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Ship-based CO_2 Injection into Subseabed Geological Formations using a Flexible Riser Pipe Pickup System

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Abstract

This report presents details of one aspect, namely, the flexible riser pipe pickup system, of a proposed ship-based carbon dioxide capture and storage (CCS) method. The liquefied CO_2 (LCO_2) to be sequestered is directly injected into subseabed geological formations through a flexible riser pipe using injection facilities contained onboard an LCO_2 carrier ship. The flexible riser pipe remains on the seabed, one end attached to the injection wellhead, until the other end is hoisted up and connected to the (dynamic positioning system (DPS)-controlled) LCO_2 carrier ship arriving at the ocean injection site. This proposed system has various advantages over the use of stationary sea surface structures for ship mooring and CO_2 injection: *i)* no need for stationary sea surface structures, e.g., ship-mooring-buoy or platform; *ii)* simplifies ship handling, especially in rougher sea states; and *iii)* the flexible riser pipe can remain on the seabed in rough seas. Details of a pickup buoy system for retrieving the riser from the seabed and the structure of the flexible riser pipe are presented in this paper. The riser pickup system consists basically of shipboard equipment such as a coupling valve, crane, winches and A-frame and offshore equipment such as a pickup buoy, pickup float, messenger line, sinker and pickup wire rope. The flexible riser pipe, outer diameter of 309 mm, was designed with due consideration of the stresses encountered with repeated retrievals from the seabed.

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Keywords: CO_2 injection; shuttle ship; subseabed; flexible riser pipe; pick-up buoy

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1. Introduction

Carbon dioxide capture and storage (CCS) is one of the key technologies essential to achieve greenhouse gas reduction. The injection of liquefied CO_2 (LCO_2) into geological formations, both inland and offshore in subseabeds, has been studied by the petroleum industry and national organizations. The proposed ship-based LCO_2 subseabed injection system described herein is characterized by both the presence of LCO_2 injection equipment located onboard the LCO_2 carrier ship and the absence of any stationary sea surface structures at the offshore CO_2 storage site. The LCO_2 carrier ship features, besides the LCO_2 cargo tanks, an onboard injection pump capable of delivering pressurized LCO_2 directly from the ship to the seafloor injection well through a flexible riser pipe that remains connected to the wellhead.

The shuttle ship, containing about 3,000 m^3 of LCO_2 loaded into two cargo tanks, is designed to be capable of injecting about 3,000m^3/day (about one million tons of LCO_2 per year) into the target reservoir via the flexible riser pipe: LCO_2 transported to the offshore injection site at minus 10 ^oC and 2.65 MPa. At the injection site, the temperature of the LCO_2 is increased from minus 10 ^oC to 5 ^oC before the injection through the flexible riser pipe into the seafloor well at an LCO_2 pressure of 10 MPa.

The use of an unmanned offshore facility for mooring and injection results in lower facility construction/maintenance costs as well as increased safety of the entire operation. Figure 1 illustrates the LCO_2 injection *a)* directly from the ship to the storage layer via the flexible riser pipe and *b)* through the use of a stationary structure.

The design of the offshore surface/underwater facilities and the configuration of the ship onboard equipment for the flexible riser pipe pickup operation required in this study involved detailed examinations of the following areas:

- dynamic and static analyses of the flexible riser pipe movement to determine the maximum tension and the minimum allowable bending radius,
- fatigue analysis of the proposed flexible riser pipe design to estimate the pipe lifetime, and
- dynamic and static analyses to determine the requirements for the pickup wire rope, messenger line, pickup float and sinker.

