TURBYLEC: DEVELOPMENT AND EXPERIMENTAL VALIDATION OF AN INNOVATIVE CENTRIFUGAL OIL – WATER SEPARATOR

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ABSTRACT 299795:

An innovative oil/water separator (TURBYLEC) has been developed in the frame of the HOVERSPILL™ European project (Fast Air Cushion platform for Oil Spill Remediation), partly funded by the European Commission's 7th Framework Program.

Conventional separation solutions are not appropriate to the remediation scenarios targeted by the HOVERSPILL™ project, mainly because low weight and compactness are absolutely required for transportation on a hovercraft. Namely, high separation efficiency, imposed to satisfy environmental legislation for water release, is particularly difficult to achieve with a compact separator when skimmed flow rate, oil content and density contrast are submitted to large variations.

This paper describes the development of a customized patented centrifuge separator devoted to the specific needs of the HOVERSPILL™ project. Conceptual studies, prototype manufacturing and experimental validation are described.

The TURBYLEC prototype tested at CEDRE's facilities has a bulk (size and weight) compatible with its integration on the HOVERSPILL™ platform. Tests results show that TURBYLEC matches with expected use (i.e. downstream of a non-selective skimmer). In this configuration, TURBYLEC separator shows very good oil / water separation performances for inlet oil contents up to 25%. In this range of operating conditions its cut diameter has been evaluated to 60 µm. In order to achieve the same separation performances as with TURBYLEC, which weighs only 70 kg (with liquids), it would be necessary to install an 8 m^3 gravity separator.

TURBYLEC separator has been developed for a very specific duty (i.e. for integration on an Hovercraft for Oil Spill remediation). Nevertheless, its proven performances render it particularly attractive, as a standalone system, for many other specific tasks in the field of oil spill remediation. It could also interest various other water treatment applications.

INTRODUCTION:

In the frame of the HOVERSPILL™ European R&D project, a dedicated air cushion platform (hovercraft) has been developed for oil spill fast response and post emergency interventions. The HOVERSPILL™ platform, illustrated on Figure 1, is an amphibious system mainly dedicated to operate on the transitional areas between land and sea, where shoals, difficult access areas and long distance from ports, make difficulties more relevant, and where traditional vehicles/vessels cannot access. During remediation this platform works as an independent power generator and one of its purposes is to operate as a mobile oil-water collection and separation unit.

FIGURE 1. HOVERSPILL™ PLATFORM (DEVELOPED BY HOVERTECH) TO BE EQUIPPED WITH TURBYLEC SEPARATOR.

In this context, a specific double stage collection and separation system had to be developed. This separation unit must be compact and light enough for installation on the hovercraft, as illustrated on Figure 2, or more generally for rapid transportation and installation in difficult access areas.

Low or moderate viscosity hydrocarbons are generally confined using floating booms. Then, a first stage separation is usually achieved by a conventional skimmer and volumetric pump system. As oil layer thickness is generally small within the confinement system, the oil - water mixture produced by the first stage separation system is usually water rich and may contain relatively small oil droplets. Residual oil content in separated water must be low enough for re-injection in the environment. For these reasons a high performance second stage separator is required downstream the first stage skimming and pumping system.

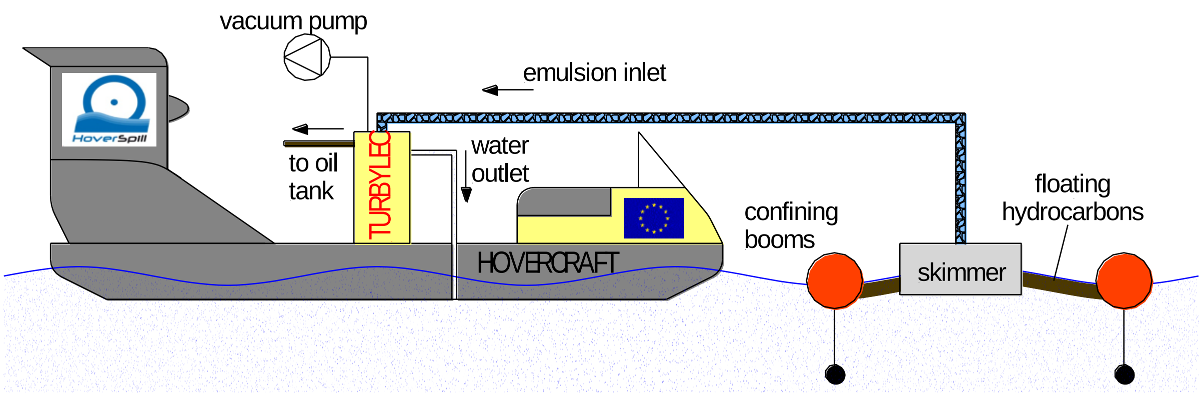

FIGURE 2. USE OF TURBYLEC SEPARATOR IN THE FRAME OF THE HOVERSPILL PROJECT.

