A CONTRAFLOW TETHERLESS MECHANICAL PIPELINE CRAWLER

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Abstract

This paper outlines the principal functions of the base carrier tool, its potential accessory modules and a commercial basis for its adoption by operators.

1. Background.

On some subsea pipelines access for in-line operations is restricted to the downstream end only. In these cases conventional pigs can only be used by reversal of the flow in the line, and this is often difficult due to the problems of temporary storage of the line product. In some cases it has been injected back into the well but this can lead to later production problems.

Many subsea pipelines are in laid in parallel pairs and equipped so that they can be configured as a loop. This allows conventional pigs to be sent down one flowline and return along the other.

Single lines are equipped with subsea pigging and purging facilities for conventional pigging operations.

Both these arrangements require considerable capital and operational expenditure.
In these, and other situations, it would be desirable to have a tool that could enter and leave an operational flowline from one end.

Market research by Shell Global Solutions identified various tools proposed by a number of contractors with drive mechanisms that would be capable of traveling against the well stream flow. In a model trial a mechanism developed by Astec Developments Ltd. was deemed to have the closest fit to the desired parameters and to be the most robust, as it was a derivative of their down-hole coiled tubing tractor.

Three years ago a joint project was set up with the aim of developing a tool that could travel against the flow from a well and return to the launch point with the flow in a manner similar to a conventional pig.

Astec Developments Ltd. has been acquired by Weatherford, who together with Shell, are continuing with the investment and field testing programme based at the Weatherford Pipeline & Specialty Services R&D centre in Edinburgh.

2. Potential Applications.

A tool with this capability could be used as a vehicle to carry devices designed to perform a wide range of specific tasks, including : -

- Removal of wax deposits.

- Removal of other pipeline debris, e.g. scale or asphaltine
- Pipe wall thickness inspection.
- Wall surface or pipe feature inspection.
- Product or contaminant (e.g. water at pipeline low points) sampling.
- Placement of on-line monitoring equipment, for later collection or inductive down-load
- Precise placement of an isolator.
- Change-out of valve choke, if facilities were so designed.

3. Benefits.

Subsea intervention is expensive, both in the facilities required to undertake pigging and in the deployment and operation of pigs. The impact on production can be great, with the possibility of an inoperable pipeline if the operations go very badly.
There are benefits in all these areas from the use of crawler tools.

Infrastructure cost savings on:

- Subsea pigging and purging facilities
- Parallel pipelines and crossover valves

Operational cost savings on:

- DSV or ROV vessel costs to perform pigging
- Deferment of production
- Provision of and removal or storage of secondary pigging liquids

A study by the subsea team at Shell International of the conceptual design of new subsea developments has identified a potential cost saving in excess of 100 million USD if this technology was applied on all deep-water developments between 2002 and 2007.

Other benefits:
If a tools' operating parameter is breached or if the tool is obstructed it will return to base by default through a known passable bore pipe.
Unlike conventional subsea pigging activities the water depth makes little difference to the tool.

In pipe cleaning applications :-

- Removed deposits will be carried with the flow away from the crawler
- Receipt of removed deposit will be at a low continuous rate in controllable quantities that can easily be removed from the pipeline.
- Removed deposits can never accumulate in front of the crawler and block the pipeline it is cleaning.

4. Scope For Use.

In the Northern Sector of Shell Expro alone there are 40 single ended oil pipelines and flowlines and 12 single-ended gas lines in which a crawler would be cost effective over conventional sub-sea intervention pigging. All are potential candidates for inspection and some may be in need of wax removal.

Extrapolating this to similar pipeline inventories of all the other Operators and it can be seen that there is a substantial potential scope for crawler use in the North Sea, and a casual look at the world oil map shows that there are potentially many single ended lines in deep-water fields to address.

Cleaning and/or inspection of tanker loading lines are other possible areas for tool application.

5. Contra Flow Crawler.

Description.

The tool has progressed through several development stages and the current, near optimum configuration has been patented. It comprises a number of different types of module, each having a specific function, joined together with articulating couplings to make a long segmented body able to negotiate bends. The modules have large internal or external bypass passages to allow the produced fluid to pass the unit when in crawler mode, and when this bypass is prevented the unit operates in conventional pig mode.

These are described below, and in more detail in the Appendix.

Beginning at the front of the tool the modules are :-

TASK MODULE – a custom module appropriate to the required task. Wax cutting and removal is illustrated.

FRONT RETURN MODULE – to make the tool travel with the flow and return to its start point.

TURBINE MODULE - to generate power to operate the Tractor Module.

TRACTOR MODULE - to transport the tool along the pipe against the flow.