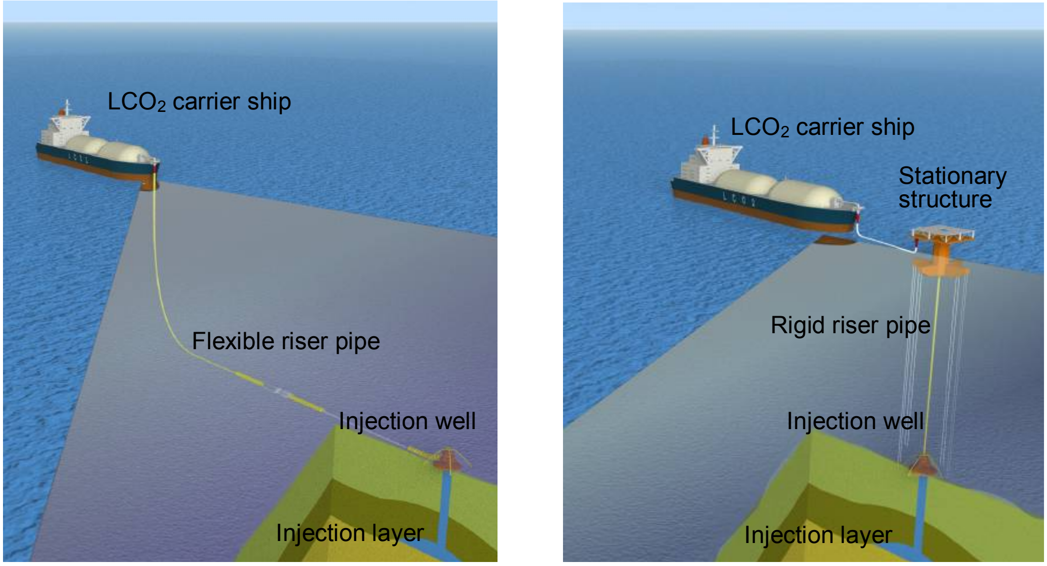

Fig.1 Illustrations showing direct LCO_2 injection from the ship to the storage layer (left) and LCO_2 injection through a stationary structure (right).

This report, primarily focused on presenting the results of the riser pipe pickup system and the flexible riser pipe structure studies, is a component of the "Preliminary Feasibility Study on CO_2 Carrier for Ship-based CCS" and its follow-up study sponsored by the Global CCS Institute. The other technical aspects of the study are presented in the following papers: “Ship-based Offshore CCS Featuring CO_2 Shuttle Ships Equipped with Injection Facilities” by M. Ozaki *et al*., "Offshore Operational Availability of Onboard Direct Injection of CO_2 into Sub-seabed Geological Formations" by T. Miyazaki *et al.* and "Cargo Conditions of CO_2 in Shuttle Transport by Ships" by N. Kokubun *et al.*

2. Flexible Riser Pipe Pickup System

2.1 Pickup buoy systems

The flexible riser pipe, also used as a riser flow line to carry oil or gas from the seafloor wellhead, remains on the seabed and is connected to the DPS-controlled LCO_2 carrier ship only after it has arrived at the ocean site. The entire pickup buoy system is shown in Fig. 2. This system has the following advantages over a stationary surface structure:

- no buoy system necessary for ship mooring,
- less stringent ship handling requirements than mooring at stationary surface structures, especially in rougher sea conditions, and
- the flexible riser pipe remains on the seabed in rough seas.

