the natural drive energy of the reservoir is not strong enough to push the petroleum to the surface, artificial lift is employed to recover more production. While some wells contain enough pressure for petroleum to rise to the surface without stimulation, most don't, requiring artificial lift. Hence, 95% of the petroleum wells worldwide require artificial lift from the very beginning. Even those wells that initially posses natural flow to the surface, that pressure depletes over time, and artificial lift is then required. Consequently, artificial lift is generally performed on all wells at some time during their production life.

Although there are several methods to achieve artificial lift, the two main categories of artificial lift include pumping systems and gas lifts. An emerging method of artificial lift, gas lift injects compressed gas into the well to reestablish pressure, making it produce. Even when a well is flowing without artificial lift, it many times is using a natural form of gas lift. The injected gas reduces the pressure on the bottom of the well by decreasing the viscosity of the fluids in the well. This, in turn, encourages the fluids to flow more easily to the surface. On the contrary, the gas that is injected is recycled gas produced from the well. With very few surface units, gas lift is a good choice for offshore applications. Occurring downhole, the compressed gas is injected down the casing tubing annulus, entering the well at numerous entry points called gas-lift valves. As the gas enters the tubing at these different stages, it forms bubbles, lightens the fluids and lowers the pressure. The gas lift system has some disadvantages. There has to be a source of gas, some flow assurance problems such as hydrates can be triggered by the gas lift.

Additionally, the most common type of artificial lift pump system applied is beam pumping, which engages equipment on and below the surface to increase pressure and push petroleum to the surface. Consisting of a sucker rod string and a sucker rod pump, beam pumps are the familiar jack pumps seen on onshore oil wells. Above the surface, the beam pumping system rocks back and forth. This is connected to a string of rods called the sucker rods, which plunge down into the wellbore. The sucker rods are connected to the sucker rod pump, which is installed as a part of the tubing string near the bottom of the well. As the beam pumping system rocks back and forth, this operates the rod string, sucker rod and sucker rod pump, which works similarly to pistons inside a cylinder. The sucker rod pump lifts the petroleum from the reservoir through the well to the surface. Usually pumping about 20 times a minute, the pumping units are powered electronically or via gas engine, called a prime mover. In order the beam system to work properly, a speed reducer is employed to ensure the pump unit moves steadily, despite the 600 revolutions per minute the engine achieves.

Another artificial lift pumping system, hydraulic pumping equipment applies a downhole hydraulic pump, rather than sucker rods, which lift petroleum to the surface. By this system, the production is forced against the pistons, causing pressure and the pistons to lift the fluids to the surface. Similar to the physics applied in waterwheels powering old-fashion gristmills, the natural energy within the well is put to work to raise the production to the surface. In general, hydraulic pumps are composed of two pistons, one above the other, which are connected by a rod that moves up and down within the pump. Both the surface hydraulic pumps and subsurface hydraulic pumps are powered by power oil, or clean oil that has been previously lifted from the well. The surface pump sends the power oil through the tubing string to the subsurface hydraulic pump installed at the bottom of the tubing string, the reservoir fluids are then sent up a second parallel tubing string to the surface. Such systems usually produce up to 20,000 bpd.

Furthermore, the electric submersible pump systems employ a centrifugal pump below the level of the reservoir fluids. Connected to a long electric motor, the pump is composed of several impellers, or blades, that move the fluids within the well. The whole system is installed at the bottom of the tubing string. An electric cable runs the length of the well, connecting the pump to a surface source of electricity. The electric submersible pump applies artificial lift by spinning the impellers on the pump shaft, putting pressure on the surrounding fluids and forcing them to the surface. A mass producer, electric submersible pumps can lift up to 90,000 barrels of fluids per day.

The energy demand for petroleum and gas will increase up to 2030 by 50-60%, as it is increasing worldwide yearly at a pace of 1.5 to 2.0%. Thus, for the on-shore and off-shore petroleum and gas reservoir exploration was proposed by E.G.Ladopoulos [1]-[17] the new theory of *"Non-linear Real-Time Expert Seismology"*. According to the above modern technology a non-linear 3-D elastic waves real - time expert system was proposed for the exploration of petroleum and gas resources worldwide, including the off-shore petroleum reserves, of the seas and oceans in the whole world in deep waters ranging from 300 to 3000 m, or even much more. Also, the above technology is the best device for searching the on-shore and off-shore hydrocarbon resources in very deep depths, even approaching 20,000 m or 30,000 m.

Consequently, for the new and the existing oilfields there is an absolute need for the improvement of the existing methods of well development. For this reason, by the present investigation the *"Non-linear ESP Artificial Method by Multiple Pumps"* is further improved and investigated. According to the above new technology the ESP Artificial Lift Method will be extended to non-linear forms by adding multiple electric submersible pumps (ESP), in order to increase the production of each well to 500,000 bpd, or even up to 1 million bpd. The above multiple ESP pumps are used in a definite range of pumping rates. The new method has many benefits beyond the existing ESP Artificial Lift Method [18]-[20], as the petroleum production for each well is increased very much and so there are no limits for the oil well production any more.