REAR RETURN MODULE – similar to that at the front.

6. Crawl Mode

In crawl mode a turbine extracts power from the produced fluid and a magnetic coupling applies a torque to a harmonic drive gearbox concentric with the turbine.

The gearbox output shaft is connected via a universal joint to a central shaft in Tractor Module upon which are a series of radially offset and skewed cranks with axial thrust bearing surfaces.
Mounted on each crank is a hub with five equi-spaced skewed spokes. These spokes are the "legs" of the crawler, are flexible, have a grip stud in the end, an enclosing diameter less than the pipe inside diameter and are prevented from rotating within the body of the crawler. As the central shaft rotates they are brought into interference contact with the pipe wall by the eccentric rotation of the crank.

As the cranks are offset and skewed, each leg oscillates forwards and outwards, backwards and inwards as the central shaft rotates. The end of each leg contacts the pipe wall at its most forward point and remains in compression contact with it until it has moved back behind the plane radial to the central shaft axis that passes through the mid point of the skewed crank centerline. At this point the crank eccentricity and their angle to the crank axis moves them away from the wall until they again move forward. The other four legs of the set follow the same cycle, contacting different portions of the wall at different times.

A number of leg sets are mounted on the central shaft at regular angular spacing to balance the shaft and provide continuous traction.

Thus the module progresses along the pipe in an effective walking action.

6.1 Return Mode

Return mode (or conventional pig mode) is entered when the return mechanism is actuated. The fluid pressure drop over the tool is then sufficient to provide enough force to overcome the traction force and the tool travels with the produced fluid to the recovery station.

The return mechanism consists of a metal cone and anular ring with a conical internal face. The cone is normally separated axially from the ring allowing fluid to pass through the ring. When mechanically triggered a spring pushes the cone along a rod to seat in the ring and closes off the flow. Two such mechanisms are fitted, well spaced along the crawlers length, to ensure passage over tee and wye pipe branches.

The mechanism can be triggered by any of several mechanisms on the unit :-

- A contact probe on the tool front – when bends are more acute than the tool is designed to negotiate or an obstruction is met.
- A gauge ring on the tool front – when a greater than allowable reduction in pipe bore is met.
- A pressure differential valve – when pressure across the tool is beyond design limits
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Controlled triggers can be initiated by:

- A pressure pulse generated in pipeline – valve closure
- A Signal external to pipe– magnetic, radio, acoustic, etc. (with a suitable actuator)
- Temperature –a fusible link could be incorporated to "fail" when hot and initiate return mechanism. i.e. for operation in a specific temperature zone in a pipe where wax deposit.

6.2 Application Tailoring

Using these basic operating principles various design parameters of the tool can be modified to optimise it for different applications and duties, for example by varying :-

- The turbine blade shape, configuration and quantity, to change the power developed.
- The drive gear ratio, to change the walk speed.
- The leg hardness, diameter, cross-sectional area and grip stud material, to change the allowable diameter variation.
- The number of leg sets per traction module, to change the traction forces. *
- The angle of skew of the cranks, to change the length of its stride.
- The number of traction modules, to pass unusual pipeline features.

* The current 6" prototype can only contain five leg sets per traction module if it is to pass a 5D bend. Thus to provide the necessary drive there are two traction modules and two turbine modules as shown.

The current design is totally mechanical. However further advancements might be made by incorporating electronics or hydraulic systems for its own operation or to serve other functions, but it would remain a requirement that the tool can function and default to base if these systems were to fail.

Power generated by the turbines can be captured mechanically, hydraulically or electrically directly from the rotating magnetic coupling and used to power auxiliary modules as required.
The rotation of the gearbox shaft could be used to rotate a module for inspection purposes.

A tracker or location tool, e.g. acoustic, radio, etc can be fitted.

A crawler can be designed to walk in both directions by changing the operating geometry of the legs, though this may not be possible in some combinations of small pipe diameter and minimum bend radii due to module length constraints.

6.3 Design Specification

The initial development requirement was to address the following Pipeline Features:

- Diameter: 6", later this will be expanded to range from 4" to 12" and larger, as required.
- Bends: to address 5D in a 6" pipe, in larger diameter applications the bends may be more acute.
- Branches: All sizes of branches were to be expected, with axial bars fitted to those in excess of 50%.
- Wyes: Up to full diameter to be accommodated with the angle generally in the 25 - 30° range.

- Steps: accommodate radius steps of +/- 10mm on the 6"D, or 5mm fully circumferential.
- Ovality: accommodate 1% ovality in bends.