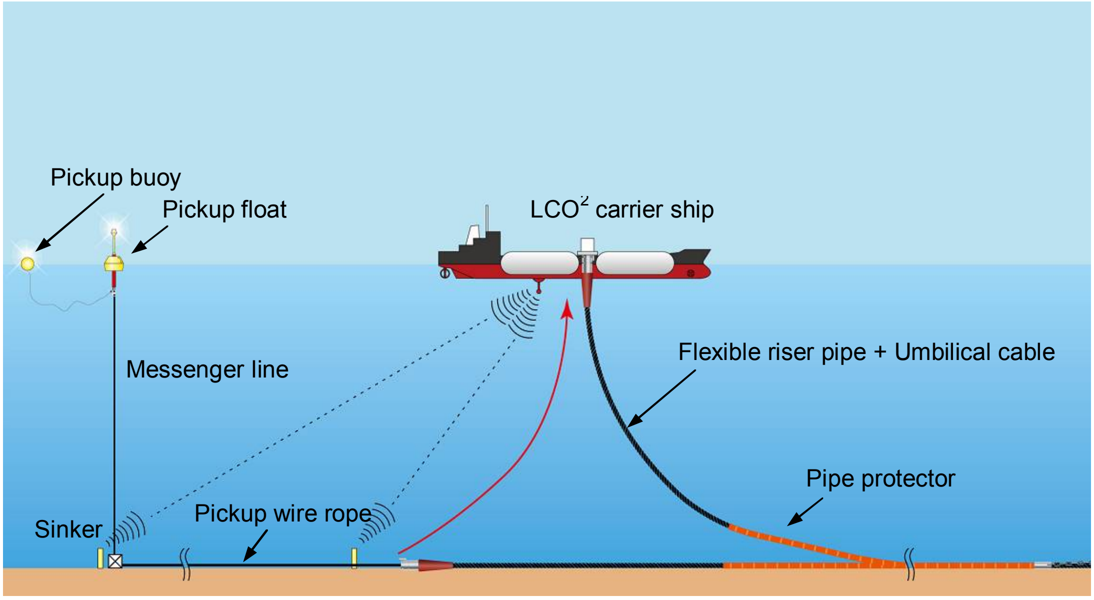

Fig. 2. Illustration showing the pickup buoy system components; the flexible riser pipe is connected to the LCO_2 carrier ship by first taking up the pickup buoy and the pickup float.

2.2 Flexible riser pipe pickup operation

The design conditions for the flexible riser pipe pickup operation, detailed in Table 1, can be explained as follows:

- the buoy pickup operation can be carried out in sea conditions up to a significant wave height ($H_{1/3}$) of 2.5 - 3.0 m, according to a survey of ship operators,
- the pickup buoy and float must be stable in heavy weather conditions and have no kinetic influence on the flexible riser pipe on the seabed,
- the specification of the pickup wire rope is determined by the pickup conditions listed in Table 1,
- the specifications of the messenger line, sinker, and pickup float are determined by the storm conditions listed in Table 1.

Table 1 Design conditions of the flexible riser pipe pickup operation.

Design criteria	Pickup operation	Storm condition
Sea water depth	500 m	500 m
Significant wave height ($H_{1/3}$)	3 m	12 m
Significant wave period	17 sec	15 sec
Wind speed (10 min. mean)	15 m/sec	50 m/sec
Tidal current (at 100 m depth)	1.5 knot	1.5 knot
Safety factor of lifting apparatus	6	6
Flexible riser pipe weight in water	20 kg/m	20 kg/m

Components of the pickup buoy system are shown in Fig. 3. The pickup buoy is picked up first, followed by the pickup float, which is connected to the flexible riser pipe through the messenger line and the pickup wire rope. The junction of the messenger line and the pickup wire rope is kept on the seabed, using an attached sinker, except during CO_2 delivery; this system isolates the flexible riser pipe from any pickup float motions caused by waves. The pickup float, with an attached light, serves as a dan buoy (marker) for the LCO_2 carrier ship.

The length of the pickup wire rope is 750 m, 1.5 times the water depth. The 550 m (1.1 times the water depth) messenger line is designed with sufficient mechanical strength to draw both the sinker and the pickup wire rope up to the LCO_2 carrier. The pickup float is designed with 10 kN buoyancy to sustain the combined weight of the messenger line and the buoy light and radar reflector.