In addition, if the pumps are working outside the specified range, then system efficiencies rapidly deteriorate and several mechanical problems may occur. However, in such case there are two possible solutions: (1) the installation of a wellhead hydraulic choke or (2) by using a variable speed drive (VSD) unit. By using the first solution, then the wellhead hydraulic choke restricts the pumping rate and forces the ESP pump to operate within its recommended liquid rate range. The current research investigates the detrimental effects of surface chokes on the power efficiency of ESP systems and discusses an alternative solution.

Thus, nodal analysis is further presented in order to investigate the negative effects of surface production hydraulic chokes on the energy efficiency of ESP systems, as compared to the application of VSD drives. A calculation model is therefore investigated in order to evaluate the harmful effects of wellhead hydraulic choking and to find the proper parameters of the necessary VSD unit. By this way, the beneficial effects of using a VSD drive are shown. Consequently, the major petroleum companies all over the world must be ready to face the new challenges of drilling of very big flow rates approaching 1,000,000 bpd for a single well.

From the above described analysis it is clear the evidence of the applicability of the new method of *"Non-linear ESP Artificial Method by Multiple Pumps"*. Furthermore its novelty, as it is based mostly on a theoretical and very sophisticated model and not to practical tools like the existing methods. Hence, the new method will be the best technology for drilling of very big flow rates for a single oil well.

## 2. 4-D Non-linear Real-Time Expert Seismology

The research and development aspects of the off-shore petroleum reserves can be divided into three main areas:

(a) The acquisition and analysis of geophysical, geological and reservoir engineering data to enable an appreciation to be made of the reserves.
(b) The determination of all-necessary standards and data for the safety to offshore operations.
(c) To assist the development of the offshore supplies industry, and to enable it to play a full part in the development of the marine hydrocarbon resources in worldwide markets in the future.

Worldwide geological surveys by the major petroleum companies and scientific institutes indicate that such prospects do not necessarily end at the edge of the continental shelf. Normal probability considerations indicate that main resources will be found in areas of thick sedimentary sequences developed on the continental crust. Thus, there is an expectation with good possibilities for finding marine oil resources in deep waters, too. These will be on the shelf, slope and rise of the Earth's margin, and the depths of water would not only range up to 300 m, but also in deeper waters from 300 m to 3000 m, or even much more.

Consequently, the behavior of a reservoir, depends not only on the properties of the liquid and gas, but also on a series of factors that may be termed as the "properties of the environment". Amongst these are such items as capillary - pressure effects, the reaction of rock when subjected to high stress, pressure and temperature gradients at the shallower levels in the Earth's crust and influences of the compressibility as pressure are reduced by fluid withdrawals.

There are four conditions that must be satisfied so that a geological formation, or a part thereof, should form a suitable reservoir, for example for the accumulation of petroleum. These are porosity, permeability, seal and closure. The first defines the pore space in the rock - space in which the petroleum may collect. Permeability is the attribute of the rock that permits the passage of fluid through it. Generally, it is a measure of the degree interconnectedness, of the pore space, but some reservoir (e.g. in the massive limestone deposits, or in igneous intrusions) depend for fluid flow on a network of fractures within the rock.

Moreover, the seal is the "cap" of the reservoir and prevents the oil from leaking away, while closure is a measure of the vertical extent of the sealed trap or, in the case of resources accumulation bounded below by a moving body of water, of the "height" of the sealed trap where that height is measured along a line perpendicular to the oil - water contact.

Almost all resources occur in sedimentary basins, in porous standstones or limestones and that seal or cap rock is often a clay or shale, or massive unfractured limestone having little or no permeability. On the contrary, three general categories of resources can be mentioned for marine reserves: structural traps, stratigraphic traps and combination traps.

Additionally, through the new method exact 3-D images are produced of the underground topography of the area. In addition, 4-D imaging can be taken on a given area multiple times over an extended period of time. So, through the current research 4-D seismic imaging is proposed, which incorporates many 3-D seismic surveys over the same reservoir at specified intervals of time. Studying multiple time-lapsed 3-D surveys, or three-dimensional subsurface images, portrays the changes in the reservoir over time. 4-D seismic can determine changes in flow, temperature, pressure and saturation. By scanning a reservoir over a given period of time, the flow of the hydrocarbons within can be traced and better understood. For example, as hydrocarbons are depleted from a field, the pressure and composition of the fluids may change. Also, geologists are interested in understanding how the reservoir reacts to gas injection or water flooding. Hence, 4-D seismic can help to locate untapped pockets of petroleum or gas within the reservoir. Typically, 4-D seismic data is processed by subtracting the data from one survey from the data of another. The amount of change in the reservoir is defined by the difference between the two. If no change has occurred over the time period, the result will be zero.

Elastic waves are sound waves, generally three - dimensional and they may be transmitted through matter in any phase - solid, liquid, or gas. Any body vibrating in air gives rise to such waves, as it alternately compresses and rarefies the air adjacent to its surfaces. A body vibrating in a liquid, or in contact with a solid, likewise generates similar longitudinal waves. The frequency of the waves is of course the same as the frequency of the vibrating body which produces them.

