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Design of a Swab Cup Running Tool to Reduce Fluid Bypass during Liquid Swabbing Operations in Dual Size Tubing Completion Oil and Gas Wells

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ABSTRACT - Swabbing is a liquid unloading method used in the oil and gas industry to reduce hydrostatic pressure caused by fluid accumulation in the wellbore. In wells with dual-size tubing completions (4.5-inch and 3.5-inch), tubing diameter transitions can reduce Swab Cup sealing performance, causing fluid bypass and lowering lifting efficiency. This study develops a modified Swab Cup Carrier and swab mandrel to support continuous fluid lifting in dual-size tubing completions. An engineering design research approach was applied, including field problem identification, conceptual design, Computer-Aided Design (CAD), Finite Element Analysis (FEA), prototype development, tubing simulation, and functional evaluation. The proposed design incorporates a cam-guided release-and-carry mechanism that enables the Swab Cup Carrier to release at the tubing X-over during Run In Hole and reconnect during Pull Out of Hole. FEA of AISI 4130 alloy steel showed a maximum von Mises stress of 278.6 MPa, below the material yield strength of 460 MPa, indicating adequate structural safety. Prototype testing using a PVC tubing simulation verified the proposed mechanism. The design has the potential to minimise fluid bypass, maintain lifting continuity, and improve swabbing effectiveness in dual-size tubing completions. Further laboratory and field validation is required to confirm its operational performance.

Keywords: swabbing, swab cup carrier, dual-size tubing completion.

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1. Introduction

In the oil and gas industry, sustained well production is highly dependent on the ability of reservoir fluids to flow continuously to the surface. As producing fields mature, reservoir pressure commonly declines, which may lead to the accumulation of liquids within the production tubing. This condition is referred to as liquid loading, in which liquids such as water, condensate, or oil accumulate in the wellbore and increase the hydrostatic pressure acting against the reservoir.

As oil and gas fields mature, declining reservoir pressure and deteriorating well performance often require appropriate production optimization and well intervention strategies to sustain or restore hydrocarbon production. [Turnip et al. \(2024\)](#) demonstrated the importance of systematic well candidate selection for matrix acidizing in mature fields, where appropriate stimulation candidates can provide significant production improvement. [Maurenza et al. \(2023\)](#) further showed that changes in the production system, particularly the installation of artificial lift, can influence well production performance and the predicted productive life of the well. In addition, [Hamzah et al. \(2021\)](#) evaluated hydraulic-fractured well performance using empirical correlations and machine-learning approaches, highlighting the importance of systematic performance evaluation in supporting well candidate selection and production enhancement. Collectively, these studies indicate that maintaining production from mature wells requires intervention strategies that are selected according to specific well conditions and dominant production constraints. In wells experiencing liquid accumulation, one of the key operational constraints is the increasing hydrostatic pressure inside the tubing, which may restrict reservoir inflow and eventually lead to production decline or cessation.

Liquid accumulation increases back pressure on the reservoir, reduces hydrocarbon deliverability, and may eventually cause the well to stop producing if it is not properly mitigated. [Lea et al. \(2003\)](#) described liquid loading as one of the major causes of production performance decline in mature wells, particularly in low-pressure gas wells. Similarly, [Lea et al. \(2003\)](#) emphasized that liquid accumulation in the tubing can disturb flow stability and significantly reduce well productivity. One of the widely applied methods for mitigating liquid loading is liquid unloading through swabbing operations. Swabbing is a mechanical well intervention method used to lift accumulated fluids from the wellbore by means of a Swab Cup conveyed on wireline, either slickline or braidedline. The fundamental principle of this method is to reduce the hydrostatic pressure inside the tubing, thereby creating an underbalanced condition that enables reservoir fluids to resume flowing to the surface.

[Bourgoyne et al. \(1991\)](#) stated that swabbing is commonly applied in low-pressure wells because of its operational flexibility and relatively lower cost compared with other liquid unloading methods. In line with this, [Saputra et al. \(2022\)](#) reported that several wells in mature fields with depleted reservoir pressure require continuous liquid unloading before gas production can be restored. In certain applications, periodic dewatering is performed using rig-less intervention techniques, such as coiled tubing operations or slickline swab jobs.

The success of swabbing operations is highly dependent on the ability of the Swab Cup to maintain sealing contact against the tubing wall during the fluid-lifting process. In wells with single size tubing completion, swabbing operations are relatively stable because the tubing diameter remains uniform along the operating path, allowing continuous contact between the Swab Cup and the tubing wall to be maintained. However, in wells with dual size tubing completion, changes in tubing diameter may become a technical constraint that reduces swabbing effectiveness. [Lyons and Plisga \(2004\)](#) explained that variations in tubing geometry can affect the interaction between intervention tools and the tubing wall, particularly in terms of mechanical contact and flow stability. [Economides et al. \(1994\)](#) also stated that changes in production conduit dimensions may influence differential pressure stability during fluid lifting, thereby potentially reducing operational efficiency.

This problem was observed during swabbing operations in Oil and Gas Field X, particularly in wells with a 4.5-inch and 3.5-inch dual size tubing configuration. Based on preliminary observations of operational conditions, when the Swab Cup moves from the 3.5-inch tubing into the 4.5-inch tubing, sealing loss occurs due to the change in tubing diameter. This condition allows the lifted fluid to bypass through the clearance between the Swab Cup and the tubing wall and subsequently fall back into the lower section of the well. As a result, the liquid unloading target becomes difficult to achieve optimally, the number of swabbing runs may increase, and the overall operation time becomes longer. This issue indicates that conventional Swab Cup designs, which are

generally intended for uniform tubing diameters, are not fully capable of accommodating operational requirements in dual size tubing completion.

Although numerous studies have addressed liquid unloading methods, swabbing operations, and well intervention optimization, studies specifically focusing on the development of Swab Cup designs for dual size tubing completion applications remain limited. Most existing discussions emphasize unloading method selection, production evaluation after intervention, or operational aspects of swabbing units. Meanwhile, the design of Swab Cup components capable of adapting to tubing diameter transitions has not been extensively investigated. This gap indicates the need to develop a Swab Cup design that can accommodate changes in tubing diameter and reduce the potential for fluid bypass during swabbing operations.

Based on these conditions, this study aims to develop a modified Swab Cup design concept incorporating a cam groove and a cam-guided release-and-carry mechanism for the 4.5-inch Swab Cup in dual size tubing completion applications. During Run in Hole, the 4.5-inch and 3.5-inch Swab Cups are lowered simultaneously as part of a single tool assembly. The 4.5-inch Swab Cup Carrier is designed to be released and temporarily positioned at the X-over area, while the 3.5-inch Swab Cup continues moving downward to reach the liquid level to be swabbed. During Pull Out of Hole, the 3.5-inch Swab Cup lifts fluid from the lower tubing section. When the assembly passes through the transition from the 3.5-inch tubing to the 4.5-inch tubing, the fluid-lifting function is then continued by the 4.5-inch Swab Cup. Through this mechanism, sealing contact between the Swab Cup and the tubing wall is expected to be maintained up to the surface, thereby improving the effectiveness of liquid lifting.

This study focuses on the design stage using an engineering design approach, including problem identification, evaluation of existing design limitations, development of the modified design concept, and analysis of the proposed working mechanism. The results of this study are expected to provide a basis for developing an adaptive Swab Cup Carrier for swabbing operations in dual size tubing completion and serve as a reference for further studies involving numerical simulation, prototype fabrication, and field testing.