Released water quality required to satisfy environmental legislation may be particularly difficult to achieve with a compact high capacity separator, especially when high flexibility is necessary to tolerate large variations of operating conditions in terms of skimmed flow rate, oil content and density contrast.

REQUIREMENTS:

Specificities of the HOVERSPILL™ context

Requirements concerning quality of separated water, to be released on site has been here-above mentioned. Large volume of emulsions are to be treated in most oil spill scenarios. Therefore it is necessary to reduce as much as possible the volume of residual water contained in separated hydrocarbons to be stored on board or in auxiliary floating tanks, or to be pumped to the shore.

It must be emphasised that the oil quality is never the same in oil spill remediation scenarios. The thickness of the oil layers may differ. The physical properties such as viscosity, relative density contrast or surface tension may vary largely. The oil may contain large proportions of water. These properties are not constant with time.

Detailed analysis of the scenarios targeted by the HOVERSPILL™ project leads to the following specifications for selection or development of an appropriate second stage separator:

- Inlet emulsion flow rate: 0 - 2 l/s (7.2 m^3/h)
- Hydrocarbons density: 800 kg/m^3 - 980 kg/m^3
- Weight (with liquid): < 100 kg
- Tolerate intermittent or continuous air ingestion
- Be able to handle a large range of Water-Cut (water content of emulsion): 0 - 100 %
- Easily dismountable on board for rapid cleaning in case of ingestion of foreign substances such as weeds, sand or stones.
- Cut diameter: < 100 µm

Cut diameter, is a very important parameter, which characterizes separation efficiency. It refers to the diameter of the smallest oil droplets that are all separated.

Existing solutions

An evaluation and comparison of different oil-water separation technologies was completed in 1992 in a project jointly sponsored by the U.S. Coast Guard R&D Center and the Marine Spill Response Corporation (Murdoch 1995). Conventional or existing separation solutions and their main limitations, regarding the specific requirements of the HOVERSPILL™ project, can be summarized as follows:

- Gravity separators are static and robust solutions that can handle large variations of operating conditions in terms of inlet flow rate, gas injection and Water-Cut. Their main drawback is that they are bulky and heavy, especially when they have to operate within a large range of hydrocarbons density and to ensure a low cut diameter. Nevertheless when weight is not a key limiting factor, gravity separators can often be considered as viable solutions for oil spill remediation (Gates 1985, Peigne 1993).

- Static cyclonic separators are well-known compact separation solutions (Bradley 1965). Their main drawback is that they can operate efficiently only within a narrow range of inlet flow rate (typically ± 30% of nominal flow rate) (Jones 1993). These systems are also very sensitive to density contrast. A complex control system is necessary to ensure a correct positioning of oil-water interface inside such separators. Furthermore, static cyclone performances are limited by the phenomenon of inlet autoemulsification at high injection velocity, which would practically limit cut diameter to approximately 500 µm for the present application. Some solutions using cyclonic flows have been specifically developed or adapted for oil spill remediation (Mensing 1971, Guerin 1977, Le Guen 1987, Simms 1992).

- Existing centrifuge separators, although they are quite efficient separation technologies (Harvey 1973), are usually too heavy for our specific need (their weight generally exceeds 1000 kg for the required flow rates). Moreover, their separation performances are very sensitive to density contrast. They are also generally quite sophisticated and thus not appropriate to oil spill remediation activities where rapid dismantling for cleaning is required.

- Another solution to be considered is the centrifugal oil-water separator, proposed by Ocean Therapy Solutions, which has been evaluated in the frame of the Alternative Response Technology (ART) Program following the Deepwater Horizon incident (Cortez 2012). This solution is based on the concept of annular centrifugal contactors (Meikrantz 1989).

- Other recent separation technologies, such as rotating cyclones, like the OPTISEP® separator developed by YLEC Consultants for TOTAL (Gay 2002), or the VORAXIAL® technology (Hansen 2011), have been taken into consideration. As well as centrifuge, rotating cyclones can operate in a large range of inlet flow rate, if compared to static cyclones. Furthermore they can ensure very low cut diameter and thus achieve very high separation efficiency. Nevertheless, they can require sophisticated and complex control system for operation with variable inlet conditions.

It has been decided to equip the HOVERSPILL™ platform with a dedicated rotating separator, which has to be specifically developed to operate with no level control system in wide ranges of density contrast and inlet Water-Cut.

SUGGESTED ALTERNATIVE SOLUTION:

In order to answer the very specific requirements for oil/water separation in the frame of the HOVERSPILL™ project, and the practical problems of cleaning and control, a totally new device, called TURBYLEC, has been designed and patented (international patent application WO 2013/113903).

Basic principle

TURBYLEC is a motorised rotating oil-water separator, able to handle large variations of inlet flow rate, and air ingestion. The flow within the separator is of the centrifugal, or solid rotation, type and the residence time is long enough (about 15 s) to establish a free interface between oil and water without control.

TURBYLEC is operated at a limited speed (1500 RPM) to prevent too much emulsification at inlet. Emulsification would result in a more finely dispersed emulsion to be treated, and consequently in an increased hydrocarbons content at water outlet.