The distance between two successive maxima (or between any two successive points in the same phase) is the wavelength of the wave and is denoted by $l$. Since the wave form, traveling with constant velocity $u$, advances a distance of one wavelength in a time interval of one period, it follows that the velocity of sound waves $u$ as following:

$$u = l\,v \tag{2.1}$$

where $v$ denotes the frequency.

It is obvious that the velocity $u$ differs when the sound waves are traveling through solid, liquid, or gas. In a solid the elastic waves are moving faster than in a liquid and the air, and in a liquid faster than in the air. Hence, if somebody is searching for example for petroleum marine resources over the sea, by transmitting sound waves, then there will be a difference in the velocity of the waves in the air, the sea, the solid bottom and in a potential reservoir.

In order to better explain the new method, consider the example of Figure 1. In this case consider that in the bottom of the sea there is a potential petroleum reservoir. Then, the speed of the elastic waves in the air ($u_{air}$), will be different from the speed in the water ($u_{water}$), and different from the speed in the solid bottom ($u_{solid}$) and different from the speed in the potential reservoir

($u_{oil}$), while the frequency of the elastic waves remaining the same when transmitted through every different matter.

A real - time non-linear 3-D plane - polarized elastic waves expert system is proposed in order to explore the marine oil resources, for the several closed seas all over the world, according to the modern technology of *"Non-linear Real-time Expert Seismology"* as proposed by Ladopoulos[1]-[17], in contrast to the old theory of *"Reflection Seismology"*. Such Generic Sound Waves Technology will work under Real Time Logic for searching marine hydrocarbon reservoir developed on the continental crust and on deeper waters ranging from 300 m to 3000 m, or even much deeper (Figure 2). There are many deeper water prospects around the seas all over the world, but because of the paucity of the available information it is not possible at present to quantify the amounts that may be recoverable from them. For this reason the proposed real - time elastic waves expert system will be the best device for the exploration of the continental margin areas (shelf, slope and rise) and the very deep waters, too.

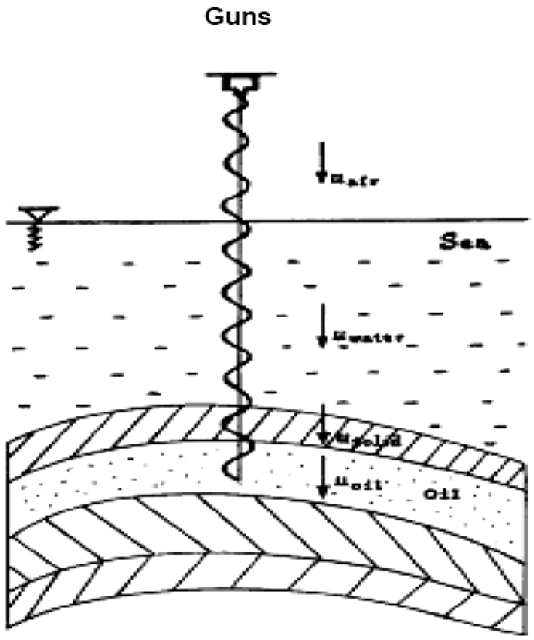


**Fig. 1** Elastic Waves Method for the Exploration of Marine Resources.

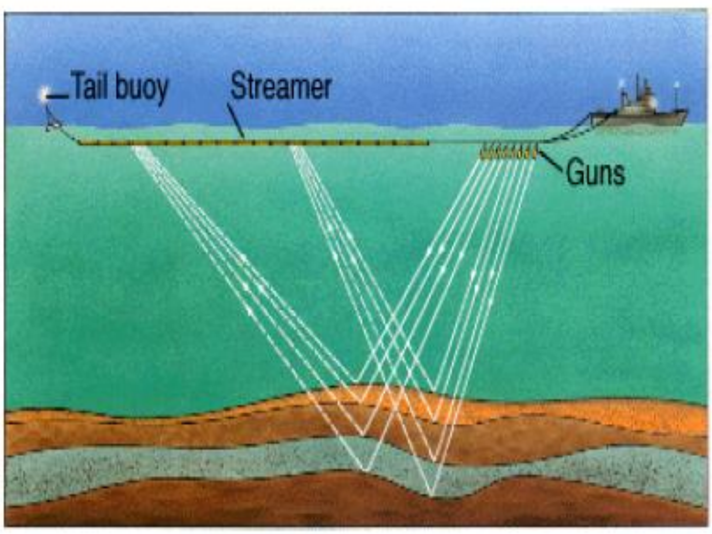


**Fig. 2** Real-time Expert Seismology.

Thus, by using the sophisticated method of *"Real-Time Expert Seismology"* the average velocity of the sound waves is calculated by providing important information about the composition of the solids through of which passed the sound waves. For example the velocity of the sound waves through the air is 331 m/sec, through liquid 1500 m/sec and through sedimentary rock 2000 to 5000 m/sec. In addition, according to the law of Reflection the angle of reflection equals the angle of incidence (Figure 3). Then according to the new method the arrival times of the seismic waves are analyzed. After the sensor measures the precise arrival time of the wave, then the velocity of the wave can be calculated by using the method which follows.