2. Methodology

2.1 Research approach

This study was conducted through a sequential engineering design research approach, consisting of problem identification, evaluation of the existing design, conceptual design development, computer-aided design (CAD) modelling, finite element analysis (FEA), prototype development, mock-up tubing testing, and analysis of the proposed working mechanism.

2.2 Problem identification

Problem identification was carried out through a review of swabbing operation reports, well diagrams, and observations of operations performed in wells with dual size tubing completion. The initial stage of the study focused on evaluating swabbing operations in Field X, particularly wells with a combined completion configuration consisting of 3.5-inch tubing in the lower section and 4.5-inch tubing in the upper section. Based on the operational review, fluid bypass was frequently observed when the Swab Cup passed through the tubing diameter transition area. This condition is associated with the loss of sealing contact between the Swab Cup and the tubing wall as the tool moves across the X-over section. The well configuration with 4.5-inch and 3.5-inch tubing is illustrated in [Figure 1](#), while the mechanism of fluid bypass when the 3.5-inch Swab Cup enters the 4.5-inch tubing section is illustrated in [Figure 2](#). This condition resulted in several operational consequences, including loss of sealing integrity, reduced fluid-lifting efficiency, an increased number of swabbing runs, and failure to meet the targeted liquid-unloading performance. These operational issues were subsequently used as the basis for developing a new design concept.

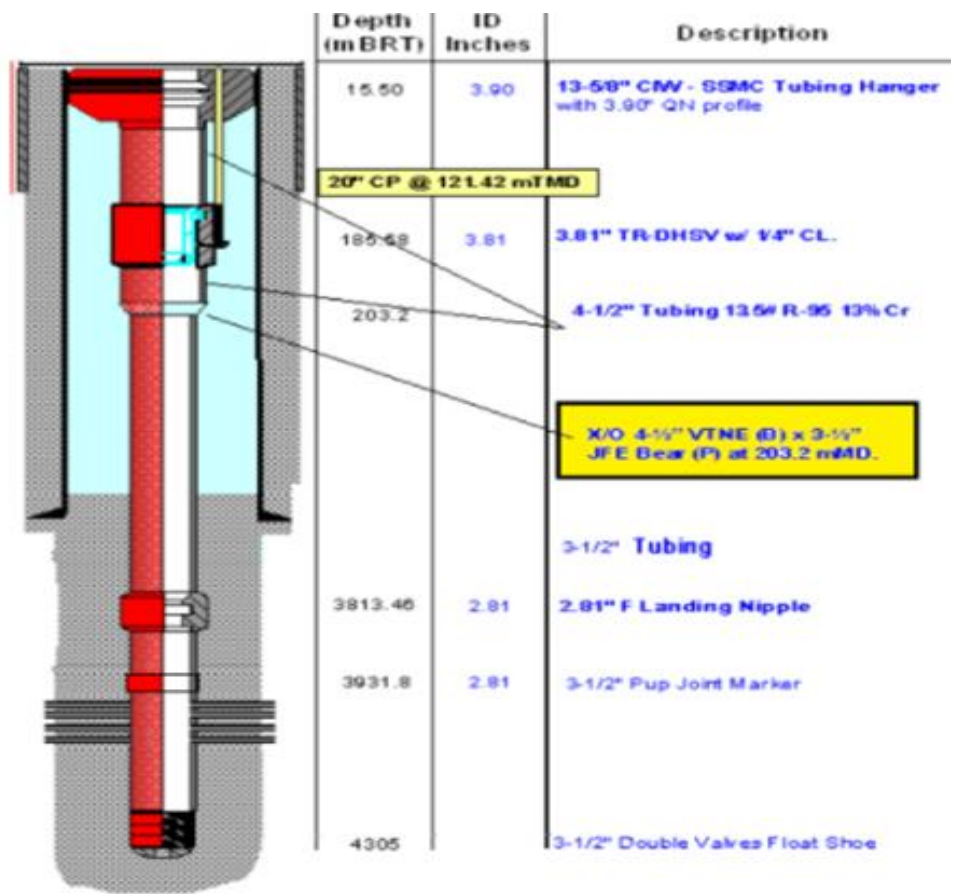


Figure 1.
Schematic well configuration showing the 4.5-inch tubing in the upper section, the 3.5-inch tubing in the lower section, and the X-over connecting the two tubing sizes.

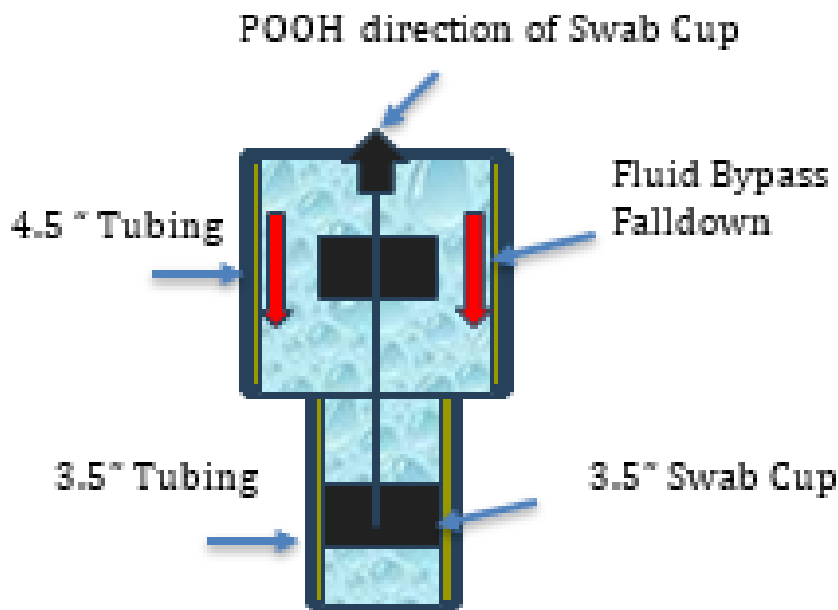


Figure 2.
Schematic illustration of fluid bypass when a 3.5-inch Swab Cup enters the 4.5-inch tubing section during Pull Out of Hole. The clearance between the Swab Cup and the tubing wall allows part of the lifted fluid to flow downward.

2.3 Evaluation of the existing swab cup design

The evaluation of the existing design was conducted on conventional Swab Cups commonly used in swabbing operations for wells with single size tubing completion. In this configuration, one Swab Cup size is specifically selected for one tubing size. A 3.5-inch Swab Cup is used in wells or intervals equipped with 3.5-inch tubing, whereas a 4.5-inch Swab Cup is used in 4.5-inch tubing. Therefore, each Swab Cup is designed to operate within a relatively uniform tubing diameter along its operating path.

A conventional Swab Cup generally consists of an elastomeric sealing element mounted on a mandrel and designed to establish sealing contact against the inner wall of the tubing. During the Pull Out of Hole operation, the pressure differential between the lower and upper sides of the Swab Cup causes the elastomeric element to expand and press against the tubing wall, thereby enabling the fluid to be lifted toward the surface. The effectiveness of this mechanism is highly dependent on the dimensional compatibility between the outer diameter of the Swab Cup and the inner diameter of the tubing.