Motorisation can be ensured by an electrical motor, but in the frame of the HOVERSPILL™ project, a small size and lightweight hydraulic motor will be used. This hydraulic motor will be fed by a high pressure hydraulic pump entrained by the diesel machine used for the hovercraft control and propulsion. This high pressure hydraulic entrainment solution enables to minimize the weight of components.

Detailed concepts of TURBYLEC separator (international patent application WO2013/113903)

A conceptual drawing describing the working principle of TURBYLEC is proposed on Figure 3. The emulsion enters the separator through a static vertical pipe (1) and falls in a secondary rotating pipe (2). Then the emulsion is pumped and entrained in rotation through the vanes (3) placed in the rotation induction stage (4) at the bottom of the separator.

Rotating emulsion enters the so-called separation chamber (5), which is also equipped with rotating vanes (6) that maintain solid rotation flow all along this chamber. Due to the rotation, the liquid is stuck to the outer wall (7) of the separation chamber. A gas core (8) is thus created at the middle of the device. Hydrocarbons droplets migrate towards the rotational axis under the effect of centrifugal forces (9). After some time, an oil-water interface (10) is created between the air core and the outer wall. Water is free to escape through orifices (11) placed at the outer diameter and at the top of the separation chamber.

Clean water enters an outlet passage (12) and can be freely eliminated over a rotating water weir (13). Oil, due to its lower density, is evacuated over a second rotating weir (14). For a given density contrast, the radial locations of oil and water weirs impose the location of the oil-water interface within the separation chamber. The consequence of specific arrangements is that TURBYLEC can operate optimally within a great range of operating conditions, which means with no entrainment of the separated oil layer through water outlet, nor entrainment of the separated water layer through the oil outlet. Only the water weir must be changed, in some particular applications, where oil density is likely to vary within a wide range. This eliminates complex control and measuring systems which would be necessary in cyclonic separators for example.

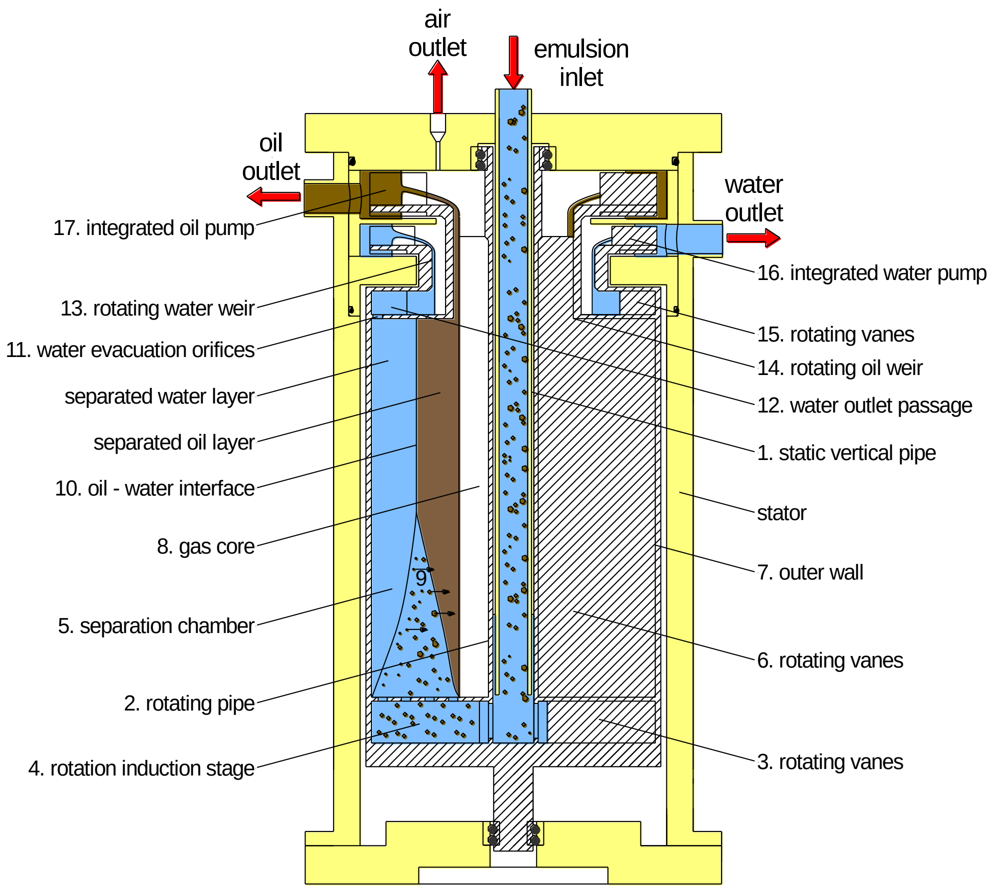

FIGURE 3. PRINCIPLE OF TURBYLEC SEPARATOR - CONCEPTUAL DRAWING (INTERNATIONAL PATENT APPLICATION WO2013/113903).