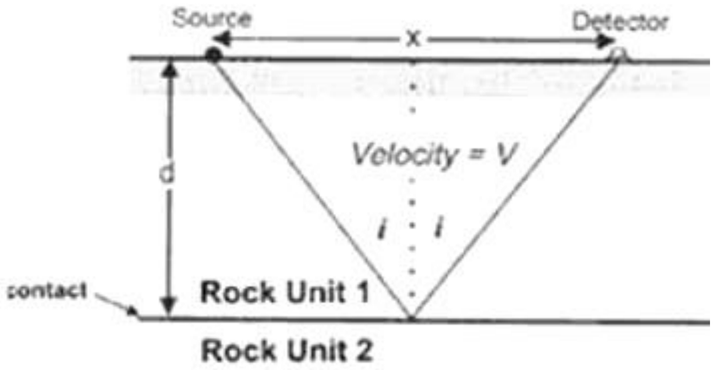


**Fig. 3** Law of Reflection.

The travel time $T$ of the seismic waves is given by the relation:

$$T = \frac{2\left(d^2 + x^2/4\right)^{1/2}}{v} \tag{2.2}$$

in which $d$ denotes the depth, $x$ the distance between source of wave and the geophone or hydrophone detector and $v$ is the average speed.

Moreover, from (2.2) follows equation (2.3):

$$T^2 = \frac{4d^2 + x^2}{v^2} \tag{2.3}$$

Beyond the above, the normal incident time $T_o$ is given by the formula:

$$T_o = \frac{2d}{v} \tag{2.4}$$

From eqs (2.3) and (2.4) finally follows:

$$T^2 - T_o^2 = \frac{x^2}{v^2} \tag{2.5}$$

Hence, from eqn (2.5) follows that the travel time curve for a constant velocity horizontal layer model is a hyperbola whose apex is at the zero-offset travel time $T_o$:

$$\frac{T^2}{T_o^2} - \frac{x^2}{(T_o v)^2} = 1 \tag{2.6}$$

Finally from (2.5) the mean velocity is equal to:

$$v = \frac{x}{\sqrt{T^2 - T_o^2}} \tag{2.7}$$

A real time expert system is therefore used and the apparatus permitted excitation of any combination of elements and reception of any other, visual analysis of the responses, and transfer of the signals to the PC for post processing. The sequencing of transducer excitation, digitizer configuration and subsequent data analysis was performed by a rule based Real-Time Expert System. From the information gathered, the Expert System applies knowledge via a series of software coded rules and provides any one of the following conditions: speed in the air ($u_{air}$), speed in the water ($u_{water}$), speed in the solid bottom ($u_{solid}$) and speed in the potential reservoir ($u_{oil}$),

Real-time logic (RTL) is a reasoning system for real-time properties of computer based systems. RTL's computational model consists of events, actions, causality relations, and timing constraint This model is expressed in a first order logic describing the system properties as well as the systems dependency on external events. The RTL system introduces time to the first logic formulas with an event occurrence function, which assign time values to event occurrences. Beyond the above, real-time computing in common practice is characterized by two major criteria: deterministic and fast response to external stimulation, and both human and sensor and actor based interaction with the external world. Real-time is an external requirement for a peace of software; it is not a programming technology.

In general, Real-Time Logic uses three types of constraints:

a. Action constants may be primitive or composite. In a composite constant, precedence is imposed by the event-action model using sequential or parallel relations between actions.
b. Event constants are divided into three cases. Start/stop events describe the initiation/termination of an action or subaction. Transition events are those which make a change in state attributes. This means, that a transition event changes an assertion about the state of the real-time system or its environment. The third class, which are the external events, includes those that can be impact the system behavior, but cannot be caused by the system.
c. Integers assigned by the accurance function provide time values, and also denote the number of an event occurrence in a sequence.

Besides, the RTL System introduces time to the first order logic formulas with an event occurrence function denoted by e. The mechanism to achieve a timing property of a system is the deduction resolution.

Consider further the following example: Upon pressing button ≠ 80, action TEST is extended within 900 time units. Dusting each execution of this action, the information is sampled and subsequently transmitted to the display panel. Moreover, the computation time of action TEST is 800 time units.

This example can be further translated into the following two formulas:

$$\forall\ x : e(\Omega\ \text{button } 80,\ x) \leq e(\uparrow \text{TEST},\ x) \wedge$$
$$e(\downarrow \text{TEST},\ x) \leq e(\Omega\ \text{button } 80,\ x) + 800$$
$$\forall\ y : e(\uparrow \text{TEST},\ y) + 800 \leq e(\downarrow \text{TEST},\ y)$$

**3. Multiple Pumps for Non-linear ESP Artificial Lift**

In general, when petroleum is first found in the reservoir, it is under pressure from the natural forces that surround and trap it. If a well is drilled into the reservoir, an opening is provided at a much lower pressure through which the reservoir fluids can escape. The driving force which causes these fluids to move out of the reservoir and into the wellbore comes from the compression of the fluids that are stored in the reservoir. The actual energy that causes a well to produce petroleum results from a reduction in pressure between the reservoir and the producing facilities on the surface. So, if the pressures in the reservoir and the wellbore are allowed to equalize, either because of a decrease in reservoir pressure or an increase in wellbore and surface pressure, no flow from the reservoir will take place and there will be no production from the well.

