Oscillating Back Pressure Regulator (OBPR) for High-Pressure Core Flooding

Sanjay Dubey[1], *Hossein* Khorshidian[2], *Maziyar* Mahmoodi, [1]*Edison* Sripal[1], *Lesley* James[1*]

[1] Hibernia EOR Laboratory, Memorial University of Newfoundland, St. John's, Canada
[2]Opla Energy, Calgary, Canada

Abstract. The challenge in the core analysis industry is the availability of a versatile back pressure regulator (BPR) that can operate efficiently at ultra-low or no-flow conditions at very high pressure. The existing models of back pressure regulators are limited to a specific range of operating conditions, automation, and robust core flooding environment. In this work, we developed an initial stage prototype of an Oscillating BPR (OBPR), emphasizing detailed instrumentation and implemented automation. The critical component in an OBPR is the valve that needs to operate within defined close and open position based on the feedback received from an encoder rather than the oscillation created by the flow system or by using a square wave oscillator. The paper investigates the static and dynamic characteristics of the newly designed OBPR instrument. The paper discusses the graphical programming LabVIEW software used to create the feedback control loop using the PID controller. Initial results of the test run were done with the different core flooding systems like Water, Brine, and CO_2. The study also included comparing OBPR pressure performance with the standard back pressure regulator in the market.

1 Introduction

A novel oscillating back pressure regulator (OBPR) was developed to control the backpressure downstream of a two-phase or three-phase core flooding experiment. Core flood experiments are used to investigate the multiphase behavior of fluid flow in rock cores at reservoir operating conditions. Core flooding technology and instrumentation play a significant role in accurately measuring physical characteristics (relative permeability, connate water content, fluid saturation, pore-space, etc.) and better analyzing the core data. BPRs applied in core flood experiments are subjected to very high pressure (~68 MPa) and temperature conditions (~200°C). Commonly, mechanical regulators accompany all core flooding experiments to provide back pressure and control flow/pressure. The primary purpose of the BPR is to maintain reservoir operating conditions in the core holder and keep a steady low-flow and stable backpressure for in-situ reservoir analysis, and reliable displacement of fluid. As fluid at the core outlet are produced, the backpressure decreases. The goal is to keep a constant backpressure while collecting sampling fluid at core outlet. BPRs can also be used to enhance the downhole pump performance and well productivity in large oil reservoirs [1]. Role of BPRs in the different core flood experiements is disucsssed in the following paragraphs. BPRs are also especially important in gas injection core flood experiments, core flooding involving live fluids (oil or Brine), or EOR applications such as carbonated water injection (CWI) as in-situ pressures maintained to ensure appropriate phase saturations and relative fractional flow during oil production. BPR are used in the Ion Chromatography analysis of advanced ion management carbonate core-flood experiments [2]. Foam stability is an essential factor in understanding the displacement of the oil efficiency in porous media, BPR adopted in this chemical flooding experiment allows setting the desired pressure and temperature [3]. BPR is applied to build the pressure of 98066.5 Pa in the studies of microbial enhanced oil recovery for the core flood utilizing the model ex-situ bioaugmenting a thermo-, and halo-tolerant rhamnolipid generate using Pseudomonas aeruginosa [4]. Gas drainage strategy, such as enhanced coalbed methane, is used to recover the coalbed methane to provide safe conditions for underground coal mining. The lab-scale adsorption investigation was used to observe the displacement of methane by injecting gas (CO_2 or N_2) into intact coal core samples. BPR was used to hold the constant pore pressure during the core flooding experiment [5]. The above applications illustrate that BPR is an important component in core flooding research and justify the need for better BPR design.

Zero flow rate can be challenging to achieve using the conventional BPRs. The high flow coefficient makes the system inefficacious for the core flood application [6]. The backpressure regulator used in the core flood experiments must be able handle multiphase flow. Perfectly designed BPR must minimize the fluctuation in core outlet pressure. Designing the high-precision feedback control system for OBPR can provide highly reliable pressure regulation for core flood applications. Low-precision BPRs cannot maintain the core pressure holder at a specific pressure. The precision of BPR is essential in measuring relative permeability, MMP in WAG, apparent viscosity of foam, and many other applications. Imperfect BPRs can cause drastic measurement error, such as distorted breakthrough concentration profiles during the measurement of dispersion coefficient of CO_2 in CH_4 as part of the CO_2 sequestration for the enhanced gas recovery

---

[*] Corresponding author: ljames@mun.ca

[7]. High dead volume for the backpressure regulator will allow more process fluid to be stagnant, which can be a problem in specific applications. Most of the samples are collected and analyzed by using chromatography; hence this can be a severe problem for chemical-sensitive core flood experiments. During the experiment to study the effect of oil saturation on foam propagation, the diaphragm BPR requires to clean the regulator since the experiment is susceptible to undesired chemical reactions and could cause measurement error [8]. Commercial BPRs available in the market are complicated in design and to operate during the core flood experiments. The newly designed OBPR is easy to use, maintain, clean, and troubleshoot. The newly designed OBPR is an improved version of the predecessor OBPR model[6]. Old design uses the square wave oscillator to create oscillation, whereas this OBPR uses nitrogen in the flow system, which causes the feedback loop into the oscillation. This makes the nitrogen to act as a damper for avoiding large pressure fluctuations in the system. According to the literature review, the OBPR design is indistinguishable from another back pressure regulator in the market. The newly designed OBPR is only the adjustable active system in the market. It means that once the set point is given and it is actively controlling the pressure. OBPR automation design can regulate the pressure up to 9,500psi. The BPRs in the market is primarily are passive types. The active system of the OBPR automation is based on the PID LabVIEW design. Fig.1 illustrates a research flow diagram for the new OBPR design completed at the Hibernia EOR lab.

