NON-RADIOACTIVE SLURRY DENSITY MEASUREMENT FOR INLAND DREDGERS

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Abstract: Inland dredgers are only moderately equipped with dredging sensors. Notably, small dredging contractors resign from use of conventional radioactive density transmitters, due to the difficulties and additional costs of the special safety regulations regarding use and transportation. As a consequence, the operator is left without any feedback about the crucial parameter of the pumped mixture. To address this problem, IHC Systems initiated the development of a non-radioactive slurry density measurement suitable for inland dredgers.

The resulting patented device is a kind of electric transducer, where a beam of electromagnetic energy is used to radially penetrate the centre of the pipeline. Information about the amount of solids, averaged over the whole measurement pipe volume, is obtained.

Prototypes were built and tested in laboratory and finally placed onboard an inland dredger for long duration field tests. We noticed that the presence of the density meter boosted the efficiency of the vessel up to 50%. Currently, the technology is only applicable for inland river water environments, where electromagnetic absorption due to water salinity is manageable. Further developments of this technology are in progress to test the applicability for sea water conditions.

Keywords: density measurement, non-radioactive, efficient dredging

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1 INTRODUCTION

Modern control engineering, applied in the dredging industry, brings about strong improvements to dredging efficiency. The implementation of control engineering drives the dredging equipment manufacturers to place more and more sensors to monitor the excavation and slurry pumping process. Mixture density is among the most basic and vital parameters to be monitored. To measure mixture density, the gamma gauge, an ionising radiation based measurement is commonly used and considered the high standard in the dredging industry (see figure 1). The usage of a radioactive isotope is however, the main drawback of this method. Despite the radioactive source is contained in a protective casing, providing the highest level of radiation shielding, the system is still subject to very strict radiation safety regulations. Permits for operation, as well as separate ones for transportation and storage need to be issued by a national radiation safety authority. This causes additional cost of ownership and extra bureaucratic and logistic attention. A hurdle, small inland dredge operators are reluctant to take. Hence, many small dredgers operate without a density measurement, resulting in loss of dredging production and efficiency. It also increases the environmental costs like excessive fuel and lubricants usage, CO_2 emissions, and sediment spill, to name a few. Given the mentioned drawbacks, the inland dredging segment will be greatly helped by having an alternative, non-radioactive density measurement available.

Figure 1. The RadioActive (RA) density meter, commonly used in the dredging industry

Developing an alternative method is no trivial matter, though. It is very hard to find a measurement principle which can accurately measure the mixture density, composed of any type of dredged soil, while tolerating the range of environmental and process conditions. These include e.g. violent pressure fluctuations, vibrations and a range of flow velocities in the slurry pipeline. And above all: resistance to dredging wear and tear. The robustness and versatility of the current radioactivity-based system set the bar very high for an alternative, attempting to replace it.

Royal IHC devoted many years of research and development efforts to a system which would provide a dredging proof and radioactivity-free density measurement for the inland dredging sector. We aimed to find an apparatus which can sense density in across volume of the pipe, to closely resemble the RA density meter operation. In this paper, we present the development of a patented density meter which uses radio waves to sense the volume ratio of the total dry solids present in the carrier fluid. First, the theoretical background and the shape of the meter is presented. We discuss the mechanical and electrical design, followed by a description of the testing method we adopted. The final step of the development included long term trials onboard an inland dredger. Results and conclusions from this valuable experience will be presented in the last section.

Since the **R**adio**A**ctive density transmitter is commonly referred with the acronym "**RA** meter", the new system will be called "**RF** meter" abbreviated from the **R**adio **F**requency technique.

2 MEASUREMENT PRINCIPLE

Our measurement method relies on characterising the slurry in terms of its electrical parameter, namely the dielectric permittivity (which quantifies the materials resistivity to an external electric field). Water has the highest relative permittivity ($\varepsilon_r=79$) among all natural materials, whereas soil exhibits a relatively low value ($\varepsilon_r \approx 4$ for quartz sand). This contrast – of an order of magnitude – implies that even the smallest addition of solids into the water will result in a detectable reduction of the total mixture permittivity. Thus density can be calculated by relating the measured permittivity of the mixture to the permittivity of water.