On the other hand, in many wells the natural energy associated with petroleum will not produce a sufficient pressure differential between the reservoir and the wellbore to cause to flow into the production facilities at the surface. In other wells, natural energy will not drive petroleum to the surface in sufficient volume. The reservoir's natural energy must then be supplemented by some form of artificial lift.

Furthermore, the most common method of artificial lift for big petroleum production is the ESP Artificial Lift Method [18]-[20]. By this technology an electric submersible pump (ESP) is used, working in a definite range of pumping rates. This method can lift up to 90,000 barrels of fluids per day. So, by the big petroleum companies in order to increase the production of each well, there is an absolute need for the establishment of a new technology of artificial lift so that the produced oil quantity to be very much increased.

So, by the current research a sophisticated technology of artificial lift is improved, the *"Non-linear ESP Artificial Lift Method by Multiple Pumps"*. By the modern technology instead of using one ESP pump, multiple pumps are used, by adding the corresponding head of each pump. By this way the production of each well is increased to 500,000 bpd, or even up to 1 million bpd.

The power *P (*in *KW)* of an ESP pump is given by the following formula:

$$P = \frac{Q(\gamma H - p_{\text{int}\,ake})}{\eta \cdot \eta_{surf}} \tag{3.1}$$

where $Q$ is the pumping rate ($m^3/\sec$), *H* the head of the pump (*m*), $\gamma$ is the specific gravity of the produced liquid ($KN/m^3$), $p_{\text{int}\,ake}$ ($KN/m^2$) is the pump suction pressure, called pump intake pressure, $\eta$ is pump's efficiency and $\eta_{surf}$ (usually 0.97) is the power efficiency of the surface equipment.

Since the ESP motor converts the electrical energy input at its terminals into mechanical work output at its shaft, then the energy conversion is characterized by the motor efficiency.

Hence, the power $P_e$ *(KW)* of the electric motor is given by the formula:

$$P_e = \frac{P}{\eta_e} \tag{3.2}$$

in which $P$ is the power of the ESP pump and $\eta_e$ the efficiency of the electric motor.

In (3.1) the head *H* of the pump is equal to:

$$H = h_{depth} + h_f + h_{wh} + h_{cable} \tag{3.3}$$

where $h_{depth}$ is the pump setting depth, $h_f$ are the frictional pressure losses in the tubing string, $h_{wh}$ are the backpressure losses, as the pump has to work against the well's surface wellhead pressure and the power consumed by overcoming this backpressure is not included in the useful power and $h_{cable}$ are the electrical cable losses.

In (3.3) the frictional pressure losses in the tubing string $h_f\,(m)$ are given by Darcy-Weisbach equation:

$$h_f = f \frac{L}{D} \frac{v^2}{2g} \tag{3.4}$$

where:

$$L = h_{perf} - h_{depth} \tag{3.5}$$

with $h_{perf}$ the depth of perforations, *D* diameter of tubing (*m*), *v* the velocity of the liquid (*m/sec*), g gravity acceleration (=9.81 $m/\sec^2$) and friction coefficient which is calculated through the equation of Colebrook-White.

Furthermore, in (3.3) the backpressure losses are equal to :

$$h_{wh} = \frac{p_{wh}}{\gamma} \tag{3.6}$$

with $p_{wh}$ ($KN/m^2$) the wellhead pressure.

On the contrary, since the ESP motor is connected to the power supply through a long power cable, a considerable voltage drop occurs across this cable. Then, the Voltage drop creates a power loss proportional to the square of the current flowing through the system, as given by the following relation:

$$\Delta P_{cable} = \frac{3I^2 R_T}{1000}\,(KW) \tag{3.7}$$

where $I$ is the required motor current (Amps) and $R_T$ is the resistance of the power cable at well temperature (Ohms).

Then, the electric cable losses $h_{cable}$ are equal to:

$$h_{cable} = \frac{\Delta P_{cable}}{\gamma \cdot Q} \tag{3.8}$$

By the new method of *"Non-linear ESP Artificial Lift with Multiple Pumps"* instead of one pump are used multiple in several positions of the well. Consequently, the total head is the sum of the heads of each ESP pump separately :

$$H = H_1 + H_2 + \dots\dots\dots.. + H_m \tag{3.9}$$

if used $m$ pumps.

Hence, by using the proposed new technology the production of petroleum for each single well is increased too much, up to 1 mill. bpd, as by each pump is covered a part of the requested head.

## 4. Petroleum Well Development with Wellhead Chokes

The most ESP artificial lift pumps are designed to operate using electricity at a fixed frequency, usually 60 or 50 Hz. For this reason the ESP pump runs at a constant speed and develops different heads for different pumping rates as predicted by its published performance curve. Thus, when designing for a constant production rate, a pump type with the desired rate inside of its recommended capacity range is selected.