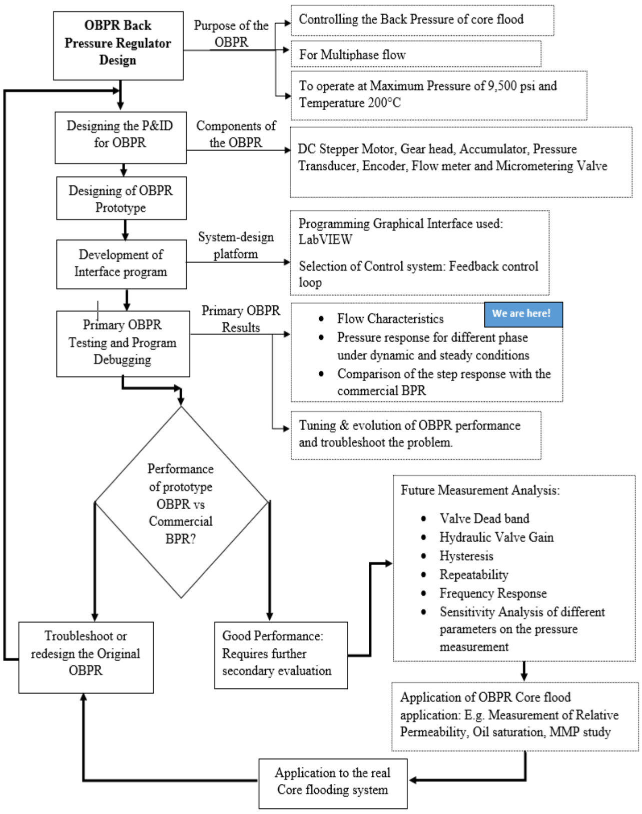

Figure 1a. OBPR Design Algorithm

Initial steps include understanding the desired operating conditions of the OBPR and construction and assembling the components into the OBPR prototype. The preliminary results obtained at the debugging level were used to compare the OBPR performance of the regulator to the commercial BPRs available in the market and to improve the original design. Preliminary results obtained during the initial run include the core outlet pressure response at different flow rates around 2000 psi, core outlet pressure at different pressure, and core outlet pressure response for the gaseous phase. Understanding the strengths and weaknesses of the OBPR feedback control system will improve its application to core flooding. Future work shown in the design algorithm includes a sensitivity analysis of different components affecting the control performance of the OBPR.

1.1 Back Pressure Regulators

Regulators are differ from control valves; generally, a control valve uses an external power system to control the process variable [3]. BPRs are self-actuating valves used for large and small-scale fluid flow experiments. BPRs are classified based on the mechanism (spring load, dome load, air load and diaphragm, etc.), construction material (steel and elastomer), type of fluid, and application. Selection criteria for a BPRs are based on the pressure and temperature operating conditions, accuracy and precision, piping sizing, and desired flow rate. Based on the design, the elementary regulator comprises three essential elements: restricting, sensing, and loading. Depending on the type of regulator, the downstream or upstream port communicates with the sensing element like a diaphragm, piston, and spring. All the regulators are self-powered and considered throttling valves as they modulate according to fluid or system pressure.

There are several types of regulators: pressure reducing, pressure relief, pressure switching, vacuum, etc. It is important to understand the BPRs and why it is different from other types of valves. Fluids are accumulated at the sampling point using manual, fractional or rotatory collectors used for the various displacement study, chemical analyses, which gives more details about the fluid-rock interaction within the core[10, 11]. BPRs can be used as a Low-Pressure Safety Relief Valve (SRV), but the primary goal of an SRV is to self-actuate and safeguard the equipment and life. An SRV only opens when the system's pressure exceeds the design pressure of the material [9]. It is also difficult to control fluid discharge flow through several SRV during blowdowns, making it an inappropriate choice for core flood experiments. The OBPR shown in Figure 2 was designed based on the feedback control system, which may provide a better result for the physical measurement for core flooding experiments. It allows a better pressure dynamic response and handling of for open and closed-loop controllers [10]. This paper focuses our discussion on the design, automation, and preliminary pressure response results of this new back pressure regulator.

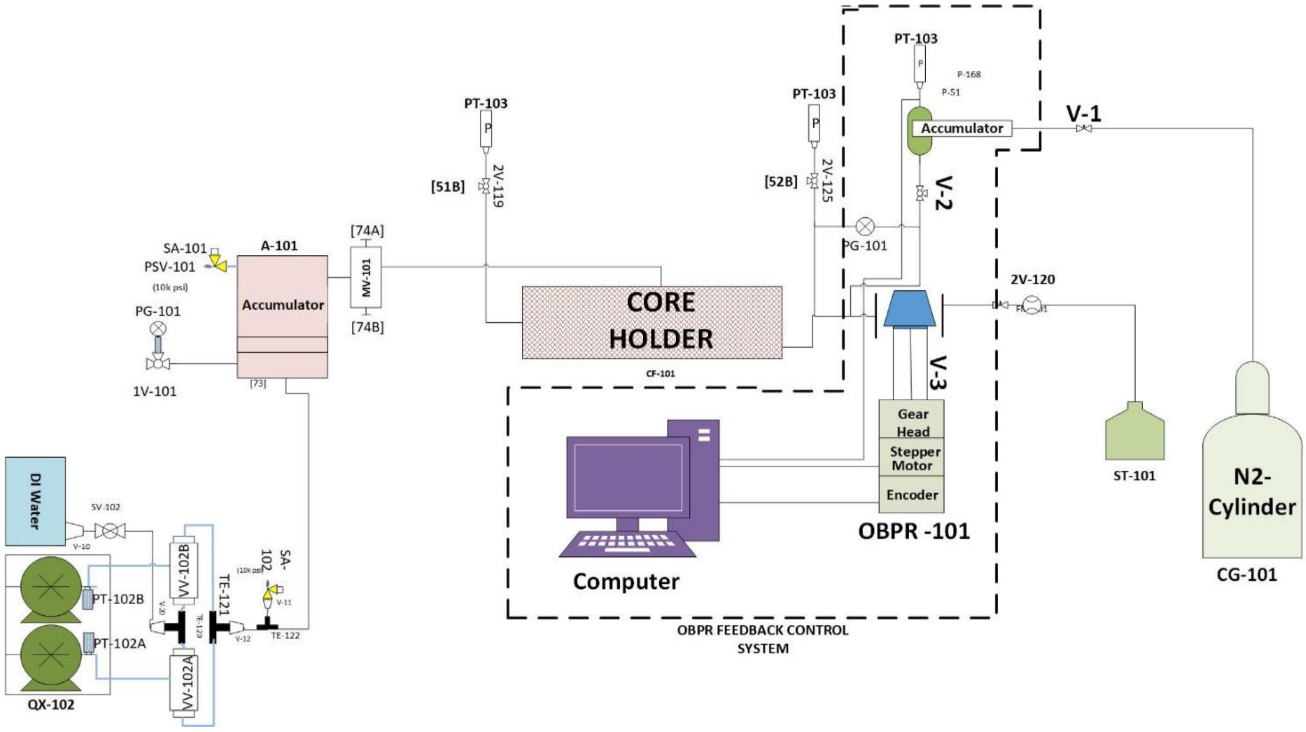

Fig 1b. Hibernia core flood experimental setup with newly OBPR feedback control system [13]

