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# Unveiling the Hydrodynamic of Fluid Flow: Revolutionizing Research in Petroleum Production Systems Through Innovative Multiphase Flowloop Design

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## Abstract
This study details the design of a multiphase flowloop that integrates the entire petroleum production system into a single facility. It utilizes the "fluid flow pentagon" concept, focusing on five key elements: Fluid, Geometry, Condition, Flow, and Instruments. Based on a global review of flowloops, this high-pressure-high-temperature (HPHT) flowloop supports research in flow assurance, oilfield chemistry, drilling, and fracturing. It simulates real field conditions with advanced instrumentation and flexible configuration, making it ideal for testing flow meters, chemical inhibitors, drag reduction, emulsions, separator internals, and artificial lift equipment. This facility, one of the best globally, is a unique asset in the Middle East, providing a premier environment for hydrodynamic studies and setting new standards for flowloop facilities worldwide.

## Keywords
Multiphase; Petroleum Production System; HPHT; Flowloop; Pentagon

## Introduction
Multiphase flow, involving the simultaneous movement of different phases in pipelines, is crucial for oil and gas industries, power plants, and chemical plants. It impacts flow assurance, especially under high-pressure and temperature conditions. Understanding multiphase flow is challenging, necessitating experiments to explore its characteristics. Various flowloops are used globally for studying gas-water-oil flow, hydrates, corrosion inhibitors, drag-reducing agents, phase separation, foaming, and more.

Research on multiphase flow spans multiple disciplines—physics, mathematics, and engineering (mechanical, nuclear, chemical, civil, petroleum, environmental, aerospace)—investigating different flow scenarios under various conditions. While numerous flowloops exist, each has limitations in replicating all real field conditions due to variations in pressure, temperature, fluids, flow regimes, and pipe configurations. This paper presents a critical review of multiphase flowloops worldwide, highlighting each facility's strengths and limitations in reproducing and monitoring different multiphase flow situations. The review underscores the need for these flowloops in fundamental and applied petroleum production research. Despite numerous flowloops addressing specific petroleum production problems, technical constraints such as dimension, pressure, temperature, and fluid type limit their usage. Multiphase flow, encountered in wells, flow lines, risers, and multiphase flow lines, presents significant challenges due to the simultaneous presence of different phases and compounds. Combining empirical observations with numerical modeling has enhanced the understanding of multiphase flow. Traditional models based on empirical correlations for hold-up and pressure gradient have evolved into multi-fluid models requiring closure relationships for interface and pipe wall friction. Experimental measurements are essential to complement theoretical efforts and verify these models, hence the existence of numerous multiphase flowloops globally. A review of major facilities worldwide is presented in Table 1 [1].

Table 1: A brief list of the flowloops in academic and industry institution worldwide

| Worldwide Flowloop | Reference |
|---|---|
| TUFFP1 (Tulsa), US | [2] |
| TUFFP1 (Tulsa), US | [2] |
| SwRI (South West Research Institute), US | [3] |
| CEESI 1 (Colorado Engineering Experiment Station, Inc.), US | [4] |
| CEESI 2 (Colorado Engineering Experiment Station, Inc.), US | [5] |
| TAMU1 (Texas A&M University), US | [6] |
| CSM (Colorado school of Mines), US | [7] |
| NFL (Memorial University of Newfoundland), CA | [8] |
| SINTEF*(SINTEF Petroleum Research), NO | [9] |
| IFE, NO | [10] |
| K-Lab (Statoil), NO | [11] |

| | |
|---|---|
| Atalaia (Petrobras), BR | [12] |
| Trecate (ENI), I | [13] |
| IFP (Institut Français du petrole), FR | [14] |
| NEL (National Engineering Laboratory), UK | [14] |
| CRAN (Cranfield University), UK | [15] |
| BHRA (BHR Group Limited), UK | [16] |
| ICL (Imperial College London), UK | [17] |
| WASP (Imperial College London), UK | [18] |
| ITE (Petroleum Engineering Institute of TU Clausthal), DE | [19] |
| MPC (Middle East Technical University), TR | [20] |
| SHELL (Rijswijk), NL | [21] |

Flowloops worldwide have specialized capabilities, often limiting their broader research use. For instance, the University of Tulsa has loops for cutting transport, foam flow, and multiphase characterization, while SwRI focuses on testing services. Norwegian loops excel in large-scale multiphase studies, IFP in separation technology, and institutions like Colorado School of Mines and CSIRO in gas hydrates. Many facilities need modern upgrades.
In the Middle East, flowloops for flow assurance are rare despite the region's oil and gas dependence. To address this, King Fahd University's College of Petroleum Engineering and Geosciences is creating a cutting-edge HPHT multiphase flowloop in Dhahran. This facility, guided by the 'Fluid Pentagon' framework, will support comprehensive research in oil field chemistry, corrosion, drilling, and flow assurance.