To obtain the mixture permittivity, we consider a radio-frequency transmission measurement geometry, where the slurry pipeline is fitted with a pair of collinear antennas, see figure 2. An electromagnetic (EM) field, excited by a transmitting antenna (T_x), propagates across the pipe and is picked up by the receiving antenna (R_x). The complex transmission coefficient, consisting of magnitude and phase, characterising the propagation of electromagnetic wave in the mixture, must be obtained by an advanced electronic device.

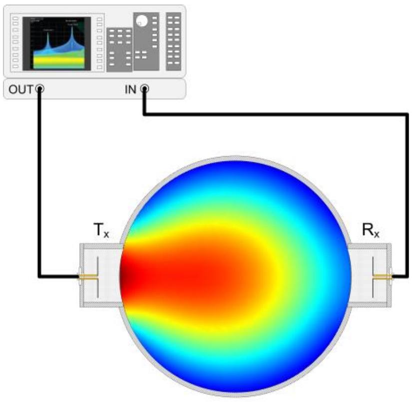

Figure 2. Schematic view of the measurement principle in the slurry pipe. The colour map shows the intensity of the EM field emerging from the transmitter antenna

The colour map in figure 2 is a result of a computer simulation, visualising the electric field intensity. We see that the beam of electromagnetic energy is being transmitted, and the whole volume of the pipe is penetrated. Consequently, the measurement principle represents the mixture density averaged over the entire cross section of the pipe.

This measurement principle is greatly influenced by the salinity of water. Natural bodies of water contain varying amount of salts which cause it to be electrically conductive. That, in turn, causes attenuation of the electromagnetic wave. With rising conductivity, the amplitude of the received signal will drop exponentially. When the received signal falls below a minimum discernible signal required by the measurement instrument, the density cannot be measured anymore.

The electrical conductivity is measured in Siemens per meter (S/m, S is the reciprocal of the resistance unit Ω). Conductivity of natural waters depends on the location and the distance to the coast, see figure 3. Fresh river water, as well as household tap water, is practically non-conductive. River water close to the delta regions reaches 0.2 -0.3 S/m. In the estuaries and harbour areas where fresh water mixes with highly saline seawater, the conductivity rises abruptly. In this region, the electromagnetic wave is already substantially attenuated. Seawater, which is defined as 4 S/m and above, may practically block the radio wave propagation. We set the design requirement that the system must be operational in brackish water, up to 1 S/m, which should be sufficient to maintain operation for most of the estuary waters the inland dredger can encounter.

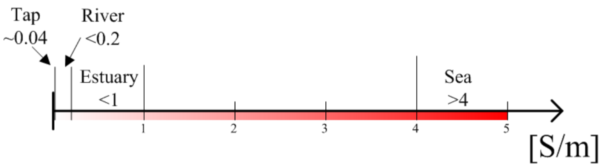

Figure 3. The scale of water conductivity

3 DESIGN & DEVELOPMENT

The development effort focused on converting the principle of operation into an industrial, robust hardware version density measurement for dredging slurry. Implementation requires the design of an entirely new type of measurement pipe, followed by the development of the measurement electronics. Then the complete system must be tested in a controlled laboratory environment to validate the theoretical model we developed, and perform fine-tuning of the system.

3.1 Mechanical design

Our aim was to create a new sensor, embodiment of which will be compatible with a standard RA measurement pipe, to offer drop-in exchange between the systems in the future. The 500 mm diameter pipe size was chosen, as it matches the top-end range of slurry pipeline used among the inland dredgers.