As shown in Figure. 1b, BPRs are generally employed at the downstream position of the core flooding experimental setup[11]. The core flooding assembly for this experiment was designed to conduct experiments with single-core plugs for water, Brine, and CO_2. The essential components of the setup are a hassler core holder, accumulators, Quizix pumps, quartz pressure sensor, flow meter, oscillating back pressure regulator (OBPR), and sample collector. The flooding system was designed to operate at 150 to 200°C, pore pressure of 9500 psi and overburdened pressure of 10000 psi. Water and brine were injected using the Quizix pump through the floating piston accumulator to the core holder inlet port. CO_2 was injected into the core holder using the booster pump. Core outlet pressure was maintained constant using the OBPR feedback control system, as shown in the dotted box of Fig 1b. Flowmeter was used to measure gas flow, and liquid manual measurement was performed using the standard graduated cylinder. A nitrogen gas tank is placed at the corner of the accumulator to use nitrogen gas as the pressuring gas for the OBPR operation. The biaxial core holder was used with no overburden pressure. Experiments were conducted from ambient conditions to 2000 psi pressure. The initial pressure of the sample core (sandstone core, length: 5.29 cm, diameter: 3.75 cm, area: 11.04 cm^2, total porosity: 16% sample obtained at a depth of 3862m of Hibernia formation, no overburden pressure) enclosed within in rubber sleeve. Core outlet pressure response was measured at 500, 1000 and 1500 psi. The core flood experiment was designed to understand the core outlet pressure response under static and dynamic conditions. Core outlet pressure response obtained from the OBPR was compare with the core outlet pressure response behavior of the commercial BPR.

1.2 Oscillating Back Pressure Regulator (OBPR) Design

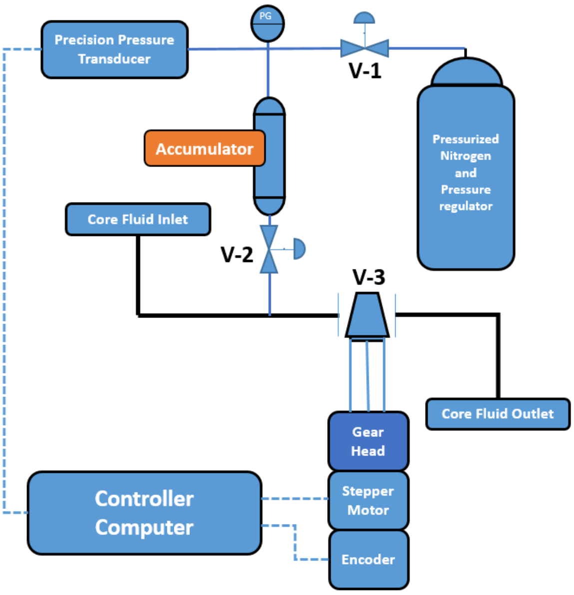

Fig 2. OBPR P&ID Instrumentation Diagram

The OBPR apparatus has been developed to control the backpressure of the core holders during the core flooding experiments and routine core analysis. Figure 2 represents a typical embodiment of the OBPR piping and instrumentation diagram. The OBPR consists of a precision needle valve (micro-metering valve), which is actuated by a high-resolution stepper motor (20,000 steps per revolution), to build up intended backpressure by restricting the flow area.

During the start of the experiment V-3 micro metering valve is closed, and the nitrogen has been charged while keeping the valve V-2 open. As the core fluid pump through the core holder, the pressure at the outlet increases through the line between the V-2 and V-3. The primary fluid enters the accumulator tube, which will increase the nitrogen pressure to the back pressure set point. As the desired back pressure is achieved, the V-3 starts to open and let the excess pressure down by letting some fluid flow out and closing the valve V-3 again to maintain the pressure. This open and close phenomena case at a particular valve location causes the oscillation hence the name of the valve, motor, and feedback control system is given as Oscillating Back Pressure Regulator. Once the desired set pressure is achieved, the flow rate is being controlled. The generated back pressure is measured by a precision pressure transducer, and the data is sent to a controller that sends commands to drive the stepper motor based on the processed data. The stepper motor actuates the stem of the needle valve by a gear head that increases the stepper motor torque and enhances the resolution. The LabVIEW program executes the controlling code using the National Instruments data acquisition system (model no NI PXle 8430/16).

1.3 OBPR Components and Assembly

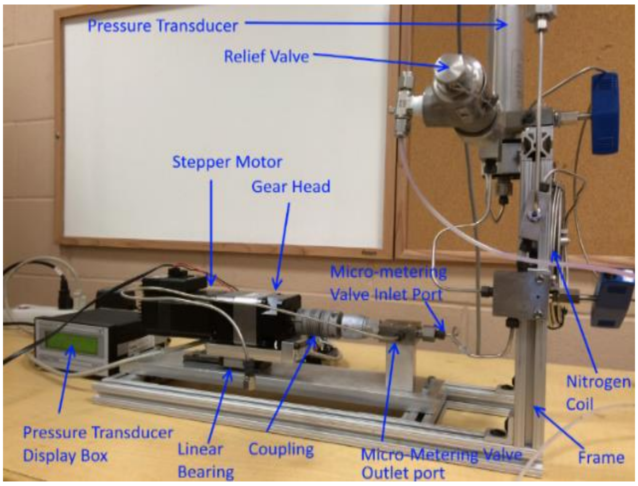

Fig. 3. Assembled OBPR Components

Figure 3 shows the assembled OBPR component. The motor power system provides electricity for the stepper motor. The gearhead is installed on the stepper motor shaft to increase torque and reduce motor speed (70:1). The gearhead shaft is connected to the valve stem using a precision coupling. The coupling should be disengaged when the valve positioning is implemented. The linear bearing is mounted beneath the motor since the motor moves back and forth by opening and closing the micro-metering valve. The micro-metering valve inlet (1/8" Autoclave Speed-bite) is connected to a flow line (e.g., the core holder outlet) to control its backpressure.