The existing design does not incorporate a cam groove, guide pin, or cam-guided release-and-carry mechanism. Consequently, the Swab Cup can only operate effectively within tubing sizes that correspond to its designed dimensions. A 3.5-inch Swab Cup is unable to maintain adequate sealing when entering a 4.5-inch tubing section because a clearance is formed between the sealing element and the tubing wall. Conversely, a 4.5-inch Swab Cup cannot be run through a 3.5-inch tubing section because its outer diameter exceeds the available internal tubing clearance.

The evaluation of the existing design focused on the geometry and dimensions of the Swab Cup, sealing mechanism, elastomer deformation capability, compatibility with the tubing inner diameter, and tool response when approaching the transition area or X-over. The analysis also considered the potential occurrence of fluid bypass caused by the loss of sealing contact when the 3.5-inch Swab Cup moves from the smaller-diameter tubing into the 4.5-inch tubing section. The primary limitation of the existing design is the absence of a mechanism that enables the automatic transfer of the fluid-lifting function between the 3.5-inch Swab Cup and the 4.5-inch Swab Cup within a single operating assembly. This limitation makes the conventional design less suitable for direct application in wells with dual size tubing completion. The analysis of these limitations was subsequently used as the basis for developing a modified Swab Cup Carrier and swab mandrel design incorporating a cam-guided release-and-carry mechanism.

2.4 Design concept development

The design development was carried out through a design modification approach applied to the conventional Swab Cup system. The proposed concept is intended for wells with a dual size tubing completion configuration, consisting of 4.5-inch tubing in the upper section and 3.5-inch tubing in the lower section. The design integrates a 3.5-inch Swab Cup and a 4.5-inch Swab Cup within a single operating assembly, enabling the fluid-lifting process to be performed sequentially according to the tubing size encountered along the operating path.

During the Run In Hole stage, the 4.5-inch Swab Cup and the 3.5-inch Swab Cup are lowered simultaneously as part of one tool assembly. The 4.5-inch Swab Cup Carrier is designed to reach the release position and remain temporarily retained at the X-over area between the 4.5-inch and 3.5-inch tubing sections. Meanwhile, the swab mandrel and the 3.5-inch Swab Cup are allowed to continue moving downward toward the lower section of the fluid column to be lifted.

During the Pull Out of Hole stage, the 3.5-inch Swab Cup functions as the initial lifting element, lifting fluid from the lower tubing section toward the transition area. As the assembly moves from the 3.5-inch tubing section into the 4.5-inch tubing section, the swab mandrel re-engages with the 4.5-inch Swab Cup Carrier. Subsequently, the Swab Cup Carrier reaches the carry position and is pulled together with the assembly, allowing the 4.5-inch Swab Cup to continue lifting fluid through the upper tubing section toward the surface.

The main design modification involves the incorporation of a cam groove on the Swab Cup Carrier and a guide pin mechanism on the swab mandrel. The cam groove functions as a controlled guide path for the pin movement

to regulate the transition of the mechanism between the release and carry positions. During Run in Hole, the interaction between the cam groove and the guide pin is designed to release the 4.5-inch Swab Cup Carrier at the X-over area. During Pull Out of Hole, the same interaction is designed to reconnect the Swab Cup Carrier with the swab mandrel so that it can be retrieved to the surface. Based on the identified operational limitations and the required transfer of the fluid-lifting function across the tubing transition, the proposed design was formulated according to the following key functional requirements:

- The use of two Swab Cup sizes within a single operating assembly
- The use of the 3.5-inch Swab Cup as the initial lifting element in the lower tubing section
- The use of the 4.5-inch Swab Cup as the subsequent lifting element in the upper tubing section
- The implementation of a cam-guided release-and-carry mechanism to control the release and retrieval of the Swab Cup Carrier
- The maintenance of sealing continuity according to the corresponding tubing diameter
- The reduction of potential fluid bypass at the tubing diameter transition area.

The critical design point is located at the X-over area, where the tubing diameter changes and the fluid-lifting function is transferred from the 3.5-inch Swab Cup to the 4.5-inch Swab Cup. Therefore, the design concept was focused on the cam groove geometry, guide pin trajectory, component clearance and tolerances, stability of the release and carry positions, and the ability of the system to operate repeatedly without disrupting the sealing function of each Swab Cup. This concept was subsequently evaluated through CAD modelling, FEA-based stress analysis, prototype development, and working mechanism simulation using a mock-up tubing model.

Table 1.
Main Modelling Parameters of the Swab Cup Carrier and Swab Mandrel.

Parameter	Value/Specification
Completion configuration	Dual size tubing completion
Lower tubing section	3.5 inches
Upper tubing section	4.5 inches
Swab Cup size	3.5 inches and 4.5 inches
Design focus	4.5-inch Swab Cup Carrier
Main components	Ring, main body, cam groove, guide pin, and swab mandrel
Ring outer diameter	Ø3.3000 inches
Ring thread diameter	Ø2.3200 inches
Ring length	1.2000 inches
Main swab mandrel diameter	Ø2.3200 inches
Main swab mandrel length	8.2000 inches
Swab Cup Carrier length	5.5200 inches
Carrier connection thread diameter	Ø2.600 inches
Number of cam grooves	Two pairs
Cam groove configuration	180° symmetrical arrangement
Cam groove path radius	R1.000 inches and R1.750 inches
Mechanism system	Cam-guided release-and-carry
Swab Cup Carrier and swab mandrel material	AISI 4130 alloy steel
Sealing material	Nitrile Butadiene Rubber (NBR)
Fabrication method	CNC machining
General tolerance	±0.001 inches
Modelling software	SolidWorks

2.5 Software and data reproducibility

The three-dimensional models of the Swab Cup Carrier and swab mandrel were developed using SolidWorks 2023 software, while the structural analysis was performed using SolidWorks Simulation 2023. The principal geometric parameters, material specifications, and dimensional requirements used in the design are provided in Table 1 to facilitate reproduction of the proposed configuration. The Swab Cup Carrier and swab mandrel were specified using AISI 4130 alloy steel, whereas Nitrile Butadiene Rubber (NBR) was specified for the sealing element.

The prototype used for preliminary functional verification was fabricated using a Creality K1 Max 3D printer with PLA+ filament. Functional testing was conducted using a simplified mock-up consisting of 4-inch and 3-inch PVC pipes representing the inside diameter transition between the upper and lower tubing sections. The prototype and mock-up testing were intended to evaluate component fit, guide-pin movement, and the release-and-carry sequence rather than actual downhole structural or sealing performance.

The operational information used for problem identification was derived from swabbing operation reports, well diagrams, and field observations. These data were used to define the engineering problem and design requirements. The geometric parameters, working mechanism, material assumptions, and simulation approach required to reproduce the engineering design are reported in this manuscript. Further reproducibility of the structural and operational performance will require validation using actual engineering materials, representative pressure and temperature conditions, and field-scale testing.

2.6 Computer-aided design (CAD) modelling

The design modelling of the Swab Cup Carrier and swab mandrel was performed using Computer-Aided Design (CAD) software. The modelling process aimed to generate a three-dimensional geometry that represents the interrelationship between components, the cam groove trajectory, pin position, inter-component clearances, and the overall configuration of the cam-guided release-and-carry mechanism.