As shown in figure 2, the principle of operation requires two openings in the pipe wall, placed collinearly on the opposite sides of the pipe. That will allow the electromagnetic wave to couple into and from the pipe volume. The opening is backed by a cavity, which holds the antennas. The implementation of this structure is patented by Royal IHC and took the form of rectangular flanges, oriented axially along the pipe. The flanges are enclosed by flat lids (see figure 4). The size and construction of the flange and the lid was optimised so that the mechanical integrity of the pipe is not compromised, and can withstand the nominal working pressure. To provide protection of the antennas, the cavity was filled with the high endurance irathane polymer, well known in dredging industry for its wear resistance. The surface of the irathane inside the pipe has the same curvature as the pipe wall, resulting in a flush, protrusion-free pipe cross section, as shown in figure 4. The lid, antenna and the irathane comprise a monolithic block. In case of damage, this assembly can be detached from the pipe and replaced by a spare.

Besides the antennas, the mounting flanges for the radioactive transmitter and detector units were included in the prototype pipe. That allows to fit the RA density system, providing a reference measurement for validation of the RF meter performance.

Figure 4. The non-radioactive RF density measurement pipe. A rectangular flange lid hiding the antenna (left), and the irathane flush-mounted dielectric windows on the inside of the pipe are visible (right)

3.2 Electronics

In figure 2, we schematically indicated that the measurement is performed by a network analyser. In practice, we will not use laboratory equipment, but a robust, custom-built electronic circuit to handle the high-frequency measurement signal. The function of the circuit is to provide the electromagnetic stimulus signal for the transmit antenna and to detect, filter and amplify the faint signal from the receiving antenna.

Then, by comparing the magnitude and phase of the received signal with the stimulus, the complex transmission coefficient is obtained. Our design followed a typical modern radio transceiver architecture, where the transmitted waveform is generated, and then the received waveform processed in a digital domain, by a microprocessor (CPU). An analogue RF front-end is placed between the processor and the antennas, with separated transmit and receive paths, to provide signal filtering and amplification. The conversion between the digital and analogue paths is done by the digital to analogue and analogue to digital converters for the transmitting and receiving paths respectively.

Instead of designing a standalone electronic containing both analogue and digital parts, we used an existing signal conditioner of the type IHC MMU001 as a base platform for the development. MMU001 already contains the digital signal microprocessor required for demodulation of the measurement waveform, as well as all peripherals to communicate with the ship automation systems. What was needed to be done is to add the RF signal readout channels. Thus, the RF front-end took the form of a PCB daughterboard, which could be plugged in into the MMU001, converting it from a standard RA signal conditioner into a non-radioactive RF density measurement.

Dredging imposes a specific requirement regarding the transmit and received signal power. The system must have a very large dynamic range to accommodate signal strength swings during operation. For example, the system must seamlessly handle the transition from an empty pipe, when the signal is subject to virtually no losses, to the pipe filled with brackish water, when attenuation rises in a split of a second by 160dB (= reduction of signal amplitude by one hundred million times). An advanced power control scheme was implemented. The system continuously monitors the received signal strength, as well as the condition of the transmitter antenna, and adjusts the transmitter power to maintain an optimum signal level.

3.3 System architecture

The two main components of the system are the measurement pipe and the RF-enabled signal conditioner, see figure 5. The pipe can be located at any point of the slurry pipeline, both indoor or outdoor, with vertical or horizontal orientations. The signal conditioner can be placed in a location convenient for the crew, and the connection between pipe and signal conditioner is realised with two coaxial cables carrying input and output signals. The transmitting antenna panel contains a RF booster amplifier. It is connected between the output of the signal conditioner and the transmitting antenna, to amplify the transmitting signal to a power level of several dozens of watts. With this configuration, the transmission of an high power radio signal through the coaxial cable is avoided. So, the high power radio signal will only be present inside the pipe and is completely shielded to the outside world. The amplifier requires a normal 24V DC power supply. The RF signal booster is the only electronic device on the pipe, supplemented by several passive filters and terminals.