## Methodology

A review of flowloops for flow assurance studies highlights several key areas:
**Facility Design and Operation:** Effective flowloops must replicate field conditions, including HPHT capabilities, to mimic real-world scenarios.
**Multiphase Flow Behavior:** Research focuses on different flow regimes, such as slug and annular flow, providing insights into flow patterns and pressure drops.
**Hydrate Formation and Prevention:** Studies examine hydrate formation, inhibitors, and mitigation strategies to manage risk in production systems.
**Wax Deposition and Mitigation:** Investigations address wax deposition rates, mechanisms, and the effectiveness of inhibitors to prevent flowline blockages.
**Asphaltene Deposition and Remediation:** Research explores asphaltene deposition and the efficacy of additives and mechanical methods for remediation.
**Corrosion and Erosion:** Flowloops are used to study corrosion and erosion, evaluate inhibitors, and develop predictive models for asset integrity.
**Flow Assurance Modeling and Simulation:** Combining flowloop data with CFD modeling enhances predictive capabilities and optimizes production systems.

The development of a flowloop facility around the 'Pentagon of Fluid Flow' concept integrates five key elements—Fluid, Geometry, Condition, Flow, and Instruments—into a multiphase flowloop that replicates field conditions. This comprehensive approach ensures flexibility for various research needs in oil field chemistry, corrosion, drilling, stimulation, and flow assurance.

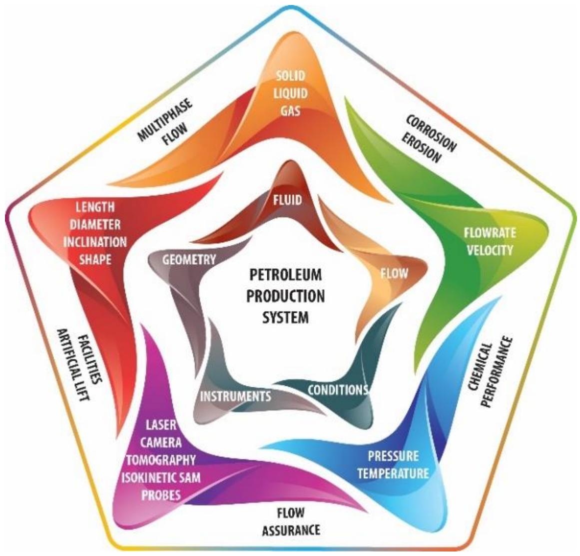

Figure 1: The pentagon of fluid flow and its five elements.

Defining the five elements of the pentagon is crucial for achieving the flowloop facility's objectives: advancing research in multiphase flow modeling and flow assurance, generating experimental data for various flow models (e.g., oil-water-gas, oil-water-solids), and studying flow assurance issues like wax, paraffin, asphaltene, and hydrate deposition. The facility focuses on multiphase flow modeling, deposition hydrodynamics, wellbore and pipeline simulation, chemical treatments, $CO_2$ corrosion, and erosion. While no single flowloop can cover all these areas, the facility aims to address most by developing two types of flowloops: a large-diameter HPHT multiphase flowloop and a small-diameter HPHT and HPLT flowloop. The facility's experimental conditions range from 0-1500 psi, −12 to 180°C, pipeline diameters of 1 to 4 inches, inclinations of 0-90°, and flow velocities of 3 to 15 m/s, simulating real field operations.

The fifth element, instruments, enables real-time measurement and control of flow rate, pressure, and temperature using advanced technologies such as Laser Doppler Anemometry, Particle Imaging Velocimetry, and high-speed visualization.

These tools provide critical insights into physical phenomena and research challenges. The fluid element, crucial to the facility, supports experiments with real field samples, accommodating all phases (solid, liquid, gas) and various combinations, including hydrocarbon oils, water compositions, chemicals, emulsions, and gases like $N_2$, air, $CO_2$, and methane.

## Results and Discussion

Based on the concept of the fluid flow pentagon and its five elements, a unique facility for facilitating research in several domains of petroleum engineering has been established. Table 2 shows the different configurations and capabilities of the HPHT multiphase flowloop facility, developed using the fluid flow pentagon concept and its five elements.

Table 2: Different configuration and capabilities of the HPHT multiphase flowloop facility

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Flowloop / Parameters | 4" Inclinable Loop | 4" Acrylic Loop | 4" Erosion Loop | 4" Long Loop | 1" HPHT Loop | 1" HPLT Loop |
| Pressure | 500 psi /35 bar | 50 psi /3.5 bar | 50 psi /3.5 bar | 500 psi /35 bar | 1500 psi /100 bar | 1500 psi /100 bar |
| Temperature | 120 ºC | 27 ºC | 27 ºC | 120 ºC | 180 ºC | -12 ºC |
| $V_{Liq}$ | 3 m/sec | 3 m/sec | 3 m/sec | 3 m/sec | 3 m/sec | 3 m/sec |
| $V_{Gas}$ | 15 m/sec | 15 m/sec | 15 m/sec | 15 m/sec | 15 m/sec | 15 m/sec |
| Material | 316 S.S. | Acrylic | Acrylic | 316 S.S. | 316 S.S./Sapphire | 316 S.S./Sapphire |
| Length | 5.3 m | 4.9 m | 4.6 m | 13.2 m | NA | NA |
| Pipe ID | 4"/0.1 m | 4"/0.1 m | 4"/0.1 m | 4"/0.1 m | 1"/0.025 m | 1"/0.025 m |
| Oil | Yes | Yes | Yes | Yes | Yes | Yes |
| Water | Yes | Yes | Yes | Yes | Yes | Yes |
| $CO_2$ | Yes | Yes | No | Yes | Yes | Yes |
| Methane | No | No | No | No | Yes | Yes |
| Nitrogen | Yes | Yes | Yes | Yes | Yes | Yes |