The model was developed for application in wells with a dual size tubing completion configuration, consisting of nominal 4.5-inch tubing in the upper section and nominal 3.5-inch tubing in the lower section. In the modelling process, the nominal tubing size was not directly used as the working diameter. The actual tubing inner diameter must be determined based on the tubing specifications, including nominal size, weight per unit length, grade, and wall thickness. These parameters were used to ensure the dimensional compatibility of the Swab Cup, Swab Cup Carrier, and swab mandrel with the available internal tubing clearance.

The sealing design employs two different Swab Cup sizes. The 3.5-inch Swab Cup is used for fluid lifting in the lower tubing section, whereas the 4.5-inch Swab Cup is used to continue fluid lifting in the upper tubing section. Therefore, the sealing element is not designed as a single adaptive component capable of accommodating both tubing sizes. Instead, each Swab Cup operates according to its corresponding tubing diameter.

The main modification in the CAD model was applied to the 4.5-inch Swab Cup Carrier by incorporating two pairs of cam grooves arranged in an opposing configuration with 180° symmetry. The cam groove functions as a guided path for the pin on the swab mandrel to regulate the transition between the release and carry positions. The modelling parameters included the cam groove path length, groove depth, path radius, fillet radius, pin diameter, inter-component clearance, and the principal dimensions of the Swab Cup Carrier and swab mandrel.

The actual design material for the Swab Cup Carrier and swab mandrel was specified as AISI 4130 alloy steel, while the sealing element was specified as nitrile butadiene rubber (NBR). The resulting CAD model was subsequently used as the basis for stress analysis using Finite Element Analysis, prototype fabrication by 3D printing, and the preparation of technical drawings for fabrication using Computer Numerical Control machining.

2.7 Finite element analysis (FEA)-based stress analysis

Stress analysis was performed using the Finite Element Analysis (FEA) method with SolidWorks Simulation 2023 software. This analysis aimed to evaluate the structural response of the Swab Cup Carrier and swab mandrel

design under the static loading conditions defined in the simulation. Particular attention was given to the cam groove, guide pin area, and other geometric transitions that may induce stress concentration during the operation of the cam-guided release-and-carry mechanism.

The three-dimensional model developed during the Computer-Aided Design stage was used as the base geometry for the simulation. The material assigned to the model was AISI 4130 alloy steel. The material properties used in the simulation included density, elastic modulus, Poisson's ratio, yield strength, and ultimate tensile strength, based on the material data adopted in this study.

The simulation procedure included material assignment, contact condition definition, fixture or boundary condition application, load application, mesh generation, solving process, and result evaluation. The mesh was used to discretize the geometry into smaller elements so that the stress response could be numerically calculated. Mesh refinement was directed toward the cam groove, guide pin area, fillets, and other regions with relatively sharp geometric transitions.

The primary parameter evaluated in this analysis was the equivalent von Mises stress. The maximum stress obtained from the simulation was compared with the material yield strength to assess the potential for plastic deformation. In addition, the stress distribution and the locations of stress concentration were examined to identify design areas requiring further evaluation or refinement.

The structural evaluation criterion was established based on the requirement that the maximum von Mises stress should remain below the material yield strength under the simulated loading condition. When required, the factor of safety was calculated as the ratio between the material yield strength and the maximum von Mises stress. This analysis was used as a preliminary structural evaluation and was not intended to replace strength testing under actual downhole pressure, temperature, fatigue, corrosion, and dynamic loading conditions.

3. Result and discussion

3.1 Problem analysis and evaluation of the existing design

Swabbing operations are among the liquid unloading methods widely applied in oil and gas wells to reduce hydrostatic pressure caused by fluid accumulation inside the tubing. The success of this operation is strongly influenced by the ability of the Swab Cup system to maintain sealing contact against the tubing wall, thereby enabling fluids to be effectively lifted to the surface. According to, the effectiveness of unloading methods is highly dependent on the ability of the equipment to maintain differential pressure during the fluid-lifting process. Loss of differential pressure due to leakage or fluid bypass may reduce operational efficiency and prevent the unloading target from being achieved.

- Analysis of swabbing operation problems in dual size tubing completion

In Field X, the main operational problem was identified in wells with a dual size tubing completion configuration using a combination of 3.5-inch and 4.5-inch tubing. Based on the evaluation of previous swabbing operations, fluid bypass occurred when the Swab Cup moved through the tubing diameter transition area. Under this condition, the contact between the sealing element and the tubing wall decreased, allowing part of the lifted fluid to flow back downward through the clearance formed between the Swab Cup and the tubing wall.

This condition reduced the effectiveness of swabbing operations and potentially increased the number of swabbing runs, overall operating time, and well intervention costs. The problem indicates that the currently used Swab Cup design still has limitations in accommodating significant tubing diameter changes. Therefore, design development is required to improve the geometric adaptability of the Swab Cup system for dual size tubing completion applications.

- Evaluation of the existing swab cup design

The existing design currently used in swabbing operations in Field X consists of a cylindrical main body equipped with multiple elastomer layers that function as sealing elements. This geometry is designed to

generate contact pressure against the tubing wall, thereby forming a sealed chamber that enables fluid to be displaced toward the surface during the pulling process.

Based on the technical drawing shown in Figure 3, the existing design has a relatively simple construction, with a multi-lip elastomer configuration arranged along the outer section of the body. This type of design is commonly used in conventional swabbing operations because it is relatively easy to manufacture and has a comparatively low fabrication cost. According to Ash-Shidiq and Suhartanto (2025), conventional Swab Cups remain a key component in various well unloading operations due to their simple design and ease of field implementation.

However, the existing design was developed for tubing conditions with a relatively uniform diameter. In dual size tubing completion applications, the change in tubing diameter causes the contact pressure distribution between the Swab Cup and the tubing wall to become non-uniform. Consequently, the sealing capability may decrease when the tool passes through the tubing diameter transition area. This condition is consistent with the explanation of Lyons and Plisga (2004), who stated that changes in production conduit geometry can affect the effectiveness of contact between intervention tools and the tubing wall, thereby increasing the risk of fluid isolation loss during operation.

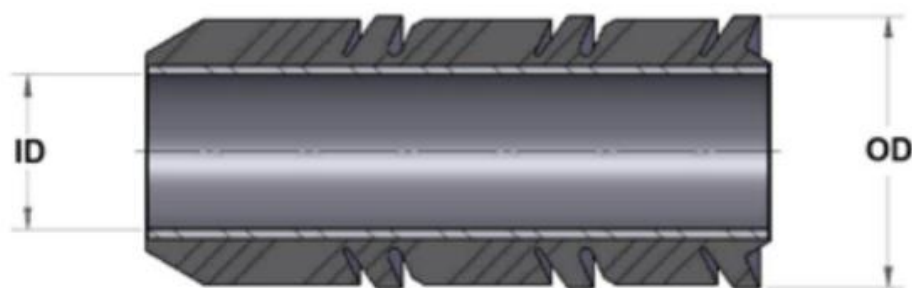


Figure 3.

Cross-sectional configuration of a conventional multi-lip Swab Cup, illustrating the inner diameter (ID), outer diameter (OD), and elastomeric sealing lips used for single-size tubing applications (adapted from CANAM Pipe & Supply 2018).