For the purpose of intended tests with the new prototype, we fitted it with a standard radioactive density transmitter. It will act as a reference measurement for the density. The RA density gauge is connected directly to the signal conditioner motherboard, since that is its primary function.

The basic version of MMU001 conditioner is a robust, marine-grade piece of equipment with proven record on hundreds of vessels. It, therefore, contains all the input and output interfaces required by maritime environment. Specially the analogue, serial and industrial Ethernet interfaces can be used to facilitate with any automation or data collection system. The presented architecture is an independent platform to be used for both the laboratory research and field tests.

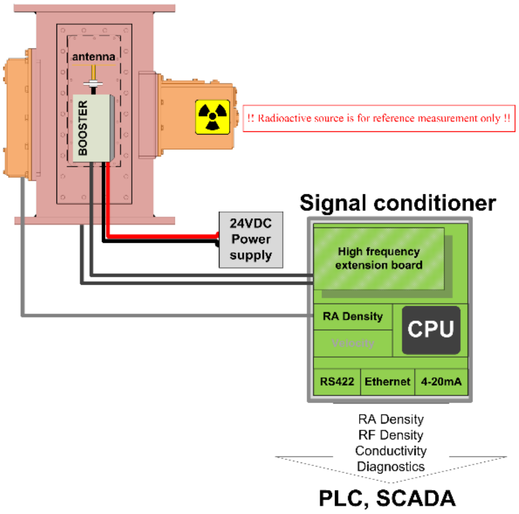

Figure 5. The architecture of the total experimental system. Note: the radioactive density transmitter is added to provide reference measurement only, RA is not part of the final system

3.4 Safety

The RF density system is totally free from ionising radiation and only uses radio waves. The highest power signals, with a maximum power of 75W, only exist after the power booster on the pipe. The power is fed to the antenna, which converts it to electromagnetic waves, directed towards the centre of the pipe. The steel structure of the pipeline provides 100% screening from any electromagnetic waves. Thus, under normal operation, the electromagnetic waves are entirely contained in the pipeline. The only time the crew could be exposed to the EM field is during maintenance work, when the measured pipe is opened, which would allow the radio waves to escape the pipe volume. In that case, the first obvious step before commencing any work around the pipe would be to power down the system and disconnect the cables. Without power supply, no EM field can be emitted.

If we want to analyse an unlikely, worst case scenario, we can consider the situation, when the measurement pipe is taken out of the pipeline without powering it down. In this case the power adjustment mechanism, described in section 3.3, would detect the pipe is empty and reduce the output power to a minimum. The resulting EM emission emerging from an open flange of the measurement pipe would be lower than the emission from a regular WiFi router.

Nowhere else in the system, high-intensity fields, nor high voltages exist. On top of that, the system complies with the IEC 60945 norm regarding the electromagnetic emissions with respect to maritime radio communication and navigation equipment.

Finally, if we note that the highest voltage in the pipe and cabling is the 24 VDC to supply the booster amplifier, we conclude that the RF density system is an inherently safe apparatus both for humans and for other on-board electronic equipment.

3.5 Laboratory trials

The proposed measurement principle and the developed hardware had to be validated by series of laboratory trials. We opted for full scale tests with a flowing slurry. This brought the challenge of finding a suitable hydraulic transport test circuit, capable of handling a 500 mm diameter pipeline. Availability of such a system is scarce. We thus decided to develop a custom-made and independent circuit, using the in-house expertise and facilities of the IHC MTI laboratory.

With a bit of clever engineering, a small-scale test circuit, housing a full-scale prototype was erected, see figure 6. The central piece was a vertical water column, 500 mm in diameter, containing the RF prototype. A high-speed water jet from a small centrifugal pump was fed into the column. As a result, a downward, laminar fluid flow was created inside the prototype pipe. Sand could be added to the circuit manually, in portions, to gradually increase the density. Sand once added, circulated continuously in the circuit, providing a stable condition for measurement.