There are two ways to pump the emulsion skimmed from water surface. A first technique can consist in using a volumetric pump, which permits a transfer of fluid with no expected major emulsification. In this case, the pressure in the separator can remain atmospheric, which simplifies the use of the system, since separated liquids can be simply eliminated by gravity without any additional pump. A second solution can utilize a vacuum pump as shown on Figure 2. Then, pressure in the separator is slightly below atmospheric pressure (~ - 0.1 bar), and the system (skimmer + suction line + separator) operates somewhat like a vacuum cleaner, sucking oil and water from water surface, releasing clean water an collecting oil. In this case, extraction of separated liquids can require two pumps (16 and 17) which are integrated to the separator.

The built in pump stages, can be made of rotating vanes, entrained with the separator rotor. They can produce pressure increase up to 2 bar, which enables for instance to pump oil over a relatively long distance for proper storage.

EXPERIMENTAL VALIDATION:

Experimental prototype

A prototype has been realized to validate the theoretical concepts of TURBYLEC separator. The rotor, which is a quite complex element, has been produced as one single piece by Selective Laser Sintering (SLS), which is a rapid prototyping technique. NYGLASS material, which is a combination of fiberglass and nylon, has been selected for this component, which must be light and strong. This approach simplifies very much the mechanical conception and the mounting of the system.

Other parts of the separator, such as the stator, are realized in marine aluminum with more conventional techniques (i.e. machining and welding).

The prototype is equipped with a 5 kW electrical motor with variable speed drive. This entrainment solution, which provides more flexibility than a hydraulic motor, has been preferred for the purpose of prototype mechanical set-up and laboratory testing.

The TURBYLEC prototype realized and used for experimental qualification is illustrated on Figure 4 :

(a) is a conceptual 3D drawing of the rotor (outer wall excluded),
(b) is a photograph of the one-piece NYGLAS rotor,
(c) is a photograph of the final system with its electrical control panel (left) and vacuum pump (below separator).

(a) (b) (c)

FIGURE 4. TURBYLEC PROTOTYPE FOR EXPERIMENTAL VALIDATION OF CONCEPTS.

Mechanical qualification and set up tests of this prototype have been successfully carried out at ACTR (Air Cushion Technologies Research Center). These preliminary tests also confirmed the expected hydraulic performances of the system. This includes:

- the functioning of the two integrated pump stages for extraction of separated liquids,
- autonomous pumping of inlet emulsion by use of the vacuum pump.

Separation tests

Separation tests have been mainly carried out at CEDRE's facilities. Various experimental configurations have been studied to test the concepts of the separator and to prove the robustness of the solution. Liquids tested include low viscosity hydraulic and engine oil or moderated viscosity hydrocarbon in combination with fresh water or sea water. Inlet emulsion was either pumped by a volumetric pump or sucked using the vacuum pump. Separation efficiency has been proven with different types of mixtures: coarsely mixed oil and water flows, dispersed Oil in Water emulsion generated by a first stage skimming and pumping system, or extremely finely dispersed Oil in Water emulsion produced by a high pressure pump and an in line mixer.

The present article focuses on the results obtained with the experimental lay out described on Figure 5, which is the most representative of a real HOVERSPILL™ scenario. This experimental configuration includes a multistage skimming and separation system comprising a conventional mechanical self-adjusting weir skimmer (DESMI Terrapin, illustrated on Figure 6), a volumetric hydraulic driven lobe pump (BORGER AL25) and the TURBYLEC separator.

The water tank is initially filled with 10 m^3 sea water. Then, the TURBYLEC motor and the pump are turned on at respectively nominal speed (1500 RPM) and nominal flow rate (2.7 m^3/h). The test begins as 50 liters hydrocarbons are poured in the water tank. Oil spillage forms a 5 mm thick hydrocarbon layer, which is progressively skimmed (see Figure 6), together with an increasing proportion of sea water. Test duration, for complete cleaning of the reservoir surface is approximately 12 minutes. Samples are collected at separator inlet and water outlet every one minute for measurement of hydrocarbon contents. The oil concentration in water was measured by UV-spectrophotometry at 580 nm after extraction of a water sample by dichloromethane which was then dried over sodium sulfate prior to the measurement.

Hydrocarbon can be considered as representative of a moderated viscosity hydrocarbon with a viscosity of 1000 cSt and a density of 0.94. Test temperature was approximately of 10°C. The viscosity of the oil samples was measured by establishing the rheological curve using a Haake VT 550 viscometer at the test temperature to get the evolution of the oil viscosity at dedicated shear rates (10, 20, 50 and 100 s^{-1}).