3.2 Results of the modified design development

Based on the problem identification and evaluation of the existing design, a modified system was developed by integrating a 4.5-inch Swab Cup Carrier and a swab mandrel for dual size tubing completion applications. The design incorporates a cam-guided release-and-carry mechanism, which enables the Swab Cup Carrier to be temporarily released at the X-over area during Run in Hole and reconnected during Pull Out of Hole. The design development involved geometric modifications to the Swab Cup Carrier, swab mandrel, cam groove, and guide pin to support the transfer of the fluid-lifting function from the 3.5-inch Swab Cup to the 4.5-inch Swab Cup.

Based on the problems identified during swabbing operations in wells with dual size tubing completion, this study developed a modified Swab Cup Carrier design concept intended to improve the adaptability of the tool to changes in tubing diameter. The well configuration considered in this study consists of 4.5-inch tubing in the upper section and 3.5-inch tubing in the lower section. Therefore, a swabbing system capable of maintaining liquid-lifting continuity across the tubing diameter transition area is required.

The developed design does not only function as a Swab Cup holder, but also serves as an integral part of the cam-guided release-and-carry mechanism. This mechanism enables the 4.5-inch Swab Cup to be lowered together with the 3.5-inch Swab Cup during Run In Hole and subsequently positioned or temporarily retained at the X-over area between the 4.5-inch and 3.5-inch tubing sections. Meanwhile, the 3.5-inch Swab Cup remains able to continue moving downward until it reaches the lower section of the liquid column to be swabbed.

During Pull Out of Hole, the 3.5-inch Swab Cup functions to lift liquid from the lower 3.5-inch tubing section. When the 3.5-inch Swab Cup passes through the X-over area from the 3.5-inch tubing into the 4.5-inch tubing section, the liquid-lifting process is then continued by the 4.5-inch Swab Cup. Accordingly, the 4.5-inch Swab Cup Carrier acts as a continuation system for liquid lifting in the upper tubing section up to the surface. This concept is intended to maintain sealing continuity, reduce the potential for fluid bypass, and improve liquid-lifting effectiveness in wells with dual size tubing completion.

Geometrically, the modified Swab Cup Carrier design consists of several main components, namely the ring, main body, cam groove, and cam follower pin, which are integrated into a single mechanical system. The primary modification was applied to the holder section by incorporating a cam groove that forms several mechanical operating segments. Unlike the existing design, which does not include a cam groove for this mechanical operation, the proposed design uses the cam groove as an additional mechanical feature that enables the tool to respond through a leave-and-carry sequence when it is run downward, reaches the transition between the 4.5-inch and 3.5-inch tubing sections, is temporarily retained at the X-over area, and is subsequently retrieved during Pull Out of Hole.

The cam groove functions as a guided trajectory for the pin, a positional control feature for the release and carry states, and a mechanical interface governing the engagement between the Swab Cup Carrier and the swab mandrel. The cam groove is designed to guide the pin movement and control the positional transition of the Swab Cup Carrier between the release and carry conditions. The sealing function remains provided by the 4.5-inch Swab Cup element, which operates according to the inner diameter of the upper tubing section. Through the integrated configuration of the 4.5-inch Swab Cup, Swab Cup Carrier, and swab mandrel, the sealing area is expected to maintain contact with the tubing wall, particularly during the diameter transition from the 3.5-inch tubing section into the 4.5-inch tubing section.

This concept was developed based on the principle of adaptive sealing, defined in this study as the capability of a mechanical system to maintain its sealing function despite dimensional changes in the operating environment. In this context, adaptive sealing is implemented through the combination of cam groove geometry and the leave-and-carry mechanism, enabling the 4.5-inch Swab Cup to accommodate the tubing diameter transition and maintain continuous liquid-lifting functionality. Budynas and Nisbett (2020) stated that systems incorporating flexible elements generally exhibit better adaptability to geometric variations because such elements can distribute stress and contact pressure more uniformly.

Table 2.
Comparison Between the Existing Design and the Modified Design

Aspect	Existing design	Modified design
Swab Cup configuration	One Swab Cup size for one tubing size	Two Swab Cup sizes integrated within a single assembly
Transfer lifting mechanism	Not available	Transfer from the 3.5-inch Swab Cup to the 4.5-inch Swab Cup
Cam groove	Not available	Available
Release-and-carry mechanism	Not available	Available
Capability to pass through the X-over	Limited	Designed for dual size tubing completion
Risk of fluid bypass	High at the transition area	Potentially lower
Application	Single size tubing completion	Dual size tubing completion

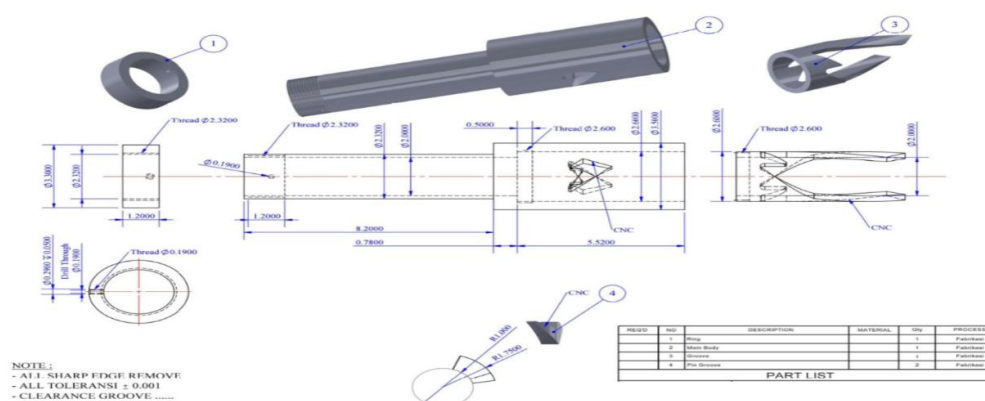


Figure 4.

Modified 4.5-inch Swab Cup Carrier consist of Upper Ring, Main Body, Pin Groove and Pin groove stopper, all are incorporating the cam groove and guide-pin mechanism for release and reconnection at the tubing X-over. (Authors' CAD model enveloped using SolidWorks).

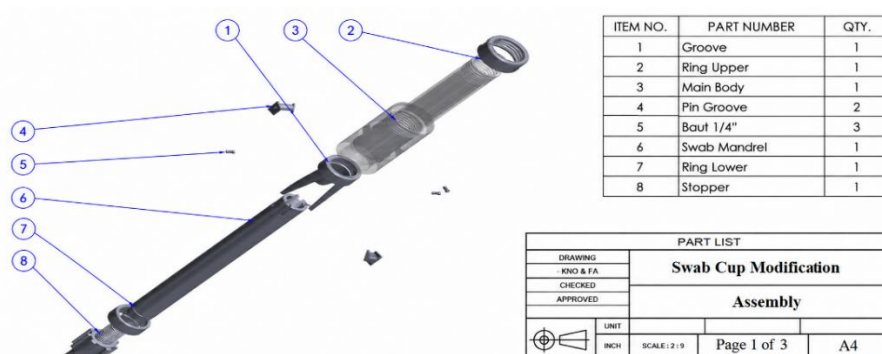


Figure 5.

Three-dimensional view of the modified Swab Cup Running Tool assembly, consisting of the Swab Cup Carrier, swab mandrel, ring, cam groove, and guide-pin mechanism. (Authors' CAD model developed using SolidWorks).