A tee and valve V-2 in Figure 2 connect the micro-metering valve inlet to the accumulator coil. The coil can be charged with nitrogen up to 10,000 PSIG with a pressurized gas cylinder or a gas booster. The set pressure must be 100 PSIG (50-150 psi is acceptable) lower than the intended backpressure. This causes the controller to keep the micro-metering valve closed before running and receiving any fluid from the core holder. Valve 2 can be opened when nitrogen charging is complete and valve 1 is closed. Valve 1 disconnects the nitrogen source from the coil accumulator. The pressure gauge and pressure transducer display box can read the coil pressure. The OBPR software also displays real-time pressure. The pressure relief valve provides additional safety for the relief of pressure in the case of OBPR failure. The relief valve cracking pressure is at 9500 PSIG. The OBPR valve can operate up to 5000 psi in a close position, but the maximum allowable pressure is 12,500 psi. The valve stem is not closed too tightly to guard the valve seat against getting damage. It is recommended to add an O-ring sealed check valve at the equipment outlet (e.g., core flood unit) to avoid backflow of pressurized nitrogen toward the equipment (e.g., core holder) due to any OBPR malfunction. In addition, using a diaphragm-type accumulator may avoid contact of fluid in the flow line and nitrogen in the coil. The composition of the oil will affect the calculation of the N_2 miscibility with the crude oil. Miscibility of N_2 is relatively high, especially 5000 to 6000 psi for an Alaskan oil[12]. As mentioned earlier, the core flooding experiments were performed with water, brine, and gas (CO_2).

1.4 OPBPR Operation Procedure

The needle valve is positioned in a near-closed condition to build up the intended back pressure inside an accumulator to create backpressure. The accumulator is a long 20ft coiled tube (0.125" OD, 0.04" ID) filled with nitrogen and positioned behind the micro-metering valve. Since pressurized nitrogen is compressible, it allows the core fluids to be charged or discharged in the coil. A higher motor speed reduces the time of the actuation of the system lag. However, it is recommended to set the rate at an intermediate value (e.g., 5 revs/sec) to avoid premature failure of the stepper motor. The pressure transducer at its standard mode provides high-quality pressure data (± 0.25 PSIG) within an acceptable period. The initial valve positioning will dramatically reduce the lag time of the valve operation. This will entirely minimize the time required to shut in a valve from its maximum opened position. The valve closed position should build up the pressure of 5000 PSIG when the core holder is flooded by water at the rate of 5 cc/hr. Although further tightening of the valve stem builds a higher pressure at low flow rates, it will damage the needle valve stem as the valve touches the seat every time it is fully closed. The valve has to be operated within a defined closed and opened position based on the feedback received from an encoder. One rotation of the valve stem is sufficient to increase the flow area for a low-pressure fluid discharge. The controlling parameters (proportional and derivative terms) must be set regarding the working conditions. An increase in the volume of the accumulator produces a smoother pressure profile. However, it increases the response time of the pressure transducer and the dead volume. The coil length is currently 20 ft (ID: 0.02"), leading to a magnitude of 1.2 ml. To run the OBPR, the following programs have to run by LabVIEW software. The required adjustments and commands must be executed in each program sequentially. In addition, the OBPR hardware has to be prepared to keep the backpressure at the desired value. The valve positioning is adjusted after the software LabVIEW adjustment before charging the accumulator with pressurized Nitrogen. In addition, the test script recommends a range of control parameters that the user can execute to obtain the desired back pressure profile. The OBPR performance is affected by different parameters and factors such as:

1. Speed and acceleration of the stepper motor
2. Accuracy of the pressure transducer data
3. Valve opened and closed positions
4. Controlling parameters
5. The volume of the accumulator
6. Pressure response

2 Automation Implementation

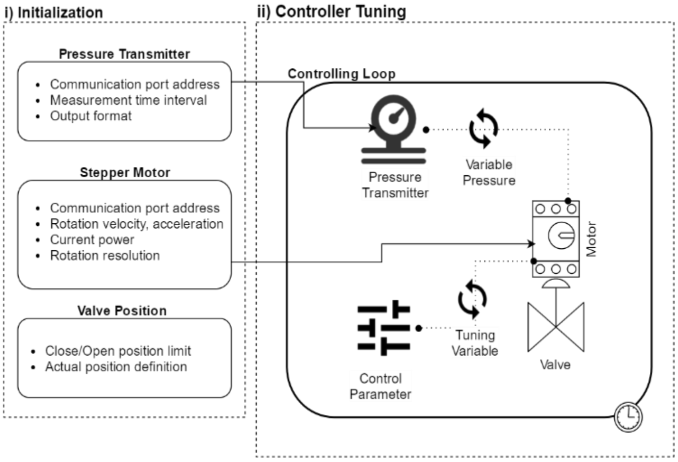

Fig. 4. OBPR Basic Layout Using LabVIEW

The design was automated using the LabVIEW program to make the system work smoothly, as shown in Figure 4. The feedback control system was developed to operate the OBPR. Application of the PID. (Proportional Integral Derivative) a controller can render optimal and robust performance for stable, unstable, and non-linear processes [15]. The programming platform used in this project is LabVIEW 2015, commercially offered by National Instruments, which has extensive application in the automation and instrumentation industries. The primary controlling code is compatible with the proposed mechanical setup (pressure transmitter and stepper motor) and provides open source for further upgrades. The logical algorithm is explained as shown in Figure 4. The overall process flow in this algorithm comprises two main steps; I) Initialization and II) Controller Tuning.

The earliest stage in initialization is to establish serial communication with active serial ports of the stepper motor and pressure sensor. The initialization task also includes the primary setting for the pressure sensor and stepper motor parts. As presented in Figure 4, the next phase is to adjust the controlling parameters determined in advance based on flowing phases, flow rate, and operating pressure. The initialization step can be broken into three subsections. First, the pressure sensor properties should be set into desired values. Second, the operation parameters of the stepper motor need to be adjusted before running the main controlling loop. Finally, the valve position, a mechanical part of the equipment, needs to be initially closed and appropriately connected to the motor shaft. After implementing these sequences, the primary controller LabVIEW program is ready to run and execute rotation commands to the motor port based on the pressure difference between set value and recorded value from the pressure sensor. The immediate critical information that constantly is needed through controlling time is the actual encoder and positions. Consequently, the calling program is used for requesting position data and sending it to PID.