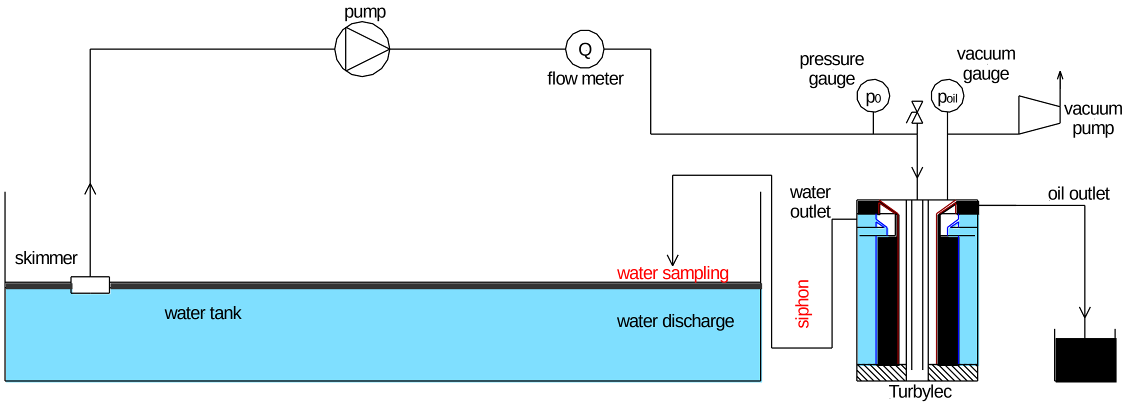

FIGURE 5. FLOW LOOP FOR EXPERIMENTAL CHARACTERISATION OF SKIMMER + PUMP + TURBYLEC SYSTEM.

FIGURE 6. MECHANICAL SELF-ADJUSTING WEIR SKIMMER IN OPERATION.

Main results: performances of the multistage skimming and separation system

Raw results of the tests are illustrated on Figure 7, in terms of inlet hydrocarbon content (inlet Oil-Cut) and residual hydrocarbon content (OiW) at water outlet. Oil-Cut at separator inlet ranges from 40% to 2% for the duration of the test. For these inlet conditions, OiW contents at separator water outlet are limited to 1000 ppm and decrease down to some 30 ppm. For 20% inlet Oil-Cut, residual HC content at water outlet is limited to 600 ppm which can be considered as very satisfactory for the targeted application. Two series of tests are compared and show a good reproducibility.

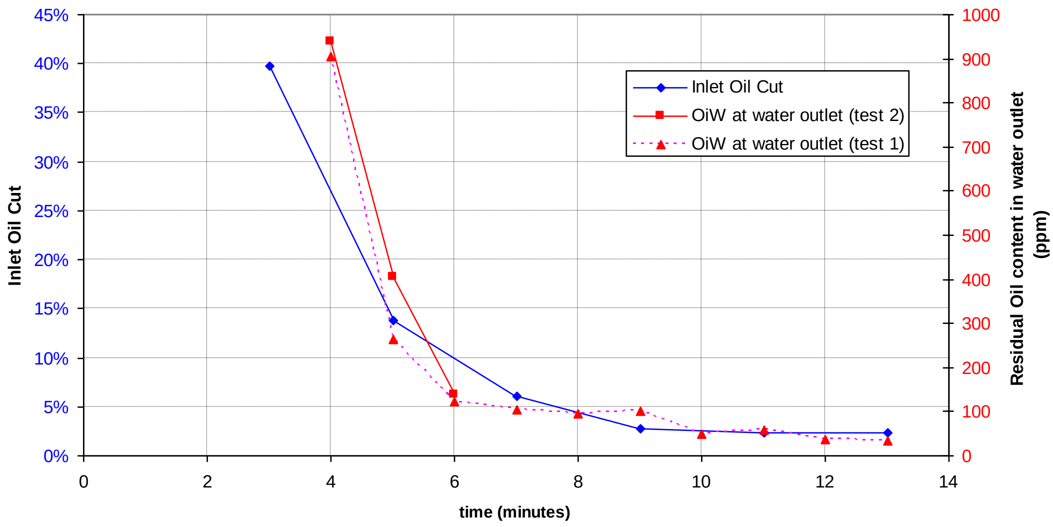

FIGURE 7. RELATIONSHIP BETWEEN INLET OIL CONTENT AND OIL CONTENT IN WATER OUTLET. TESTS OF 18 APRIL - SYNTHESIS.

Dependence of OiW at water outlet with inlet Oil-Cut is summarized on Figure 8. TURBYLEC performances can also be illustrated in terms of separation efficiency or percentage of separated hydrocarbon $\eta_{sep} = \frac{OC_{in} - OiW_{out}}{OC_{in}}$ (OC_{in}: inlet Oil-Cut, OiW_{out} : hydrocarbon residual content at water outlet). For tested operating conditions (i.e. for inlet Oil-Cut up to 25%), separation efficiency is systematically higher than 99.7% and reaches almost 99.9% for 5% inlet Oil-Cut (Figure 9).