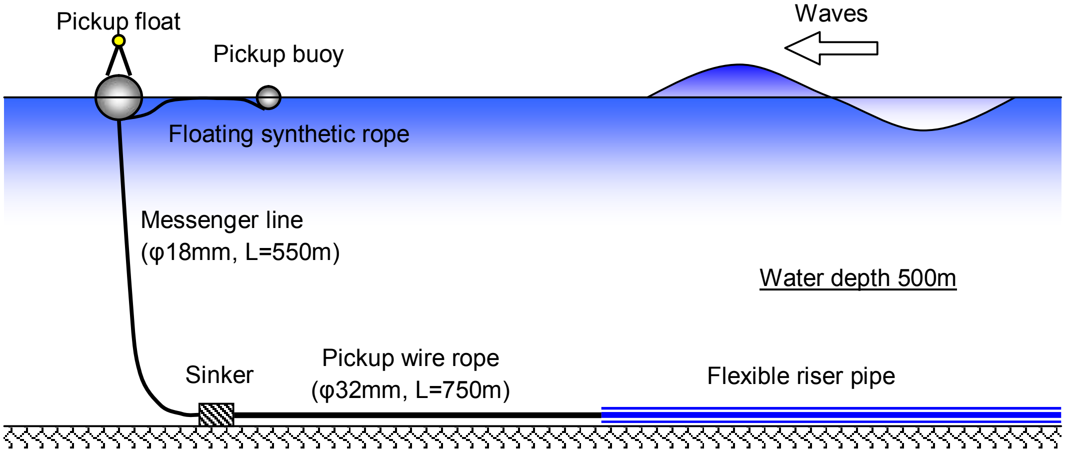

Fig. 3 Components of the pickup buoy systems.

2.3 Shipboard equipment for the flexible riser pipe pickup operation

The LCO_2 carrier requires the following equipment for the riser pickup operation:

- a coupling valve to connect the flexible riser pipe to the ship,
- a crane to hoist the pickup float onto the ship,
- winches to reel in the messenger line and the pickup wire rope, and
- an A-frame for deployment and recovery of the float and pickup wire.

This shipboard equipment for the flexible riser pipe pickup operation and details of the A-frame and the coupling operation are shown in Fig. 4 and Fig. 5, respectively.

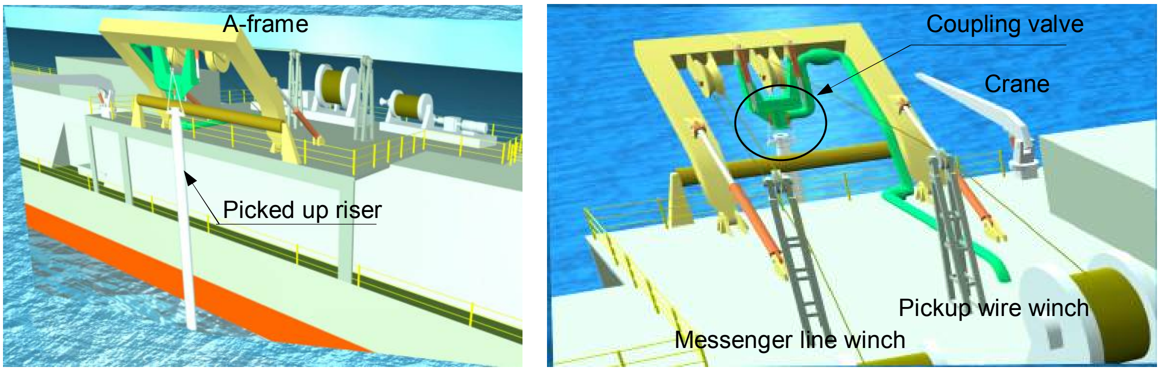

Fig. 4 Shipboard equipment for the flexible riser pipe pickup operation.

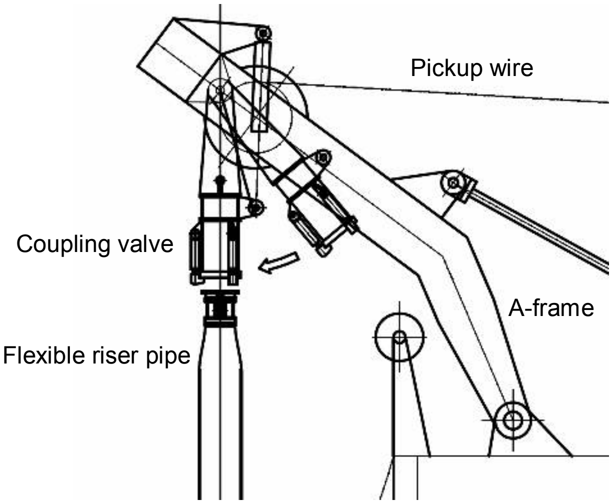

Fig. 5 Schematic drawing of A-frame and coupling operation.