First trial runs surprisingly showed, that despite its simplicity the circuit was able (after a slow and tedious filling process) to reach and maintain a density exceeding 1.7t/m^3. Secondly, by adding salt (NaCl) to the water at any point of the test run, the response of the system to brackish water could be tested. With the constructed setup, we were able to create and test the RF system against the full range of mixture conditions that could be encountered in real operations.

Figure 6. The small scale test circuit with two stacked RF measurement pipes (orange and brown) are visible. The transparent high flow water pipe, used to agitate the flow in the column, is visible to the left

As stated in previous sections, the RF system was fitted with the RA system on the same measurement pipe. Thus both measurements intend to measure exactly the same mixture. In addition, both the RF density and the reference RA density values are computed by the same signal conditioner unit. Thus both spatial (location) and temporal (synchronization) consistency between the two measurements was achieved. This enabled us to directly compare the two indications and determine the accuracy. By accuracy, we mean the full-scale root mean square (RMS) error between the indication of RF density measurement and the RA density measurement. In figure 7, a typical test run is presented. We can see the density from 1.0 t/m^3 (water) rising up to 1.7 t/m^3. The full-scale RMS error for the data presented is below 1.0%.

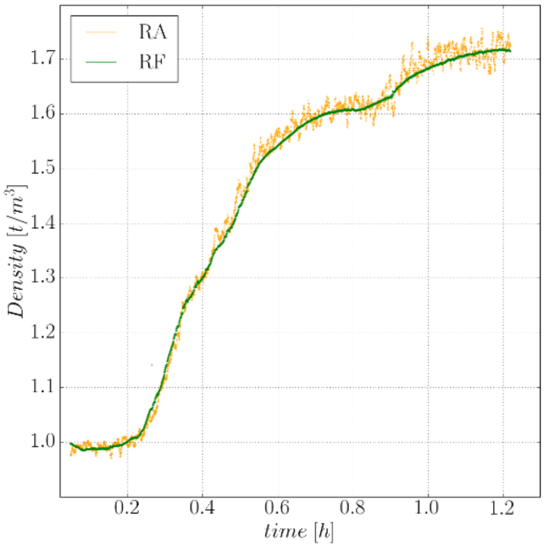

Figure 7. Test run of a density sweep in the laboratory circuit

4 FIELD TESTS

The final step in the development was to have the RF system validated in a real life dredging operation. The objectives were to first check the developed model in practice, especially in fresh river waters and low conductive estuary waters. Secondly, to check whether the system design is robust and ready for autonomous work on a dredger. Finally, the field trials would provide scenarios which were not possible to test within our test circuit: the dynamically varying density and operation with different types of soils.

4.1 Installation

Field tests require a vessel which is compatible with our 500 mm measurement pipe and operates away from seawater. We made an agreement with Dutch Dredging B.V. to install our system on their hopper dredger CORNELIS SENIOR. The RF prototype was installed in the pump room, in the vertical section of the discharge pipe just above the pump outlet. The signal conditioner was mounted next to the pipe. A picture of the installed pipe is shown in figure 8.

This ship was a perfect test ground, not only due to its availability and profile of operation. The ship originally had no production measurement equipment of any sort. The lack of a density measurement, nor any experience among the crew, is a proper initial condition to assess the impact the density measurement has on the production and efficiency of the ship.

4.2 Results

The ship operated in various locations along the Merwede and Waal rivers in The Netherlands. At each location, the operation agreed with the laboratory model. No significant deviations between RA and RF indications were observed. The ship worked with several sand grades, but we didn't notice dredging any other material than quartz sand. In no case the type of sand was causing deviation. Example of a dredging cycle with fresh river water is presented in figure 9. Also visible is the system's response to rapid density changes. The system is fast enough to track every density peak.