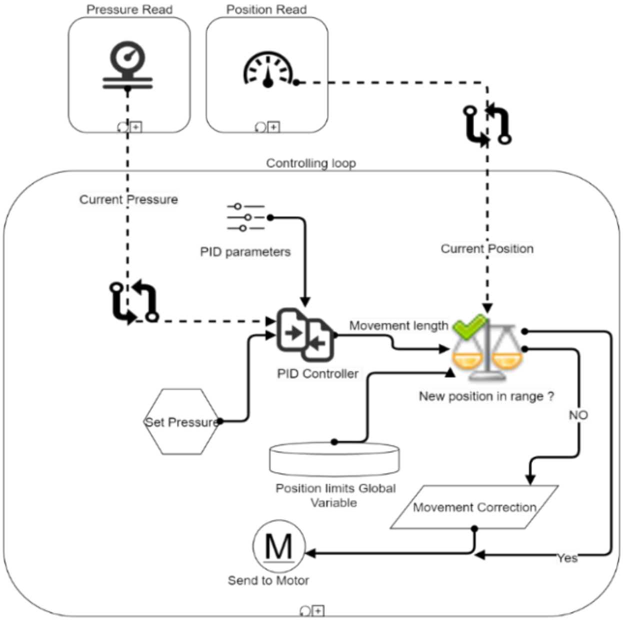

Fig. 5. OBPR Feedback Control System

Controller function Figure 5 shows the feedback control system design and its working mechanism. The initial stage of automation for this technique is to obtain the pressure information from the transducer and calculate the difference between the current. **Table 1.** Comparison of different commercial BPR model pressures and reference pressure. PID is used to calculate the proper response based on the pressure difference. Position and pressure variables are read from motor and pressure sensors and inserted into the LabVIEW control panel. The proportional, integral, and derivative terms are also adjustable in this front panel. Derivative of the pressure between two consecutive time steps is measured; it assists in creating controlling command over the stepper motor based on the differential pressure and derivative of the pressure. To correct maximum allowable displacement, the limit test is performed more or less like a trial and error to get the correct limit. The final valve position for the specific command is calculated to check if the valve position is still within the allowable range. Computed movement is then sent to the motor for execution. In the final step, the motor waits for the new pressure value

. 3 Commercial BPR.

Several studies use pressure response to analyze a regulator's performance [12, 13, 14, 15, 16, 17, 18]. To understand the initial pressure response of the OBPR, the model was compared with the pressure response of two commercial BPRs that are used for similar applications. Water, Brine, and CO_2 were chosen as the primary fluids for these experiments as they are commonly used for experimental studies in geology, oil recovery, and hydrogeology [19].

Table 1. Comparison of different commercial BPR models

BPR Model	**EBPR**	**VBPR**	**OBPR**
BPR Type	Metal Diaphragm	Piston	Metering valve
Max Temperature (ºC)	200	150	200
Max Pressure (psi)	10,000	10,000	9,500
BPR Material	SS316L	SS316L	SS316L
Flow coefficient	$1*10^{-09}$	$2.64*10^{-07}$	$1*10^{-04}$

Details of the two commercial BPRs, a diaphragm BPR and a piston dome-loaded BPR, are provided below and summarized in Table 1. The first commercial BPR used in the comparison is a dome-loaded diaphragm-based regulator (model: ULF EHP SB8) manufactured by Equilibar, referred to as EBPR. The bottom and top dome have O-rings with high-yield strain material that renders the liquid-tight seal. In the EBPR case, the elastomer material for the O-ring is stainless steel SS316L. Its sustainability at high pressure and temperature may also affect the regulator selection and internal flow pattern. The diaphragm is placed coplanar to the bottom of the dome surface. The choice of the diaphragm is essential in chosen based on the core flood experiments. The top dome (reference cap) has a reference fluid that can create uniform hydrostatic pressure over the diaphragm. When the process pressure exceeds the determined pressure, the diaphragm will lift, allowing the fluid to pass across the system.

The second commercial BPR used for the comparison is a needle valve-based BPR (model number C06-003-1), manufactured by Vinci Technologies and referred to as VBPR. It is comprised of two chambers, i.e., top and bottom chambers or dome. The bottom section consists of the needle enclosing the process fluid passage. When the bottom fluid pressure is higher than the top dome's reference pressure, the fluid's passage is open, or else it is closed. Uninterrupted flow is secured once the process and reference pressure equilibrium is attained. The newly developed OBPR feedback control system was used to study the regulator performance under dynamic and steady-state conditions. This is a preliminary study of the OBPR performance based on its design and pressure response. BPR models used for all the core flood systems have been subjected to the limited operating condition (~ up to 1500 psi) to analyze the initial functionality of the OBPR and to ensure safe working conditions. The initial pressure response of the OBPR is a BPR regulator for high-pressure core flood experiments is investigated. Before the experiments, it is necessary to ensure no leakage of the high-pressure fluid from the steam of the valves or the system. This can cause pressure loss resulting in measurement errors and malfunctioning of the valve. It is required to update the position of the stepper motor during the closing of the valve, as over-rotation of the valve handle can cause damage to the valve seating. Motor heating, power outage, or surge can increase or decrease the motor's torque ability, affecting the pressure response. LabVIEW program complications can also cause trouble in the experimental procedure. Measurement begins with the inspection of the reference pressure. Pressure measurement is continuously streamed on display rendering the real-time value of the pressure in the system. Measurement resolution is essential for this study since our pressure difference across the core holder is relatively low; it is best to use the IIR (infinite impulse response) nano-resolution filter device to report accurate pressure measurement up to 12 digits and acts as an effective in anti-aliasing. To make the stepper motor work properly, it was necessary to configure it or tune the motor. The stepper motor was initially disengaged from the gearhead coupling from the micro metering valve; the motor was also connected to the computer using an RS232 cable. Immediate and buffer types of commands were utilized through the LabVIEW program to communicate with the stepper motor. Critical parameters such as the maximum current, data format, velocity encoder ratio, encoder function, and motor ratio were initially set. The motor response was noted before it was connected for the actual experiment run. The metering valve was adjusted to the closed position to build up the pressure to 5000 PSIG. The position limit controller, which defines the incremental steps that the valve is turned for the maximum opening position (400,000 steps were optimal, sets the entire valve stem rotation at 0.56 turn), was switched on. Once the set position controller defines the current valve position, executes the run, it will communicate the motor and save the initial position of the micro metering valve when the system is at rest with no charge nitrogen flow, the PID. Constant value was input. Once the nitrogen begins to charge into the accumulator coil, the OBPR is set at the desired pressure value. The pressure source is removed once the system is ultimately charged with the Nitrogen. As the feedback control system detects the reference pressure, the gearhead rotates to set the new opening position of the micro metering valve. During the initial operation, the valve stem moves in an opening place, creating a sudden pressure drop in the system.