A basic problem with the usual design of ESP artificial lift is that the ESP installation is investigated for a single design rate only and no information is available for cases when well parameters are in doubt. On the contrary, these problems are solved if NODAL analysis principles are used to describe the operation of the production system consisting of the well, the tubing, the ESP unit, and the surface equipment. So, by NODAL analysis is possible the calculation of the necessary pump heads for different possible pumping rates and the determination of the liquid rate occurring in the total system. It should therefore the required head to produce well fluids to the separator to be equal to the head developed by the ESP pump run in the well.

In addition, the number of the required pump stages is found from detailed calculations of the required total dynamic head (TDH), which is the head required to lift well fluids to the surface at the desired pumping rate.

Figure 4 further shows a diagrammatic comparison of the conventional design with the corresponding provided by NODAL analysis. Thus, conventional design calculates the TDH at the design rate only and then selects the required type of the ESP pump. After selecting the rest of the equipment the ESP unit is run in the well and it is then only hoped that actual conditions were properly simulated resulting in the well output being equal to the design liquid rate. On the contrary, if well inflow performance data were uncertain or missing during the design phase then the ESP stabilized liquid rate is different than that from the design target. By NODAL calculations, however, can be found the required head values for different liquid rates, shown in Fig. 1 by the curve in dashed line. Then the well's actual production rate will be found where the required and the available (provided by the pump) heads are equal, at Point 1 in Figure 4.

So, as the required production of the well is usually due to reservoir engineering considerations, then production of a greater rate is not allowed. If the actual head requirement (actual TDH) is much less than the calculated design TDH, then an hydraulic choke should be placed at the wellhead to restrict the oil rate to the design target. On the other hand, at this rate the ESP pump develops the designed operating head as shown by Point 2.

Since the actual head required for lifting the well liquid to the surface, as found from NODAL calculations, is less than this value, then a sufficient head loss across the choke is needed. This head loss, which is found between Points 2 and 3, must be sufficient to supplement the system's actual TDH to reach the TDH that was used for the original design. By this way, the head requirement of the production system is artificially increased and the ESP pump is forced to produce the desired liquid rate.

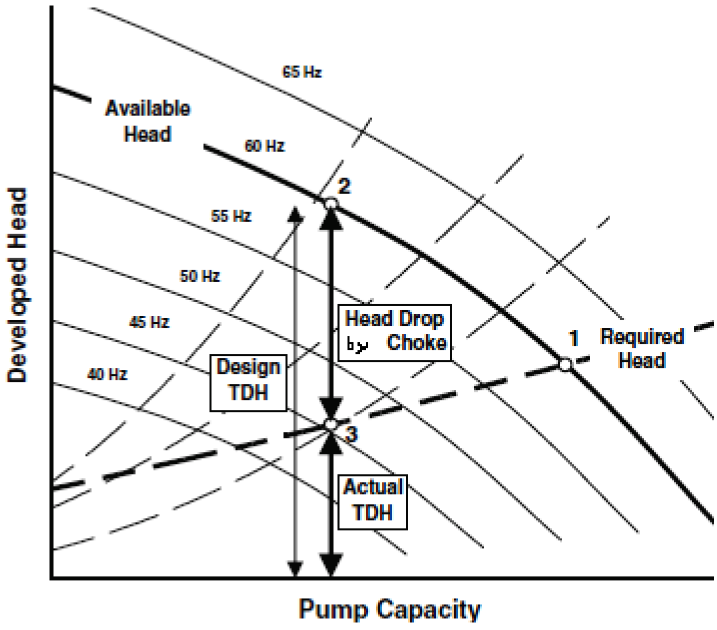


**Fig. 4** A wellhead hydraulic choke in ESP pump.

The wasted power $P_{wasted}$ *(*in *KW)* of the pump because of the hydraulic choke is given by the following relation:

$$P_{wasted} = \gamma Q \Delta H_{choke} \tag{4.1}$$

where $Q$ is the pumping rate ($m^3/\sec$), $\Delta H_{choke}$ the head loss across the hydraulic choke (m) and $\gamma$ is the specific gravity of the produced liquid ($KN/m^3$).

As the above power is wasted, then the efficiency of the ESP power system together with the profitability of oil production will decrease. Moreover, in order to apply NODAL analysis to the ESP installation, then firstly should be calculated the variation of flowing pressures in the well.

The pressure $p_d$ ($KN/m^2$) available at the ESP pump's discharge is equal to:

$$p_d = p_{wf} - (L_{perf} - L_{pump}) grad_l + \Delta p_{pump} \tag{4.2}$$

where $p_{wf}$ denotes the bottomhole pressure ($KN/m^2$), $grad_l$ the liquid gradient (*KW/m*), $L_{pump}$ (*m*) the pump setting depth, $L_{perf}$ (*m*) the depth of perforations and $\Delta p_{pump}$ ($KN/m^2$) the pressure increase developed by the ESP pump.