Figure 8. The RF density measurement prototype as installed inside the pump room of the CORNELIS SENIOR. The signal conditioner (silver box, to the left) is also visible

In the neighbourhood of Rotterdam, the ship encountered brackish water. This cycle is presented in figure 10. Water conductivity reached 0.6 S/m, and the system remained operational. The RMS accuracy is slightly degraded due to the variations in conductivity.

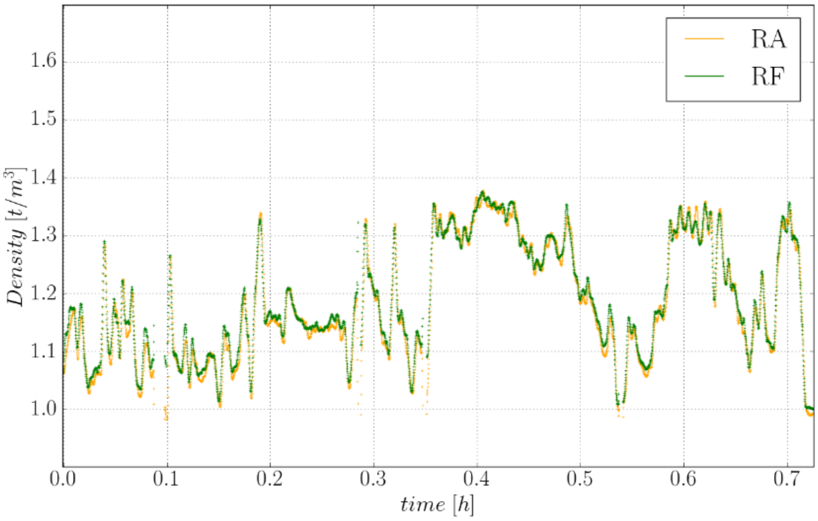

Figure 9. The performance of the RF density measurement obtained onboard CORNELIS SENIOR, dredging in fresh river water. The RMS deviation of RF with respect to RA was <1.0%

4.3 Observations

Based on the experience of dredging in estuary waters, we could draw practical conclusions regarding the applicability of the RF system. We noticed that the system operates normally as long as the maximum water conductivity of the pumped slurry is not exceeded. In practice, we discovered that the ship must stay away from regions where river water mixes with seawater. In those regions, water at the riverbed is severely more conductive than the conductivity of surface water. Thus, measuring a sample of water during project survey may not be enough to predict whether the conductivity will stay within the limit of operation of the RF meter.

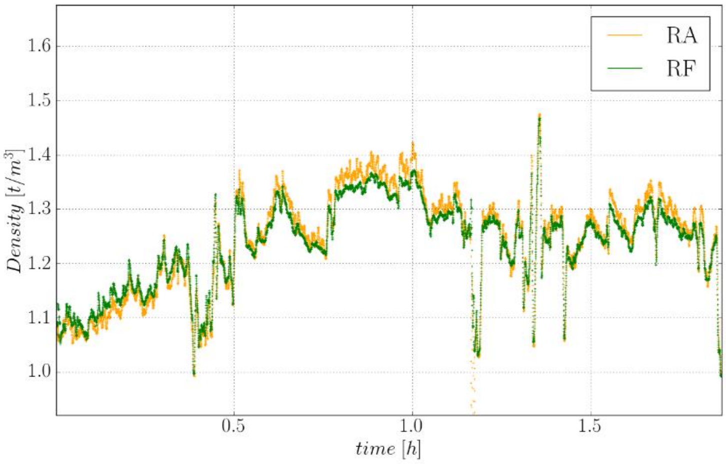

Figure 10. The performance of the RF density measurement obtained onboard CORNELIS SENIOR, dredging in brackish water, with an average conductivity of 0.6 S/m

Our last observation concerns the impact the RF density meter had on the overall efficiency of the ship. We can quantitatively assess the difference the RF system made, by comparing the operation with and without the density measurement. The data representing the operation without density measurement was gathered during the first weeks after installation of RF pipe on board. The system was working and logging data, but without making the information available to the crew. That gave us an image of what is a typical profile of operation. Afterward, the output of signal conditioner was coupled to the SCADA system of the ship, and the operator could see the real time value of the density in the pipe. The situations with and without density measurement are compared in figure 11. The figure shows significantly higher average density values and improved process stability, with the density measurement presented to the operator.