In addition to the cam groove, the design is also equipped with a cam groove pin that functions as a guiding and positional control element for the Swab Cup as it follows the cam groove trajectory. This component is designed to regulate the movement pattern of the Swab Cup Carrier so that it operates in accordance with the intended mechanism, in which the Swab Cup remains temporarily retained during downward movement and is subsequently carried upward during retrieval as the assembly passes through the X-over between the 4.5-inch and 3.5-inch tubing sections.

The tool is also designed to ensure safe operation from both mechanical and operational perspectives. Accordingly, the flexibility of the Swab Cup Carrier can be improved without compromising the stability and structural integrity of the main components.

Through this design development, the 4.5-inch Swab Cup Carrier is expected to perform three primary functions: as a component that can be temporarily retained at the X-over area, as a continuation system for liquid lifting from the 3.5-inch Swab Cup, and as a sealing system capable of maintaining contact with the 4.5-inch tubing wall until the liquid is lifted to the surface.

3.3 FEA results of the swab cup carrier and swab mandrel based on computer-aided design

The structural strength analysis of the Swab Cup Carrier and swab mandrel assembly was performed using the finite element analysis (FEA) method through SolidWorks Simulation 2023 software. The simulation was conducted to evaluate the stress distribution within the assembly and to identify critical regions with potential

failure risk. The equivalent von Mises stress was used as the primary evaluation parameter to compare the induced stress with the yield strength of the selected material.

The simulation results showed that the maximum von Mises stress occurred in the lock screw component, with a value of 278.6 MPa. The stress concentration was localized at the thread root area due to geometric discontinuity and cross-sectional variation, which generated a stress concentration effect. Since the lock screw exhibited the highest stress level compared with the other components, it was identified as the critical component. Accordingly, the maximum stress value of 278.6 MPa was used as the design governing stress for the structural evaluation and material selection.

Material selection was performed by considering that the material yield strength must be higher than the design governing stress. In addition, the selected material must possess adequate toughness, resistance to repeated loading, manufacturability, and suitability for mechanical equipment applications in oil and gas environments. Based on these criteria, AISI 4130 alloy steel was selected as a candidate material because it provides a favorable combination of strength, toughness, heat-treatability, and fatigue resistance, which supports its use in components subjected to tensile, compressive, torsional, and cyclic loading.

The main mechanical properties of AISI 4130 used in the evaluation are as follows:

- Yield strength, $\sigma_y = 460$ Mpa
- Ultimate tensile strength = 560–670 Mpa
- Maximum von Mises stress, $\sigma_{max} = 278.6$ MPa
- The factor of safety against yielding was calculated using the following Equations 1 and 2

$$FoS = \frac{\sigma_y}{\sigma_{max}} = \frac{460}{278,6} = 1,65 \quad (1)$$

therefore,

$$278,6 \text{ MPa} < 460 \text{ MPa} \quad (2)$$

These results indicate that the maximum stress remains below the yield strength of AISI 4130 and produces a static factor of safety of 1.65. Based on the boundary conditions and loading conditions applied in the simulation, the model theoretically remains within the elastic region and does not experience plastic deformation.

In addition to satisfying the initial static strength requirement, AISI 4130 also has several characteristics that support its application in swabbing equipment, including relatively high mechanical strength, good toughness, fatigue resistance, heat-treatment capability, and widespread use in oilfield components such as tool joints, subs, connectors, and other downhole components.

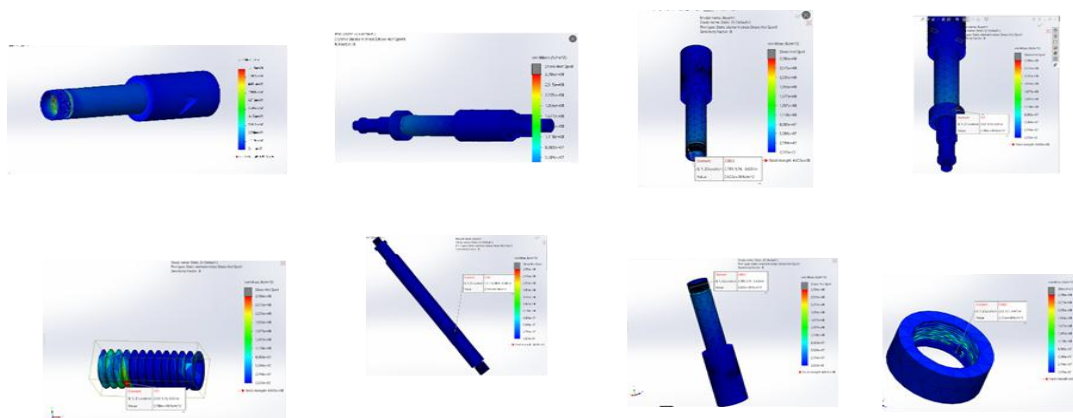


Figure 6.

Finite Element Analysis results of the Swab Cup Carrier and swab mandrel assembly, showing the von Mises stress distribution and the maximum stress of 278.6 MPa at the lock-screw thread-root area. (Authors' simulation using SolidWorks Simulation).

Nevertheless, the factor of safety value of 1.65 should be further evaluated against the applicable design criteria or minimum standard requirements. The final material selection should also consider fatigue analysis, corrosion, temperature, well fluid conditions, heat treatment, dynamic loading, and material standards for downhole equipment. Therefore, the FEA results in this study should be regarded as an initial structural evaluation and do not replace validation through material testing or testing under actual operating conditions.

3.4 Prototype development and functional testing using a mock-up tubing model

Prototype development and mock-up tubing testing were conducted to evaluate geometric conformity, inter-component connectivity, and the preliminary functionality of the cam-guided release-and-carry mechanism. The Swab Cup Carrier and swab mandrel prototypes were fabricated using the fused filament fabrication method with a Creality K1 Max 3D printer and PLA+ filament.

- **Prototype Development Results of the Swab Cup Carrier and Swab Mandrel**

The Swab Cup Carrier and swab mandrel prototypes were successfully fabricated based on the Computer-Aided Design model. The main components produced included the Swab Cup Carrier, swab mandrel, ring, cam groove, guide pin, and connection sections. Each component was printed separately to facilitate inspection, assembly, and evaluation of the mechanical interaction between components.

As shown in [Figure 7](#), the primary geometry of the prototype was successfully realized in accordance with the CAD design. The Swab Cup Carrier and swab mandrel components could be assembled into an integrated mechanical unit, while the guide pin was able to move along the cam groove trajectory. This condition enabled the evaluation of the mechanism position transition between the release and carry states. From visual and functional perspectives, the prototype demonstrated conformity in shape and configuration with the initial design. Nevertheless, the use of PLA+ filament was limited to geometric validation, assembly evaluation, and preliminary mechanical function testing. The prototype was not intended to represent structural strength, pressure resistance, temperature resistance, corrosion resistance, wear resistance, or actual downhole loading conditions.



Figure 7.

Assembly of the 3D-printed Swab Cup Carrier and swab mandrel prototype used to evaluate component fit, guide-pin movement, and mechanical engagement. (Author's documentation, Product manufactured by Creality K1 Max 3D printer and PLA+ filament).