Also, the required discharge pressure of the ESP pump $p_d^*$ is given by the relation:

$$p_d^* = p_{separ} + \Delta p_{fl} + L_{pump} grad_l + \Delta p_{fr} \tag{4.3}$$

in which $p_{separ}$ is the surface separator pressure ( $KN/m^2$ ), $\Delta p_{fl}$ the frictional pressure drop in the flowline ( $KN/m^2$ ) and $\Delta p_{fr}$ the frictional pressure drop in the tubing string ( $KN/m^2$ ).

On the other hand, the available and the required pressures should be equal ( $p_d = p_d^*$ ), then from eqs (4.2) and (4.3) follows the relation:

$$\Delta p_{pump} = p_{separ} + \Delta p_{fl} + L_{perf}\ grad_l + \Delta p_{fr} - p_{wf} \tag{4.4}$$

By dividing (4.4) by the liquid gradient, then reduces to:

$$\Delta H_{pump} = \frac{p_{separ} - p_{wf}}{\gamma} + \Delta H_{fl} + L_{perf} + \Delta H_{fr} \tag{4.5}$$

where $\Delta H_{fl}$ is the frictional head drop in the flowline (*m*) and $\Delta H_{fr}$ is the frictional head drop in the tubing string (*m*).

## 5. Oil Well Development by Variable Speed Drive (VSD) Units

If the installation design of the artificial lift is inaccurate and the ESP system produces a higher rate than desired, then the use of wellhead chokes is a common solution to control the production of the well. On the other hand, if a VSD is available, then the elimination of the choke and its associated disadvantages can be accomplished.

Thus, as could be seen in Fig. 4, by reducing the electrical frequency driving the ESP system to a level where the head developed by the pump is equal to the head required to produce the desired rate (Point 3), then the hydraulic choke is no more needed to adjust the pumping rate. Consequently, by using a VSD unit in order to control the liquid rate of the ESP system, then the several components of the system behave differently as the driving frequency is adjusted.

The use of the variable speed drive (VSD) unit would be therefore the best device to control the ESP pump. The above pump will develop different head values and will need different brake horsepower from the electric motor.

For the VSD unit the following formula is valid:

$$\frac{U_2}{U_1} = \frac{f_2}{f_1} \tag{5.1}$$

where $f_1$ , $f_2$ are the AC frequencies (Hz) and $U_1, U_2$ are the output Voltages at $f_1$ and $f_2$ frequencies, correspondingly.

Moreover, by next formula is shown that the power developed by the ESP pump is proportional with the electrical frequency:

$$\frac{P_2}{P_1} = \frac{f_2}{f_1} \tag{5.2}$$

where $f_1$ , $f_2$ are the AC frequencies (Hz) and $P_1, P_2$ are the motor power available at $f_1$ and $f_2$ frequencies, correspondingly.

Consequently, the use of a VSD unit in the ESP artificial lift system, substantially modifies the power conditions of the ESP pump and so there is no need for an hydraulic chock.

The innovative & pioneering method of *"Non-linear ESP Artificial Lift by Multiple Pumps"* will be used in combination with the VSD units. So, for each ESP pump a VSD unit will be used, in order to control the proper operation of the ESP system.

## 6. Conclusions

By the present research the new theory of ***"Non-linear Real-time Expert Seismology"*** has been introduced and studied for the exploration of on-shore and off-shore oil reserves. The benefits of the modern technology of *"Non-linear Real-time Expert Seismology"* in comparison to the existing theory of *"Reflection Seismology"* are the following:

**1.** The new theory is based on the special form of the geological anticlines of the bottom of the sea, in order to decide which areas of the bottom have the most possibilities to include petroleum.
On the contrary, the existing theory is only based to the best chance and do not include any theoretical and sophisticated model.

**2.** The new technology of elastic (sound) waves is based on the difference of the speed of the sound waves which are traveling through solid, liquid, or gas. In a solid the elastic waves are moving faster than in a liquid and the air, and in a liquid faster than in the air.
Existing theory is based on the application of Snell's law and Zoeppritz equations, which are not giving good results, as these which we are expecting with the new method.

**3.** The new theory is based on a Real-time Expert System working under Real Time Logic, that gives results in real time, which means every second.
Existing theory do not include real time logic.

From the above three points it can be well understood the evidence of the applicability of the new technology of *"Non-linear Real-time Expert Seismology"*. Also its novelty, as it is based mostly on a theoretical and very sophisticated Real-time Expert model and not to practical tools like the existing method.

Thus, by the current research the leading technology of *"Non-linear ESP Artificial Lift by Multiple Pumps"* has been further improved and investigated for the petroleum well development. So, by using the proposed modern method then it will be possible the production of very big quantities of oil in each well, which could be 500,000 bpd, or even up to 1 mill. bpd.

Hence, by the proposed groundbreaking method for energy applications it will be established a strong scientific and technical base for the Science & Technology worldwide in the emerging areas of well development in the energy field. Thus, through the modern technology of *" Non-linear ESP Artificial Lift by Multiple Pumps"*, the production of very big quantities of petroleum and gas for each well will become possible.