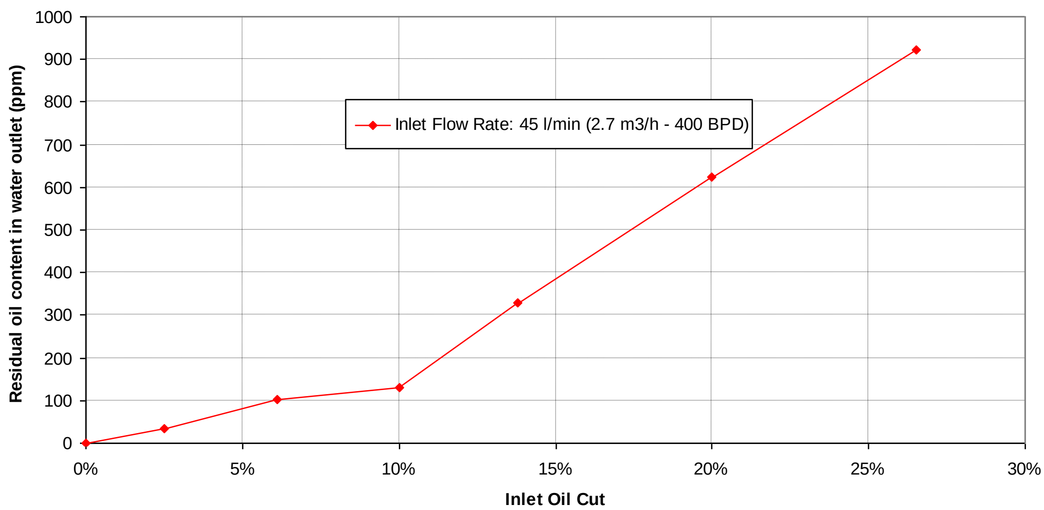

FIGURE 8. HC CONTENT AT WATER OUTLET VERSUS INLET OIL CUT.

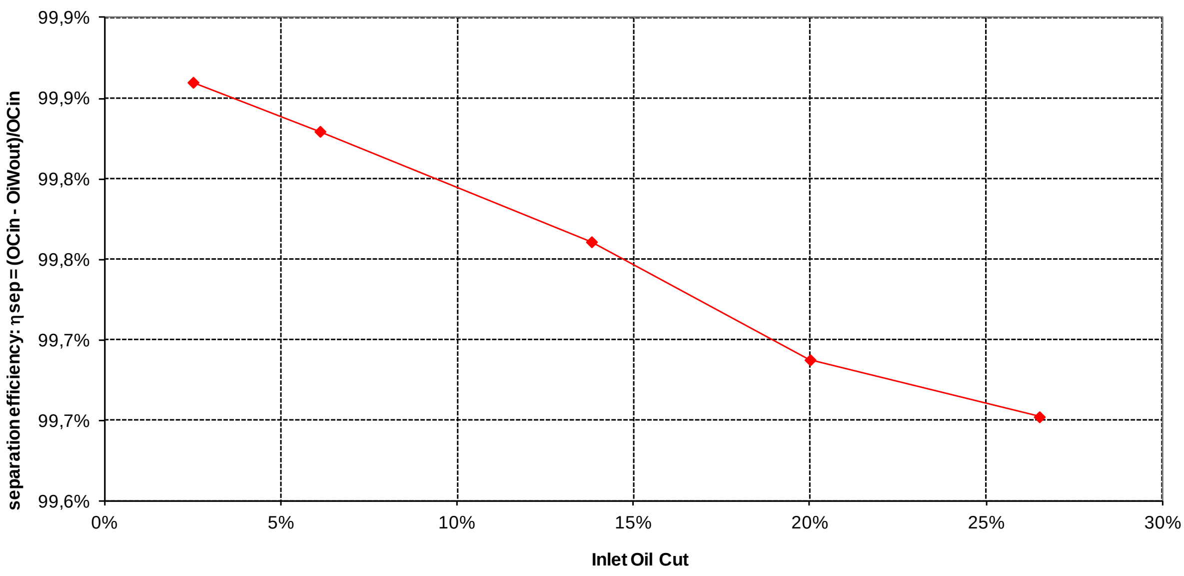

FIGURE 9. TURBYLEC SEPARATION EFFICIENCY VS. INLET OIL-CUT.

Absolute performance of TURBYLEC separator: cut diameter

A dedicated basic experimental methodology has been conducted in order to evaluate the droplet size distribution produced by the skimming and pumping system which delivers inlet emulsion to TURBYLEC. The procedure is somewhat similar to the so-called "jar test". Some “primary samples” are collected at pump outlet at various time after starting the separation test. These primary samples are stored for droplets settling. At various times after primary sampling, “secondary samples” are taken at the bottom of each primary samples. These secondary samples are analyzed in laboratory for OiW measurement. The residual Oil in Water content in secondary samples decreases with time as a result of droplets settling within primary sample. This is illustrated on Figure 10 for two primary samples collected after 1 minute and 10 minutes. This settling can be related to droplets size distribution. YLEC Consultants has developed a dedicated software to solve this problem. This numerical tool can be used to determine droplet size distribution at TURBYLEC inlet during separation test.