- **Functional testing results using a mock-up tubing model**

Functional testing was conducted using a mock-up tubing model consisting of 4-inch and 3-inch Polyvinyl Chloride (PVC) pipes. The two pipes were assembled to form a diameter transition area that provides a simplified representation of the X-over configuration in a dual-size tubing completion. A specific section of the mock-up was made open to allow visual monitoring of the Swab Cup Carrier and swab mandrel positions during the Run In Hole and Pull Out of Hole stages.

As shown in [Figure 8](#), the prototype assembly was able to move through the 4-inch pipe toward the X-over area. During the Run In Hole stage, the Swab Cup Carrier reached the release position and remained retained at the transition area, while the swab mandrel was able to continue moving toward the 3-inch pipe section.

During the Pull Out of Hole stage, the swab mandrel re-entered the Swab Cup Carrier, and the guide pin moved along the cam groove trajectory until it reached the carry position. After reconnection was achieved, the Swab Cup Carrier could be retrieved together with the swab mandrel toward the upper section of the mock-up.

The test results showed that the release-and-carry sequence could be performed in accordance with the proposed design concept. No mechanical obstruction causing movement failure was observed during the tested stages. These results provide preliminary validation of the functional feasibility of the cam-guided release-and-carry mechanism.

The field-scale mechanism simulation was carried out under simplified conditions using 4-inch and 3-inch PVC pipes. A monitoring window was provided to observe the position of the Swab Cup Carrier and swab mandrel during Run In Hole (RIH) and Pull Out of Hole (POOH), as shown in [Figure 8](#). This arrangement enabled direct visual assessment of whether the tool could operate according to the intended working mechanism.

The tool preparation procedure prior to operation was conducted as follows:

- Installation of the Swab Cup into the Swab Cup Carrier
- Insert the Swab Cup into the Swab Cup Carrier.
- Secure the Swab Cup using the top nut.
- Insert the Swab Cup Carrier into the Swab Cup Mandrel.
- Install the swab mandrel into the slickline tool string assembly.
- The Swab Cup Carrier and swab mandrel assembly is ready to be operated during Run in Hole.

The Run in Hole and Pull Out of Hole procedures were performed as follows:

- Run the tool assembly into the hole until it reaches the 4.5-inch $\times$ 3.5-inch tubing X-over depth. The X-over position is indicated by a reduction in the tool string weight.
- Pull the tool string upward until the normal pulling weight is observed, approximately ± 1 ft, to activate the leave-and-carry system of the 4.5-inch Swab Cup.
- Continue running the 3.5-inch Swab Cup assembly down to the target depth, approximately 50 m to 100 m below the fluid level.
- Pull the assembly upward to perform swabbing. As the assembly approaches the X-over area, the pulling speed is reduced to allow the swab mandrel to re-enter the Swab Cup Carrier. The assembly is then pulled further upward to the surface or lubricator.

The testing results only validate the movement sequence and mechanical interaction of the prototype. The test did not evaluate sealing pressure, fluid-lifting capacity, fluid bypass percentage, actual pulling force, temperature effects, or dynamic downhole conditions. Therefore, further testing using actual engineering materials and a more representative testing facility is still required.

3.5 Analysis of the working mechanism of the modified design

The working mechanism of the modified design was analyzed based on the swabbing operation sequence in wells with a dual size tubing completion configuration, consisting of 4.5-inch tubing in the upper section and 3.5-inch tubing in the lower section. The analysis focused on the operating sequence of the 3.5-inch and 4.5-inch Swab Cups in maintaining the continuity of fluid lifting across the tubing diameter transition area or X-over.

During the Run In Hole stage, the 3.5-inch and 4.5-inch Swab Cups are lowered simultaneously as part of a single assembly. When the assembly reaches the X-over area from the 4.5-inch tubing section toward the 3.5-inch tubing section, the 4.5-inch Swab Cup Carrier is guided into the release position and temporarily retained at the transition area. Meanwhile, the swab mandrel and the 3.5-inch Swab Cup remain able to move downward until they reach the lower section of the fluid level to be lifted.

During the Pull Out of Hole stage, the 3.5-inch Swab Cup lifts fluid from the lower tubing section toward the X-over area. When the swab mandrel re-engages with the 4.5-inch Swab Cup Carrier, the guide pin moves along the

cam groove trajectory until the mechanism reaches the carry position. The 4.5-inch Swab Cup Carrier then reconnects with the swab mandrel and is retrieved toward the surface.

As the assembly enters the 4.5-inch tubing section, the fluid-lifting function is transferred from the 3.5-inch Swab Cup to the 4.5-inch Swab Cup. This mechanism establishes the principle of transfer lifting, in which the lifting function is transferred according to the tubing diameter being traversed. The 3.5-inch Swab Cup operates in the lower tubing section, while the 4.5-inch Swab Cup maintains sealing contact in the upper tubing section.

The cam groove functions as a guide path for the guide pin to control the positional transition of the Swab Cup Carrier between the release and carry conditions. Therefore, the cam groove does not function as a sealing element or as a radial deformation zone. The sealing function is still provided by the elastomeric element of the 4.5-inch Swab Cup, whose dimensions are matched to the inner diameter of the upper tubing section.

The mock-up tubing test results showed that the release sequence during Run In Hole and the carry sequence during Pull Out of Hole could be performed in accordance with the design concept. This mechanism enables the 4.5-inch Swab Cup Carrier to be temporarily retained at the X-over area, then re-engaged and retrieved to the surface without removing the lubricator during each operating cycle, as shown in Figure 9.

Conceptually, the combination of the transfer lifting mechanism, cam groove, guide pin, and cam-guided release-and-carry system has the potential to maintain fluid-lifting continuity in dual size tubing completion configurations. Nevertheless, the present testing remains limited to mechanical motion validation. The ability of the design to maintain sealing pressure, reduce fluid bypass, and improve liquid-lifting efficiency still requires further testing using actual engineering materials and more representative operating conditions.

3.6 Engineering implications and potential implementation

The results of the design development indicate that the 4.5-inch Swab Cup Carrier with a cam-guided release-and-carry mechanism has potential applicability in swabbing operations for wells with dual size tubing completion. This design was developed to address sealing loss and fluid bypass that occur when the tool assembly moves through the transition area from the 3.5-inch tubing section into the 4.5-inch tubing section.



Figure 8.

Functional testing of the Swab Cup Carrier and swab mandrel using a PVC mock-up tubing model.

The test demonstrates carrier release at the X-over during Run In Hole and carrier reconnection during Pull Out of Hole. (Author's documentation, Swab Cup Carrier Prototype manufactured by Creality K1 Max 3D printer and PLA+ filament and PVC mock up tubing was handmade).

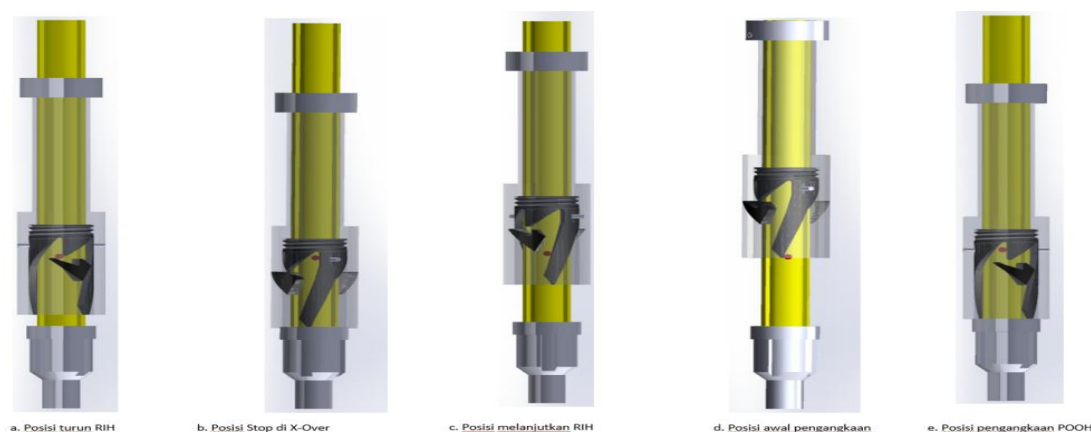


Figure 9.