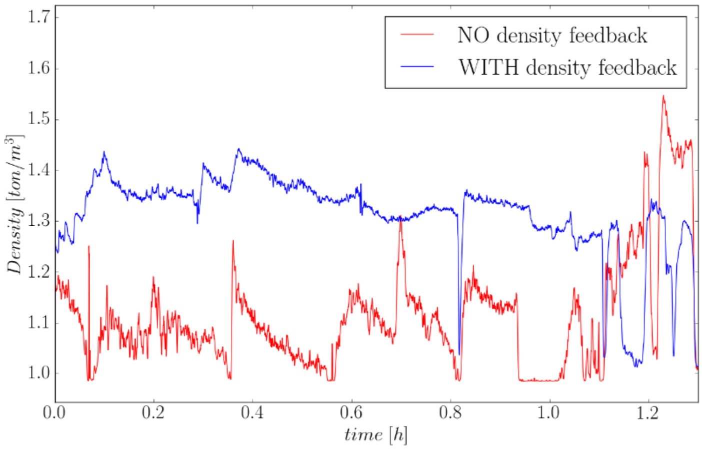

Figure 11. Comparison of the cycle density with (blue) and without (red) density measurement presented to the operator

Qualitatively, the crew formulated the result more simply: the dredging time required to fill up the hopper was reduced by a factor of two. It resulted from the ability to maintaining higher and more stable average density, as well as reducing the non-effectiveness periods. The crew stated that the meter is especially useful in the event of the drag head being clogged by debris (like a log of wood). In that situation, low production is obtained, despite high pump rpm and high vacuum are indicated. Observation of the vacuum pressure, measured at the pump inlet, on its own doesn't indicate that something is wrong. The density meter on the other hand immediately shows a density drop. The combination of density and vacuum measurements alerts the crew on abnormal operation. The drag head can be lifted, the suction mouth cleared, and within minutes the optimal performance is restored. According to the crew, the density meter saved many hours of unnecessary operation with a blocked drag head.

The adoption of the density measurement brought about a substantial improvement on the dredging efficiency, decreased fuel consumption and operational time savings.

5 CONCLUSIONS & FUTURE DEVELOPMENTS

We presented a non-radioactive density measurement system developed for the inland dredging market. The system is based on the transmission of radio waves through the bulk of the slurry pipeline, hence its name - RF meter. To provide a direct comparison between the new and the conventional RA system, both RF and RA were integrated within one, 500 mm prototype measurement pipe.

The operation and accuracy of the prototype were first confirmed with the laboratory tests, showing that the RF meter can work in density ranges peaking at 1.7t/m^3. Subsequently, the system was installed onboard a typical inland sand winning ship. Field tests proved that the RF system delivers the same performance and functionality as the RA system, provided that the ship operates in fresh river water conditions, away from coastal and estuary areas, where river water mixes with seawater.

We thus developed an alternative density measurement. Contractors can achieve substantial benefits by not being subjected to the huge administrative and legal obligations, associated with RA density measurements.

In addition, the long-term trial made evident that the availability of a density measurement onboard a dredger results in reduction of cycle-times, improved utilization of the dredging installation, and shorter downtime. It translates to increase of the overall efficiency by a factor of two.

The experience gained in this project is applied to the follow-up R&D work, that focuses on extending the operability beyond brackish water. With the ultimate goal of making the RF meter applicable for all dredging conditions including seawater. The first results clearly indicate that it is possible to measure density in seawater, utilising radio waves. However, the enormous signal attenuation caused by seawater draws serious consequences for the design and is still the great challenge to apply this method. The R&D work continues, with the full scale sea trials in sight.

ACKNOWLEDGEMENTS

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