The performance targets were :-

- Distance: initially set for flow lines from wells up to 10 Km from the platform, later this distance might be expanded to 60 Km by incorporating developments.
- Temperature: initially set at 4 to 90°C, which covers the majority of flowlines. In exceptional circumstances these parameters can be moved outwards.
- Cleanliness: pre-sweep to clean the pipe wall before any inspections.
- Pressure: a maximum of 150bar for prototype testing ; some flowlines experience pressures of up to 350bar, potential for this will be considered at a later stage in the tool development.
- Flow Medium: Well stream containing oil, gas, and water across the full range of percentages. Contaminants such as methanol and corrosion inhibitors containing amines should were expected.
- Flowrate: In general flow from a well producing predominantly liquid is in the region of 1 - 1.5 m/s.
- Water depth: no restriction
- Launch facilities: requires minimum special launch (and recovery) facilities, only an isolatable section of pipe where flow can be directed over the nose of the tool. A conventional pig launcher would require a cassette to achieve this.

7. A Specific Application.

During the course of the development a specific application for a 6” tool was identified ; to remove a surface coating of wax up to one inch thick and over a distance of up to eight kilometers, in a 6” pipeline with a low product flow rate.

Design efforts concentrated on a prototype tool configured for this task. This meant using a low gear ratio and designing an open blade turbine that could accommodate the passage of large quantities of wax. This coupled with the low flow resulted in a tool with a restricted operating range in terms of flow variation.

A wax-cutting module was designed with multiple concentric rotating cutters, driven by an additional turbine module.

Cutting trials using simulated and actual wax were done to optimise the blade configuration and gearbox ratio.

The initial design specification was 70% liquid to 30% gas, however this has not shown to be a problem with drive fluctuation, thus the operating mode will not be limited by this.

Unfortunately the pipeline operator subsequently decided to deal with the problem of wax in a different way, (a larger diameter line) and so the crawler option was dropped, and the opportunity for a wax cutting field trial has been removed, and design effort has subsequently been concentrated on the details of the delivery vehicle.

8. Testing and Trials

Design proving trials were conducted in a test facility constructed at Astec Developments using water. These have confirmed the design parameters and characteristics of the 6” prototype crawler, such as speed, operating flow rate, traction capabilities and the power developed by its turbines.

e.g. at flow of 0.75m/s crawl speed is 0,8m/min.

Traction of 1400N per tractor module has been achieved.

Material selection for components of the leg sets has been refined as a result and the required levels of durability are now being seen.

Short distance test rigs were also used to develop and prove the wax cutting module design and performance, where valuable information on the behaviour of petroleum waxes while being cut and deformed was gained.

In these tests considerable time and cost were saved by the use of rapid prototype components for the turbine wheels and stators, allowing their design to be quickly modified and optimized.
External trials have been undertaken in a 170m water-filled loop at Ellesmere Port and a 100m crude oil-filled loop at ERT Orkney.

The following objectives were set and accomplished during these :

- Launch from transport “cassette”
- Travel along a straight section of pipe
- Negotiate 5D bends
- Negotiate barred T’s, Y pieces and vertical sections (up and down)
- Operate in crude oil
- Operate in water
- Prove operation in 2 phase flows of up to 20% gas
- Remove wax from the inner diameter of the pipe
- Stop at a 3D bend in water.
- Survival at pressures of 60bar in water.
- Ability to withstand temperatures of 90ºC.
- Return with the flow to the launch point
- Evaluate wear of the components.

This meets the operating criteria required by Shell.

9. Future Work.

Further detail development and laboratory testing to establish the long-term durability of components and extended duration operation is planned at the end of 2003 before a field pipeline trial takes place.

10. Summary

The contraflow crawler offers enormous cost savings over conventional sub-sea intervention methods, thus freeing up capital for more cleaning / inspections / projects:

- The single entry and exit option offers substantial savings on conventional infrastructure.
- The single-ended entry and exit option is independent of weather.
- There is no deferment of production during tool operation.
- Not having to break into a pipeline to clean or inspect reduces risk of unforeseen events, escalating costs of the original activity.
- The tool of the tool is not limited by an on-board power source, or limited in range by a tether.
- Additional power generated is available for use by auxiliary modules.
- In increased diameter applications the crawler will have the ability of walk backwards
- The crawler can be used in pipelines that have a low differential pressure.
- The rotating shaft could be used to operate functions in add-on modules.
- It can be applied to a wide variety of inspection and intervention tasks.

11. Conclusion

There is wide scope for a range of crawlers as platforms to deliver cleaning, inspection, isolation, etc., offering substantial cost savings of many million USD per year - both against conventional operations and unscheduled pipeline replacement.