Our conclusion is that the inlet droplet size distribution (dsd) is close to the one illustrated in blue on Figure 11. This “most suitable” dsd is close to a well-known Rosin-Ramler distribution with droplets diameters smaller than 1 mm, as illustrated in red on Figure 11. Nevertheless, when focusing on dsd at small diameters, one can notice that the dsd produced by the skimming and pumping system contains much smaller droplets. This proportion of fine droplets makes the inlet emulsion very difficult to separate, unless the separator can ensure a very low cut diameter.

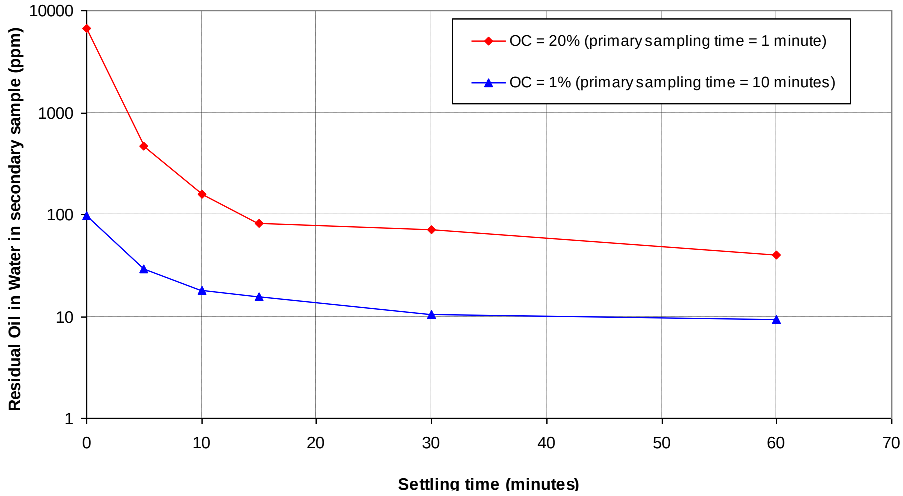

FIGURE 10. MEASURED RESIDUAL OIW IN TWO PRIMARY SAMPLES. SETTLING TIMES REFER TO SUCCESSIVE SECONDARY SAMPLING.

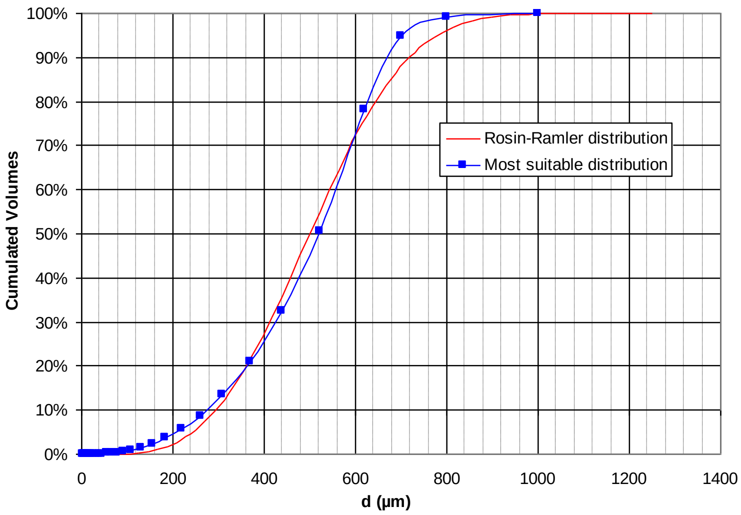

FIGURE 11. DROPLET SIZE DISTRIBUTIONS AT SEPARATOR INLET. INFLOW EMULSION PRODUCED BY THE FIRST STAGE SKIMMING AND PUMPING SYSTEM.

Taking into account this inlet dsd as well as the evolution of residual OiW at water outlet with inlet Oil-Cut, the cut diameter of TURBYLEC separator can be experimentally determined. This type of results, shown on Figure 12, illustrates the absolute separation performances of TURBYLEC. For inlet Oil-Cut up to 25% approximately, the separator cut diameter is between 50 µm and 70 µm.