3. Structure of the Flexible Riser Pipe

3.1 Design basis of the flexible riser pipe

The design basis of the flexible riser pipe is derived from the comprehensive plan developed in this study, e.g., flow rate, flow velocity, and design pressure of the LCO_2, as summarized in Table 2. The flexible riser pipe is designed using numerical analyses that consider the required dynamic strength and long-term fatigue behavior under the weather and sea condition assumptions of the hypothetical storage site. The design weight of flexible riser pipe was adjusted by selecting the material and thickness of the buoyant layer of the pipe to enable an efficient pick-up operation. The designed dimensions of the pipe are summarized in Table 3; the internal structure is schematically illustrated in Fig. 6.

Table 2 Design basis of the flexible riser pipe.

Design criteria	Requirement
Flow rate of the LCO_2	3,000 m^3 / 16 hrs. (52 liters / sec.)
Flow velocity of the LCO_2	3 m / sec.
Inner diameter	0.16 m The inner diameter of the flexible riser pipe is calculated as follows: $D = (4\,q / \pi\,v)^{1/2}$ in which, D : Inner diameter of flexible riser pipe v : Flow velocity q : Flow rate
Design pressure	20 MPa (working pressure, 10 MPa)

Table 3 Dimensions of the flexible riser pipe.

Layer	Thickness (mm)	Outer diameter (mm)	Material
Interlock conduit	5.5	163	Stainless steel
Inner pipe	6.7	176.4	High density PE
Inner pressure armor	2.0 x 2	184.4	Carbon steel
Tensile armor	2.0 x 2	192.4	Carbon steel
Buoyant layer	51.8	295	Plastic tape
Outer sheath	7.0	309	High density PE

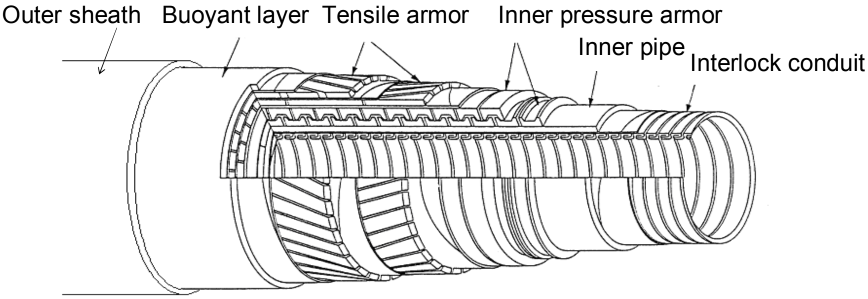

Fig. 6 Internal structure of the flexible riser pipe.

3.2 Submerged flexible riser pipe components

The flexible riser pipe remains submerged on the seabed until it is pulled up and connected to the LCO$_2$ carrier ship for the LCO$_2$ injection. The specifically designed components of the riser pipe as well as the design parameters are described below and illustrated in Fig. 7.

- A bend stiffener is installed at the topmost part of the flexible riser pipe to limit the bend radius.
- The flexible riser pipe is assumed to exhibit a free catenary configuration during the injection operation.
- A pipe protector is installed around the outer sheath of the section of the flexible riser pipe that is vulnerable to wear against the seabed as a result of the motion of the DPS-controlled LCO$_2$ carrier ship.
- An anchor to counteract the tension in the flexible riser pipe to protect the wellhead equipment is installed at the touch down point (TDP), see location *d. Anchor* in Fig. 7.
- A bend restrictor is installed to limit bending at the joint between the riser pipe and the wellhead equipment.
- An umbilical cable, used in controlling the wellhead equipment and charging the batteries in the communication buoy as well as monitoring the downhole data, is bundled together with the flexible riser pipe.
- The location of the seafloor-lying flexible riser pipe is transmitted to the LCO$_2$ carrier ship by a transponder set on the pickup wire.