The Contraflow Tetherless Mechanical Pipeline Crawler is an essential part of the pipeline operator's tool-kit.

12. APPENDIX.

Detailed Design Description.

A complete tractor for operation as a cleaning tool in a heavily waxed pipe comprises:

- 2 tractor modules
- 2 turbine drive modules
- 1 return module
- 1 cutter module

12.1 *Tractor Module.*

Each tractor module has five elastomer leg sets, each having five legs arranged around a hub with dry film journal and thrust bearings in its bore.

The hub is manufactured from a steel, onto which polyurethane is moulded to achieve the "legs". The ends of the "legs" contain tungsten inserts to achieve a wear resistant grip on the pipe wall.

This is carried on a rotating shaft, offset from the centre line of the tool like a crank, and skewed to lie out of parallel to the tool centre line. The five of these cranks are angularly equispaced around the centre shaft to ensure one leg is in contact with the pipe wall at all times.

Leg guides on the body run between all pairs of legs and prevent their rotation about their own centre. The leg guides are integral with the main body at one end, are open ended at the other end to allow assembly, and fitted bayonet style onto the end of the body. They are locked in position by the coupling sleeve.

A hollow drive shaft runs the length of the module and a nut on the end of the shaft retains and locks the hubs together.

Special applications in the future may require use of alternative materials.

Testing of the bearings has demonstrated that they operate well in a crude oil/gas environment.

12.2 *Turbine Module.*

The turbine is located on a dedicated module downstream of the tractor module. The turbine hub contains a harmonic drive gearbox and the rotation of the turbine is transmitted to the gearbox via a magnetic coupling.

The produced fluid is channelled into the turbine by a shroud to locally increase the fluid velocity in order to generate power. The shroud also centralises the turbine module within the pipe and provides a low friction contact with the pipe wall. The turbine design is specific to the tractor application. E.g. The turbine for application in a wax cleaning operation has a large area between each of the blades to allow wax cuttings to pass through the turbine easily without affecting the turbine performance. A range of custom designed turbines will be available.

The turbine has been tested at flowrates of up to 1m/s, the power generated at this flowrate, with a pressure drop across the unit of 4.5psi, is 250Watts. The maximum power required for a wax cutting operation (including safety factors) is 132Watts.

The gearbox housing is a sealed, pressure compensated unit. The coupling magnets are located on the inner diameter of the turbine and the outer diameter of a flywheel (located in the gearbox housing) which is connected to the gearbox input shaft. Above a predefined torque the coupling will slip and thus protects the gearbox from overload.

A range of gearbox ratios (50:1, 80:1, 120:1) are available which can be installed depending on the application of the tractor.

The gearbox has a through bore which allows a flexible pushrod to pass from the front to the rear of the tractor for activation of the return mechanism.

12.3 *Return Module*.

The return module is a spring loaded in-line valve type device closes automatically when its holding mechanism is tripped. This creates a high pressure drop across the unit and generates a force large enough to overcome the friction of the leg-sets and 'flip' them into drag mode. Once the initial 'flip' has been made the force required to drive the crawler in reverse like a pig will be less.

The mechanism can be activated via a push rod or by an increase in the pressure drop across the tool (to a predefined level) or by increasing the pressure in the pipeline. Other methods can be applied to suit a specific application. E.g. a thermally activated element.

12.4 *Wax Cutting Module.*

The Task Module assembly can be configured for use as a wax-removal tool using a rotary cutting head. This tool was initially designed for a specific application in a pipeline that had not been pigged for some time and had a large wax build-up.

The cutter is powered by a dedicated turbine gearbox system configured in a similar manner to the turbine module.

Extensive testing of a number of different designs of cutter were carried out prior to selecting a design that has five rotary blades of progressively increasing diameter, followed by a compliant "claw type" cutter ring. This compliance allows the final cutter to pass a 6% reduction in the pipe diameter and allows the negotiation of weld beads, partially closed valves or other obstructions.

To ensure the pipe is clear for the tractor to pass though, the turbine shroud also acts as a gauge ring. Should the "gauge ring" encounter an obstacle that cannot be negotiated, a signal will be passed through the tractor to deploy the return mechanism. The shroud also activates the return mechanism if a 3D bend (in the 6" pipe) is encountered.

12.5 *Tracking.*

The crawler has the capacity to transport an additional module, so in addition to the above modules, for field trials, the first prototype tools will be equipped with a tracking/locating unit. This is expected to be either a pinger with external transponders or similar. In later models more sophisticated methods of tracking the crawler or communicating with it will be developed.