4. Results and Discussion

A feedback control approach was applied to the OBPR system consisting of a micro-metering valve, stepper motor, pressure transducer, and control architecture like PID. During initial experiments, the efficiency of the feedback control system must satisfied the primary goal of holding desired set backpressure under safe conditions. Future work might focus on the detailed studies of the feedback control system, cost, applicability to the multiphase system, and significant OBPR performance parameters. An ideal feedback control system must have zero steady-state error and constant stability throughout the performance. OBPR results are confined to a controlled variable (pressure response) offset and PID in this discussion. The set point value which was chosen to provide the suitable control performance for given operating conditions. The results show the application of OBPR at ultra-low flow rates initially and preliminary pressure response.

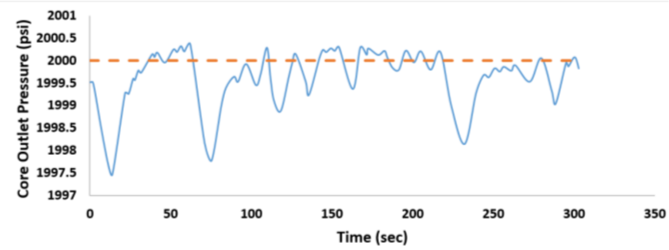

Fig. 6A. OBPR Pressure Response under 2000 psi with Maximum Fluctuation ±0.125% at 50 ml/hr (Primary Fluid: Water)

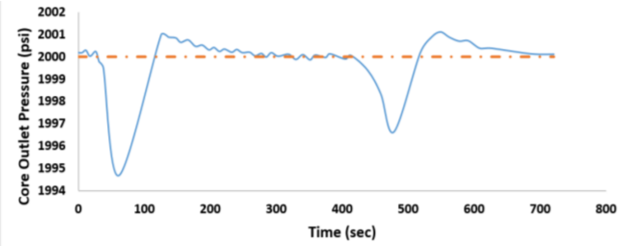

Fig. 6B. OBPR Pressure Response under 2000 psi with Maximum Fluctuation ±0.25% at 10 ml/hr (Primary Fluid: Water)

The OBPR outlet pressure response at different flow rates experiments was completed with water as the primary fluid and using two flow rates, 50 ml/hr (Figure 6A) and 10 ml/hr (Figure 6B). Figure 6A and 6B show the deviation of the core outlet pressure from the set point of the OBPR system that is 2000 psi. This can happen due to various types of elements present in the OBPR feedback control system, such as stem of the valve, pressure sensor, manual tuning, charging gas (nitrogen), stepper motor, gas pressure, etc. Disturbance or deviation seems to be non-periodic and looks like an approximated sine wave function. It is interesting to see that this disturbance frequency is too fast because of quick response from the stepper motor. Figure. 6 A and 6B shows a similar pressure response to the OBPR pressure response shown in Fig.7, but in these experiments, the primary fluid used in core flooding was water. Both the water system in Fig 6 A and B fluctuates around ±0.25% of the reference value. Figure 6B indicates a small number of fluctuations compared to the low volumetric flow rate. High flow rates might cause the system to respond more quickly to maintain the reference point pressure. Hence higher pressure fluctuation can be observed compared to a low flow rate. It was observed that OBPR feedback control system that response too quickly also results in poor performance. The amplitude ratio for the consecutive trough of the pressure response curve in Fig.6A and 6B declines as time progresses; it indicates that the OBPR feedback system reduces the steady-state error between the set point and control process variable. The decay ratio between the neighboring peaks was getting smaller for low flow rates compared to the high flow rate at the same pressure. This indicates that water testing with low flow rates at high pressure has a less settling time than high flow rates. This can cause the outlet core pressure response to reach a steady-state condition with reduced offset error. Fig. 6A & 6B both show the controlled variable overshoot which can cause the long-term degradation of valve.