The HPHT multiphase flowloop facility consists of six different flowloops. However, it is important to note that these six flowloops are divided into only two groups: the 4-inch flowloops and the 1-inch flowloops. The design of the 4-inch facility is shown in Figures 2, with a snapshot of the 4-inch facility provided in Figure 3.

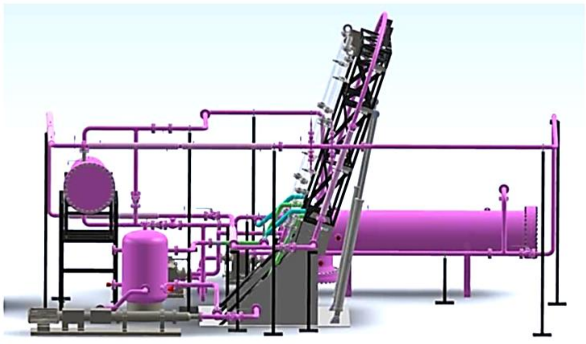

Figure 2: 4-inch flowloop facility

Figure 3: Picture of 4-inch flowloop facility

Flowloops 1-4 are 4-inch loops, while loops 5 and 6 are 1-inch loops.

**4-Inch Group:**
**Flowloop 1:** Inclinable from 0° to 90°, made of stainless steel, with a 5.3-meter test section, operating at up to 500 psi and 120°C, handling oil, water, $CO_2$, and $N_2$.
**Flowloop 2:** Made of acrylic for fluid visualization, operating at 50 psi and 27°C.
**Flowloop 3:** Similar to Flowloop 2, but also handles solids for erosion and transport studies.
**Flowloop 4:** Similar to Flowloop 1 but with a longer 13.2-meter test section, fixed in a horizontal position.

**1-Inch Group:**
**Flowloops 5 and 6:** Made of stainless steel (316 SS), designed for extreme conditions, handling up to 1500 psi and temperatures from -12°C to 180°C. They offer horizontal and vertical flow configurations, with sapphire glass sections for visualization, and are suitable for studying paraffin, asphaltenes, hydrates, and scale. Equipped with safety features, these loops handle water, oil, hydrocarbon gases, and chemicals, supporting multiphase flow with velocities up to 3 m/s for liquids and 15 m/s for gases.

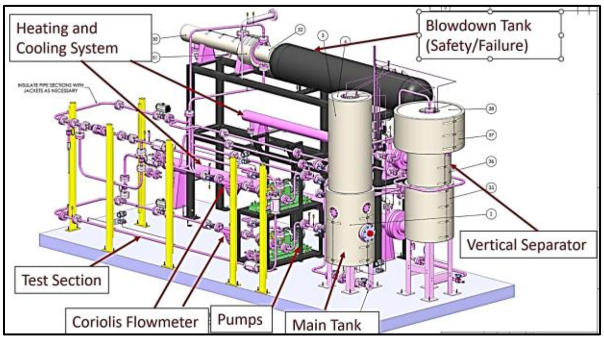


Figure 4: 1-inch flowloop facility

Advanced instrumentation is vital for understanding fluid flow in pipes. Transparent pipes allow visualization but can't handle high-pressure, high-temperature (HPHT) conditions, while HPHT materials restrict visibility. To address this, the facility includes state-of-the-art tools like Laser Doppler Anemometry (LDA), Particle Image Velocimetry (PIV), Multiphase Tomography, and others. This setup supports research in multiphase flow, flow assurance, chemical treatments, solid transport, corrosion, and erosion.

The flowloop, designed around the Pentagon of Fluid Flow concept, replicates real field conditions, offering adaptability for various research and testing needs, such as flow meters, chemical inhibitors, and artificial lift equipment, making it a unique HPHT multiphase flowloop for comprehensive production system studies.

## Conclusions

King Fahd University of Petroleum and Minerals (KFUPM) is a leading institute in the Middle East, recently establishing the College of Petroleum Engineering and Geosciences. This college focuses on cutting-edge research in oil field chemistry, corrosion, drilling, stimulation, fracturing, and flow assurance. The newly developed flowloop facility, based on the Pentagon of Fluid Flow concept, is one of the world's best, featuring advanced instrumentation and flexible configurations. It addresses key flow assurance challenges in the oil and gas industry and supports research into gas flow assurance, including natural gas, $CO_2$, and hydrogen. Future plans aim to enhance the facility's capabilities for hydrogen gas transportation.

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## Responsibility Notice

The authors are the only responsible for the paper content.

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