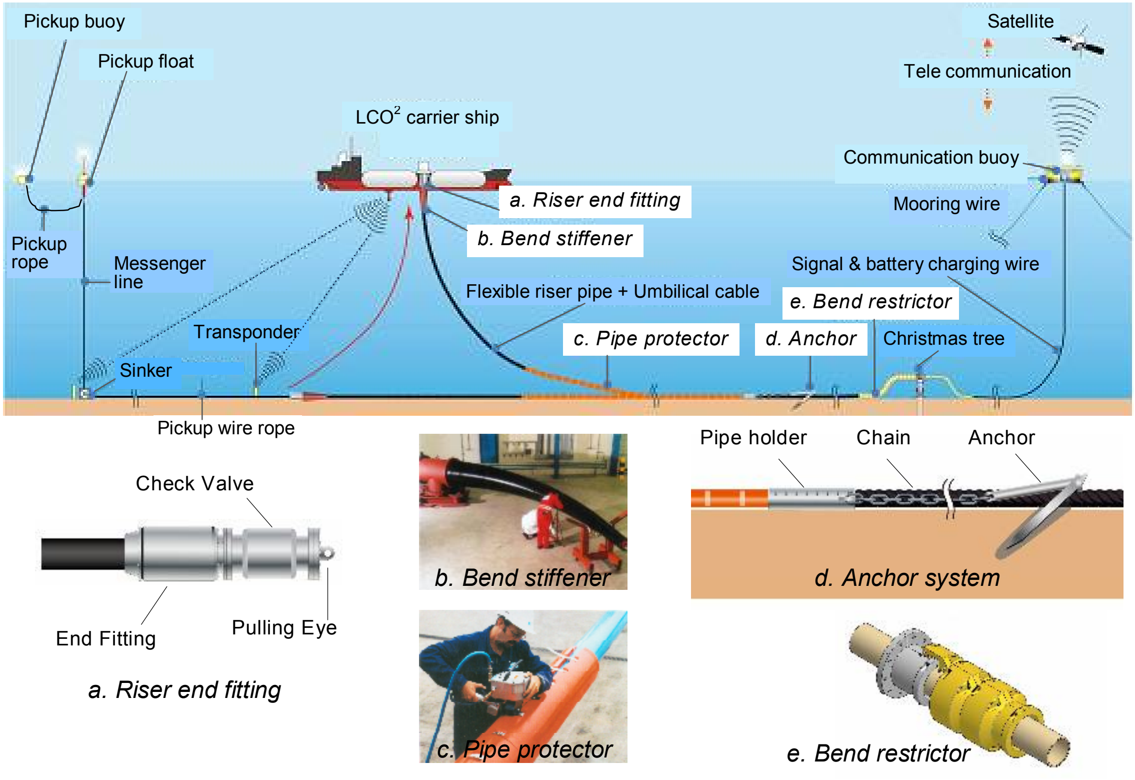

Fig. 7 Configuration of the flexible riser pipe system and its components.

4. Summary and Conclusions

i) Ship-based LCO_2 Transportation

The proposed ship-based LCO_2 subseabed injection system features LCO_2 injection equipment onboard a shuttle ship (3,000 m^3 LCO_2 load capacity) that has no need for any stationary sea surface structures at offshore CO_2 storage sites. The LCO_2 is injected at a rate of about 3,000 m^3/day into subseabed reservoirs via a flexible riser pipe that connects the shuttle ship to the wellhead.

ii) Offshore Facilities for LCO2 Injection

The proposed unmanned offshore facility for both mooring and injection features lower construction/maintenance costs and a safer operational environment than found in any manned stationary facility.

iii) Flexible Riser Pipe Pickup System

The riser pickup system consists of two basic elements, besides the riser pipe: shipboard equipment such as a coupling valve, crane, winches and A-frame and offshore equipment such as a pickup buoy, pickup float, messenger line, sinker and pickup wire rope.

iv) Flexible Riser Pipe

The flexible riser pipe (outer diameter, 309 mm), designed to withstand repeated cycles of being picked up from and laid back down onto the seabed, features an end fitting, bend stiffener, pipe protector, anchor system and bend restrictor that are designed specifically to increase longevity and facilitate the pickup procedure.

v) Future Work

A remotely-actuated quick-release coupling valve that can withstand an LCO_2 pressure of up to 10 MPa has to be developed. In addition, the umbilical cable, bundled with the flexible riser pipe and supplying electricity from the ship to both the seabed manifold valve and the communication buoy, requires a quick-release connector, which has yet to be designed.

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