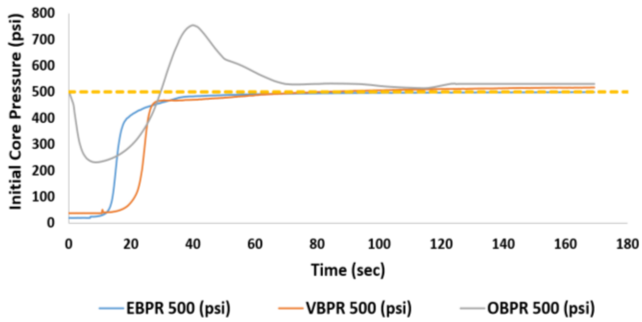

Fig. 7A. BPR Pressure Response for Single Phase Brine at 500 psi

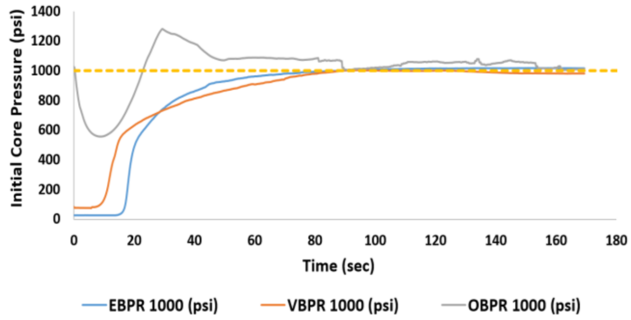

Fig. 7B. BPR Pressure Response for Single Phase Brine at 1000 psi

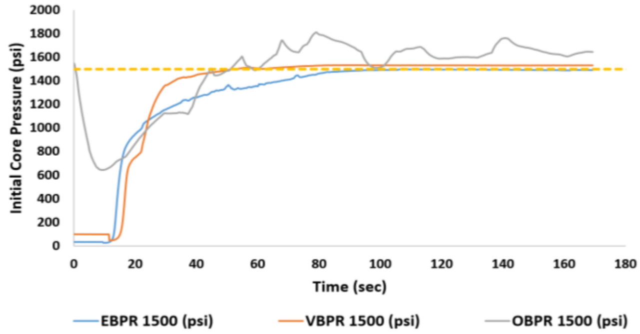

Fig. 7C. BPR Pressure Response for Single Phase Brine at 1500 psi

Dynamic pressure response from the two commercial BPRs (EBPR and VBPR) and the OBPR with initial core pressures of 500, 1000, and 1500 psi, using Brine, are shown in Figures 7A, 7B and 7C. A better understanding of the effects of pressure response dynamics can lead to a better design for the OBPR model with optimizing control and design improvement. The OBPR feedback control system is subjected to a step change disturbance, and the initially controlled pressure variable deviates for few seconds. This category is termed a step response. The pressure response vs time was graphed in Fig 7A, 7B & 7C. It can be seen from all the Fig.7 that the rise time for the OBPR pressure response varies for different pressure, Fig.7C have longest rise time. To judge the control performance of the OBPR with least disturbance, the volumetric flow was kept constant for all the pressure response. The sudden fall in the pressure for all the OBPR flow system at the early seconds of the operation is shown in Figures 7-A, B and C. Pressure drop can happen to overcome the lock-up conditions which require a fixed amount of torque to rotate the stem of the valve. Lock up is the no-flow state where the regulator has difficulty maintain the initial set pressure [20]. As the feedback control system regains, it re-adjusts the regulator opening position and runs to achieve desired reference value. From Fig. 7A, it is seen that settling time was quite less than another similar system because of the system less overshoot than other two. The core outlet pressure will start to build up and converge around the desired value making the motor run in an oscillatory mode compared to the square wave generator in the predecessor model. It can be observed that OBPR feedback adjustment had an immediate impact on the pressure variable for the initial period as compared to the VBPR and EBPR, which have dead time causing the controller to take action slowly or to get first-order delay response. OBPR feedback control system is quick and holds the least dead time. This can perform better than other BPRs designs for the step disturbance. The algorithm was used for the OBPR feedback control system to get better control performance. However, it can still result in excessive fluctuation or instability for the pressure variable. The final element that can also affect the stability and control performance is the valve. The OBPR pressure instability dampens over the period as the feedback control system approaches the steady-state pressure value. The settling time for the OBPR feed control system starts to get prolonged as the pressure increases due to high rise time—the proportional and integral mode of the PID. Controller tends to get the oscillatory and slow dynamic response. This slight pressure fluctuation can depends on various parameters, such as equilibrium condition between the inlet fluid and nitrogen pressure in the accumulator, regulator opening, PID. Value, phase of the primary fluid, stepper motor, and type BPR regulator. From Figure 7 A, B and C it can be seen that EBPR and VBPR show slow and stable dynamic responses compared to the OBPR. One of the reasons it might be that VBPR and EBPR are better self-regulating the disturbance and approach quickly to attain the desired set point. The sensing parameters (diaphragm and piston) are not significantly affected by the sudden decrease in the dome pressure. The core outlet pressure starts to build up due to restricting elements of the valve. The dome side was already pressurized EBPR and VBPR, causing slow fluid displacement and less pressure drop to cause the instability. In Fig.7 all the set points are represented in the dotted form to understand the system's dynamic and steady state response compared to a reference point. Every system has unique characteristics; the value of PID is obtained on the type of tuning methods. Manual tuning was done on the OBPR system, keeping the oscillation fluctuation at constant amplitude. The stepper motor also adds, such as oscillation or unstable phenomena to overall OBPR feedback control system [21]. It can be observed from Figure 7 that the OBPR is unstable (overshoot) during the initial phase of the operation of the system. This overshoot problem could be resolved with a better PID tuning method. The experimental results illustrated in Figure 7 help us understand the pressure's dynamic response compared to the market's commercial BPRs.

To understand the OBPR performance on a gaseous core flood system, experiments were completed using CO_2 as the primary fluid. Figure 8 shows the steady-state pressure response to the gaseous system. A higher oscillation rate is observed compared to the water and brine systems.

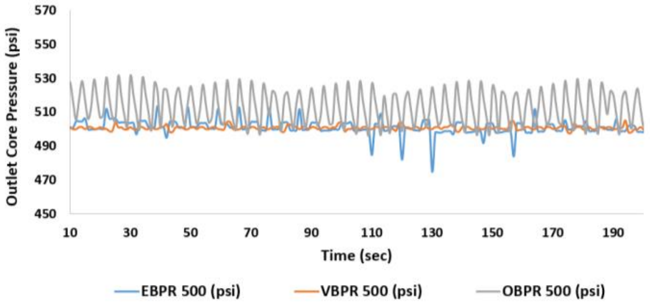

Fig. 8. BPR Pressure Response with Single Phase Gaseous CO_2

The OBPR pressure response was observed to be quick for the gaseous system, and a more periodic disturbance is kept for the OBPR than the commercial BPRs. The PID was designed to reduce the error signal fixing the PID gain and will not reduce the noise signal. This noise signal may arise from the booster pump that is used to pressurize the core holder. Along with this noise fluctuation, the OBPR was able to maintain the steady pressure with ±50 psi. The OBPR will render limitations for close measurement applications with such high delta P across. A more experimental study is required to check the performance of the OBPR for the gaseous system.

The conventional core flood experiment was designed to understand the OBPR feedback control response behavior under static and dynamic conditions. The core outlet pressure response obtained from the OBPR was compared with the core outlet pressure response behavior of the commercial BPR. The pressure fluctuation in the outlet pressure impact the comparison test result for the three BPR, if the OBPR pressure response is compared to the commercial BPR response, it can clearly be seen that the OBPR pressure fluctuation are unstable and respond aggressively to step input disturbance compared to the other two BPR. These fluctuations in OBPR feedback control system are caused by various types of elements present in the OBPR model, such as the stem of the valve, pressure sensor, manual tuning, stepper motor, charging gas, primary fluid pressure, etc. All the dynamic responses for three different BPRs were recorded under uniform test conditions except at different pressure. For the high permeable core sample, this small fluctuation can be impactful, but the all the initial experiments were plan to test the preliminary design of the OBPR model and its ability to achieve the desired set backpressure value. This fluctuation also affects the accuracy characteristics of the instrument to measure the core outlet pressure response. Even though the systematic error is reduced, there still will be some inherent errors in the instrument design. Core outlet pressure was measured with $\pm 0.25\%$ of the setpoint value. These are good initial results. The number of replicates for each experiment was around three or more. There might be a chance of precision error due to analyzing the sets of pressure measurement data for several experiments. It was found that core outlet measurements were reproducible and nearly consistent for desired set point until the tuning parameters were affected. Especially in gas phase, the OBPR system can measure the outlet core pressure response with the tolerance of around $\pm 6\%$ of the original pressure. All the core outlet pressure measurements were only valid under the controlled condition of pressure and temperature. Any variation in the ambient temperature can change the sensitivity for pressure measurement. It's better to ignore such systematic and statistical random error at the initial stage of the designing and testing process.