Guide-pin positions along the cam-groove trajectory during Run In Hole and Pull Out of Hole, illustrating the transition between the release and carry positions. (Authors' illustration made by Solidwork 2023 software).

From an engineering perspective, the modified design employs two Swab Cup sizes that operate sequentially according to the tubing diameter. The 3.5-inch Swab Cup functions to lift fluid from the lower tubing section, while the 4.5-inch Swab Cup continues the lifting process in the upper tubing section. This transfer lifting mechanism has the potential to maintain the continuity of fluid lifting up to the surface.

The cam groove on the Swab Cup Carrier functions as a guide path for the guide pin to control the mechanism transition between the release and carry positions. During the Run In Hole stage, the 4.5-inch Swab Cup Carrier can be released and temporarily retained at the X-over area. During the Pull Out of Hole stage, the carrier reconnects with the swab mandrel and is retrieved toward the surface. The sealing function remains provided by the 4.5-inch Swab Cup element, which is dimensionally matched to the inner diameter of the upper tubing section.

This mechanism offers potential operational advantages because the carrier release and retrieval process can be performed within a single operating sequence without removing the lubricator in each cycle. Therefore, the proposed design has the potential to support swabbing operations that are more practical, continuous, and efficient in terms of operating time.

From a manufacturing perspective, the main components, including the ring, main body, cam groove, guide pin, lock screw, and swab mandrel, can be produced using Computer Numerical Control machining. The modular configuration also facilitates fabrication, inspection, maintenance, and component replacement in the event of wear or damage.

The FEA results indicate that the design theoretically remains below the yield strength of AISI 4130 under the analyzed static loading condition. In addition, prototype testing using the mock-up tubing model provides preliminary validation that the release-and-carry sequence can be performed in accordance with the design concept. Nevertheless, the test has not yet demonstrated sealing performance, fluid-lifting capacity, or quantitative fluid bypass reduction.

Further research is required through more comprehensive FEA, including mesh convergence, contact analysis, fatigue analysis, dynamic loading, and variation of loading conditions. Laboratory testing using actual engineering materials is also necessary to evaluate sealing pressure, pulling force, wear resistance, fluid compatibility, temperature effects, and fluid-lifting performance prior to field validation.

Overall, the combination of the cam-guided release-and-carry mechanism and the transfer lifting function from the 3.5-inch Swab Cup to the 4.5-inch Swab Cup offers a potential engineering approach for dual size tubing completion applications. With further validation, this design can serve as a basis for developing more adaptive swabbing equipment suitable for liquid unloading operations in wells with tapered tubing configurations.

4. Conclusion

This study successfully developed a modified design of a 4.5-inch Swab Cup Carrier and swab mandrel for swabbing applications in wells with dual size tubing completion, consisting of 3.5-inch tubing in the lower section and 4.5-inch tubing in the upper section. The design was developed to address sealing loss and potential fluid bypass occurring at the tubing diameter transition area or X-over.

The proposed concept employs two Swab Cup sizes within a single assembly, integrated with a cam-guided release-and-carry mechanism. During the Run In Hole stage, the 4.5-inch Swab Cup Carrier is released and temporarily retained at the X-over area, while the 3.5-inch Swab Cup moves downward toward the lower section of the fluid level. During the Pull Out of Hole stage, the 3.5-inch Swab Cup lifts fluid from the lower tubing section, after which the 4.5-inch Swab Cup Carrier reconnects with the swab mandrel and continues the lifting process through the upper tubing section. The FEA results showed that the maximum von Mises stress of 278.6 MPa occurred in the lock screw component. This value remains below the yield strength of AISI 4130, which is 460 MPa, and results in a static factor of safety of 1.65. Based on the boundary conditions and loading conditions applied in the simulation, the design theoretically remains within the elastic region and does not experience plastic deformation.

The Swab Cup Carrier and swab mandrel prototypes fabricated using PLA+-based 3D printing were successfully assembled and tested using a PVC mock-up tubing model. The functional testing results showed that the release mechanism during Run In Hole and the carry mechanism during Pull Out of Hole could be performed in accordance with the design concept. These findings provide preliminary validation of the geometric and mechanical feasibility of the proposed design.

Overall, the modified design has the potential to maintain movement continuity and transfer lifting in dual size tubing completion configurations. However, this study has not yet evaluated sealing performance, fluid-lifting capacity, or quantitative fluid bypass reduction. Therefore, further research is required through fatigue and dynamic loading analysis, pressure and sealing tests, fabrication using actual engineering materials, and laboratory and field validation.

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6. Declarations

6.1 Author contributions

Karnando: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Visualization, Writing – Original Draft, and Writing – Review & Editing. Dedy Irawan: Supervision, Validation, and Writing – Review & Editing. Amega Yasutra: Supervision, Validation, and Writing – Review & Editing. All authors have read and approved the final manuscript.

6.2 Funding statement

This research received no external funding.

6.3 Competing interest

A patent application related to the Swab Cup Running Tool described in this manuscript is being considered. The authors declare no other financial or non-financial competing interests.

6.4 The use of AI or AI-assisted technologies

During the preparation and revision of this manuscript, the first author used ChatGPT to assist with language editing. All AI-assisted content was subsequently reviewed and edited by the authors. The authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

7. Glossary of terms and symbols

Terms & Symbol	Definition	Unit
3D	Three-dimensional.	-
AISI	American Iron and Steel Institute	-
AISI 4130	Chromium–molybdenum low-alloy steel	-
CAD	Computer-Aided Design	-
CNC	Computer Numerical Control	-
FEA	Finite Element Analysis	-
FoS	Factor of Safety	Dimensionless
ID	Inner Diameter	inch
NBR	Nitrile Butadiene Rubber	-
OD	Outer Diameter	inch
PLA+	Modified polylactic acid filament	-
POOH	Pull Out of Hole	-
PVC	Polyvinyl Chloride	-
RIH	Run In Hole	-
σ_y	Yield strength	MPa
σ_{max}	Maximum equivalent von Mises stress	MPa
$\emptyset$	Diameter	inch
R	Radius	inch
$\pm$	Plus–minus	-
$\times$	Multiplication or dimensional-transition symbol	-
$^{\circ}$	Degree	degree
MPa	Megapascal, equal to 10^6 pascals	MPa
in	Inch	inch
ft	Foot	ft
m	Metre	m
R1.000	Cam groove path radius of 1.000 inch.	inch
R1.750	Cam groove path radius of 1.750 inches.	inch
180 $^{\circ}$	Angular arrangement in which the two pairs of cam grooves are positioned symmetrically opposite each other.	degree

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