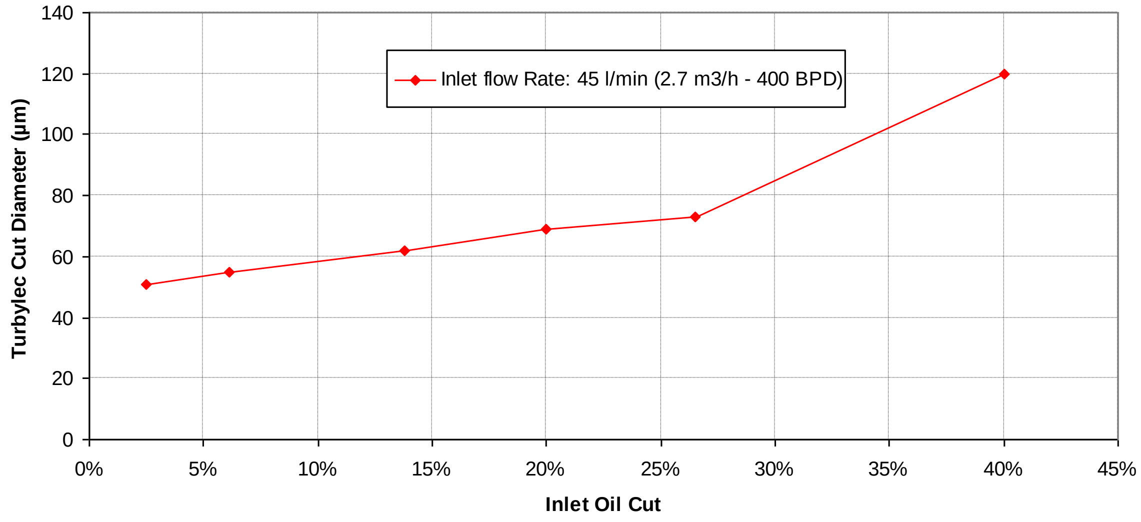

FIGURE 12. TURBYLEC SEPARATION PERFORMANCES AT 45 L/MIN INLET FLOW RATE.

CONCLUSIONS:

The prototype of centrifugal separator TURBYLEC tested at CEDRE has a bulk (size and weight) compatible with its integration within HOVERSPILL™ platform (height: 1 meter, diameter: 380 mm, weight (with liquid): 70 kg).

Tests results, summarized on Figure 13, show that TURBYLEC matches with expected use (*i.e.* downstream of a non-selective skimmer). In this configuration, TURBYLEC separator shows very good oil / water separation performances, for inlet Oil Cut up to 25% approximately. In this range of operating conditions the separator cut diameter has been evaluated between 50 µm and 70 µm for 2.7 m^3/h inlet flow rate. In order to achieve the same separation performances, it would be necessary to install an 8 m^3 gravity separator.

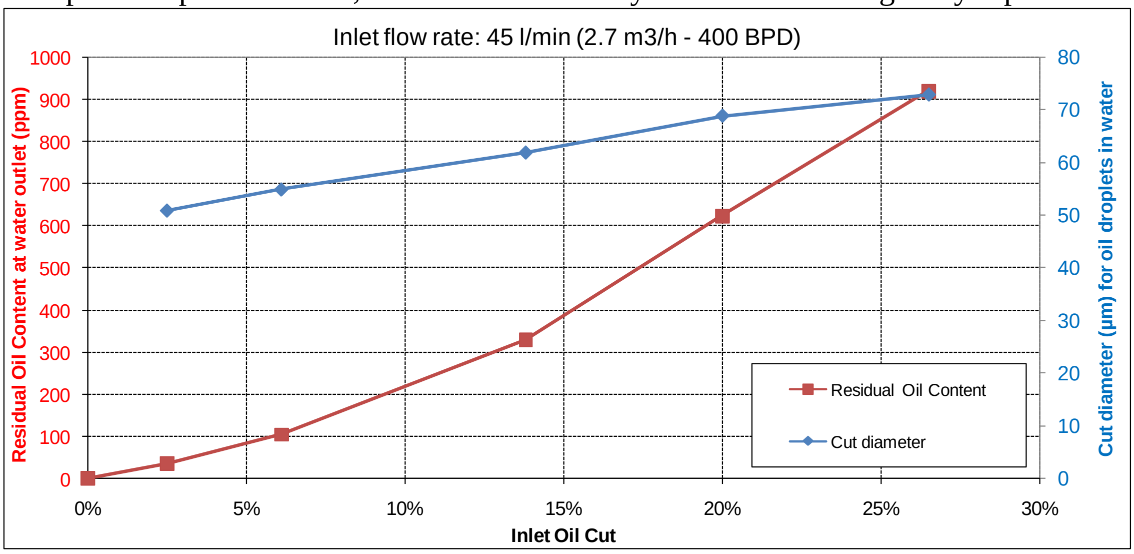

FIGURE 13. SUMMARIZED PERFORMANCES OF TURBYLEC SEPARATOR.

Although, TURBYLEC has been specifically designed for installation on a hovercraft, it can also be transported on site as a separate tool for oil spill remediation. It can also be considered as a very attractive separation device for various industrial applications. Considering its low cut diameter for moderate inlet Oil-Cut (<25%), it can mainly interest water treatment issues with with finely dispersed oil droplets, amongst whose the treatment (in port facilities or on board) of wastewater resulting from the discharge of crude oil tanks used as ballast.

The main innovative characteristics of patented TURBYLEC separator with respect to the state of the art can be summarized as follows:

- TURBYLEC can work in a wide range of density contrast.
- It can be relatively simply dismantled on board for rapid cleaning.
- It integrates built-in innovative rotating oil and water pumps.
- Its a very light system: 100 kg vs about 1 ton with conventional centrifuge systems for the same flow rate.
- It does not need any control such as level or pressure adjustment.

ACKNOWLEDGEMENTS:

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