5. Conclusions

A newly designed oscillating back pressure regulator model for core flood analysis was developed. An experimental study was undertaken to understand the pressure response of the OBPR using different core flood experiments. The OBPR was tested in three fluid flow scenarios using brine, water and CO_2. Results included are the dynamic and steady-state response of the pressure. The OBPR was found to have a faster response than the EBPR and VBPR for the gas and brine systems. The OBPR took some time to achieve the steady-state compared to the EBPR and VBPR for the liquid system. The OBPR was found to suffer from instability in pressure response compared to the commercial regulators. It can also be concluded that the OBPR feedback control performance was assessed based on the magnitude of the step input. The results from the OBPR and comparison with different commercial BPR show that this device can respond well to liquid. More experimental investigation is needed for gas phase system. OBPR system can hold the backpressure similar to another commercial device for core flood application.

6. Future works:

The OBPR requires more rigorous experimental study before applying it successfully to the core flood application. Some of the future works include to:

a. Evaluate the OBPR feedback control performance at maximum pressure up to 9,500 psi to and high temperature.

b. Improve the feedback control system to reduce the pressure offset and instability.

c. Test the OBPR on different gases and multiphase flow systems.

d. Use the diaphragm accumulator or floating piston type accumulator to avoid mixing of nitrogen with the primary core fluid such as brine, water, gas and oil.

e. Perform the sensitivity analysis of different parameter on the OBPR feedback control performance.

f. Tune the OBPR using the first principle and to use the Mat lab Simulink."

g. Develop other embodiments for the accurately controlling of the flow and pressure eliminating the comingle of Nitrogen with the process fluids.

h. Implement the well-developed OBPR design to measure the physical parameter for core flood applications such as Relative Permeability.

The authors would like to thank Chevron Canada, Hibernia Management and Development (HMDC), Department of Tourism, Culture Industry and Innovation (TCII), Natural Sciences and Engineering Research Council of Canada (NSERC) for funding my research project. Thanks are extended to Equilibar and Vinci Technologies for providing their BPR for our research study.

References

1 F. Torabi, B. Yadali Jamaloei, S. Y. Hong, and N. K. Bakhsh, "Improving downhole pump efficiency and well productivity in heavy oil reservoirs utilizing back pressure regulator," *J. Pet. Explor. Prod. Technol.*, vol. 2, no. 4, pp. 181–195, (2012).

2 L. T. Vo, R. Gupta, and O. J. Hehmeyer, "Ion Chromatography Analysis of Advanced Ion Management Carbonate Coreflood Experiments," no. Ic, (2012).

3 A. Shokrollahi, M. H. Ghazanfari, and A. Badakhshan, "Application of foam floods for enhancing heavy oil recovery through stability analysis and core flood experiments," *Can. J. Chem. Eng.*, vol. 92, no. 11, pp. 1975–1987, (2014).

4 S. J. Varjani and V. N. Upasani, "Core Flood study for enhanced oil recovery through ex-situ bioaugmentation with thermo- and halo-tolerant rhamnolipid produced by Pseudomonas aeruginosa NCIM 5514," *Bioresour. Technol.*, vol. 220, pp. 175–182, (2016).

5 L. D. Connell, R. Sander, Z. Pan, M. Camilleri, and D. Heryanto, "History matching of enhanced coal bed methane laboratory core flood tests," *Int. J. Coal Geol.*, vol. 87, no. 2, pp. 128–138, (2011).

6 W. O. Lease and C. F. Van Egmond, "Oscillating Backpressure Regulator for Low Flow Rate, High-Pressure Coreflooding Experiments.," *Soc. Pet. Eng. J.*, vol. 22, no. 6, pp. 899–901, (1982).

7 T. J. Hughes, A. Honari, B. F. Graham, A. S. Chauhan, M. L. Johns, and E. F. May, "CO_2 sequestration for enhanced gas recovery: New measurements of supercritical CO 2-CH 4 dispersion in porous media and a review of recent research," *Int. J. Greenh. Gas Control*, vol. 9, pp. 457–468, (2012).

8 K. Mannhardt and I. Svorstøl, "Effect of oil saturation on foam propagation in Snorre reservoir core," *J. Pet. Sci. Eng.*, vol. 23, no. 3–4, pp. 189–200, (1999).

9 A. P. Spence and R. W. Watkins, "Effect of Microscopic Core Heterogeneity on Miscible Flood Residual Oil Saturation.," *Soc. Pet. Eng. AIME, SPE*, (1980).

10 R. J. Hwang and J. Ortiz, "Effect of CO_2 flood on geochemistry of McElroy oil," *Org. Geochem.*, vol. 29, no. 1-3–3 pt 1, pp. 485–503, (1998).

11 M. Hellemans, "Overpressure protection," *Saf. Reli. valve Handb. Des. use Process Saf. valves to ASME Int. codes Stand.*, no. 1st edition, pp. 327–434, (2009).

12 A. Morar, "Stepper Motor Model for Dynamic Simulation," *Acta Electroteh.*, vol. 44, no. 2, pp. 117–122, (2003).

13 R. A. Nasralla and H. A. Nasr-El-Din, "Coreflood study of low salinity water injection in sandstone reservoirs," *Soc. Pet. Eng. - SPE/DGS Saudi Arab. Sect. Tech. Symp. Exhib. 2011*, no. May, pp. 187–199, (2018).

14 H. M. Sebastian and D. D. Lawrence, "Nitrogen minimum miscibility pressures," *Eighth Symp. Enhanc. Oil Recover.*, pp. 299–310, (1992).

15 V. Rajinikanth and K. Latha, "Tuning and Retuning of PID Controller for Unstable Systems Using Evolutionary Algorithm," *ISRN Chem. Eng.*, vol. 2012, pp. 1–11, (2012).

16 M. Mutlu, T. Wassar, M. A. Franchek, and J. A. Gutierrez, "Condition and performance analysis of a subsea BOP control system pressure regulator," *Proc. Annu. Offshore Technol. Conf.*, vol. 2, pp. 1193–1203, (2018).

17 R. El Golli *et al.*, "Modelling of a pressure regulator To cite this version : HAL Id : hal-01845776," vol. 84, no. 4, pp. 234–243, (2018).

18 B. Delenne, L. Mode, and M. Blaudez, "Modelling and simulation of a gas pressure regulator," in *European simulation symposium. Erlangen, Germany*, (1999).

19 H. Ott *et al.*, "Core-flood experiment for transport of reactive fluids in rocks," *Rev. Sci. Instrum.*, vol. 83, no. 8, (2012).

20 Bill Menz, "Pressure Regulator Selection Strategy," *Swagelok*, no. August, 2011

21 Pickup, I. E. D., and A. P. Russell, "Dynamic instability in permanent-magnet synchronous/stepping motors.," *IEE Proc. B (Electric Power Appl.*, vol. 134, no. 2, pp. 91–100, (1987)