The petroleum markets are multi-billion markets all over the world. Hence, such a contribution requires an international approach, rather than a local approach, as it is referred to a market all over the world with value of many billions. It is therefore expected in order the major petroleum companies to keep and to improve their leading role in the worldwide Science & Technology in the petroleum field, to get involved in the new and groundbreaking technology in the area of Energy, which is proposed by the present investigation.

Finally, as the proposed sophisticated method *"Non-linear ESP Artificial Lift by Multiple Pumps "*, is based on a very innovative modern technology, then it is expected to get the best results. Consequently, our modern method is based on a very sophisticated model by using multiple ESP pumps, instead of using only one pump like the past methods. It is therefore not necessary to open many wells in order to increase the production, like the existing methods.

## References


1. *Ladopoulos E.G.*, 'Non-linear singular integral representation for petroleum reservoir engineering', *Acta Mech*., ***220*** *(2011), 247-253.*
2. *Ladopoulos E.G.,* 'Petroleum reservoir engineering by non-linear singular integral equations', *Mech. Engng Res*., ***1*** *(2011), 1-10.*
3. *Ladopoulos E.G.,* 'Oil reserves exploration by non-linear real-time expert seismology', *Oil Asia J.,* ***32*** *(2012), 30 - 35.*
4. *Ladopoulos E.G.,* 'Hydrocarbon Reserves Exploration by Real-Time Expert Seismology and Non-linear Singular Integral Equations', *Int. J. Oil Gas Coal Tech.,* ***5*** *(2012), 299-315.*
5. *Ladopoulos E.G.,* 'New Aspects for Petroleum Reservoir Exploration by Real-time Expert Seismology', *Oil Gas Busin. J.,* ***2012*** *(2012), 314-329.*
6. *Ladopoulos E.G.,* 'Petroleum & Gas Reserves Exploration by Real-Time Expert Seismology and Non-linear Seismic Wave Motion', *Adv. Petrol. Explor. Develop.,* ***4*** *(2012), 1-13.*
7. *Ladopoulos E.G.,* 'Non-linear Singular Integral Equations for Multiphase Flows in Petroleum Reservoir Engineering', *J. Petrol. Engng Tech.,* ***2*** *(2012), 29-39.*
8. *Ladopoulos E.G.,* 'Real-time Expert Seismology by Non-linear Oil Reserves Expert System', *J. Petrol. Gas Engn,* ***4*** *(2013), 28-34.*
9. *Ladopoulos E.G.,* 'New Sophisticated Model for Exact Petroleum Reserves Exploration by Non-linear Real-Time Expert Seismology', *Univ. J. Petrol. Scien.,* ***1*** *(2013), 15-29.*
10. *Ladopoulos E.G.,* 'Real-Time Expert Seismology and Non-linear Singular Integral Equations for Oil Reserves Exploration', *Univ. J. Nonlin. Mech.,* ***1*** *(2013), 1-17.*
11. *Ladopoulos E.G.,* 'Non-linear Real-Time Expert Seismology for Petroleum Reservoir Exploration', *Univ. J. Nonlin. Mech.,* ***1*** *(2013), 18-29.*
12. *Ladopoulos E.G.,* 'General Form of Non-linear Real-Time Expert Seismology for Oil and Gas Reserves Exploration', *Univ. J. Petrol. Scien.,* ***1*** *(2013), 1-14.*
13. *Ladopoulos E.G.,* 'Oil and Gas Reserves Exploration by Generalized Form of Non-linear Real-Time Expert Seismology', *Univ. J. Engng Mech.,* ***1*** *(2013), 17-30.*
14. *Ladopoulos E.G.,* 'Multiphase Flows in Oil Reservoir Engineering by Non-linear Singular Integral Equations', *Univ. J. Fluid Mech.,**1** (2013), 1-11.*
15. *Ladopoulos E.G.,* 'Non-linear Real-Time Expert Seismology for Very Deep Drillings in Petroleum Reserves Exploration', *Univ. J. Nonlin. Mech.,* ***1*** *(2013), 18-29.*
16. *Ladopoulos E.G.,'Computational Recipes of Linear & Non-Linear Singular Integral Equations & Relativistic Mechanics in Engineering & Applied Science',* Volume I, Nova, New York, *2015.*
17. *Ladopoulos E.G.,'Computational Recipes of Linear & Non-Linear Singular Integral Equations & Relativistic Mechanics in Engineering & Applied Science',* Volume II, Nova, New York, *2015.*
18. *Brown K.E., ' The technology of artificial lift methods',*Vol 2b, PennWell Books, Tulsa, *1980.*
19. *Divine D.L.,* 'A variable speed submersible pumping system', *in: Paper SPE 8241 presented at the 54th annual technical conference and exhibition held in Las Vegas, September 23-26, 1979.*
20. *Lea J.F., Rowlan L., McCoy J.,* 'Artificial lift power efficiency', *in: Proceedings of 46th Annual Southwestern Petroleum Short Course, Lubbock, pp 52-63, 1999.*