A lecture about the use of Multiphase and Wet Gas Flow Meter: From Past to Future.

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1. ABSTRACT

Over the last 20 years, the development, evaluation, and use of multiphase and wet gas flow meters have been one of the main evolutions for well performance against standard equipment (separators). Many metering systems have been developed at the early stage (90's), some died, some have merged to be the most suitable products, and a rationalization have been going on over 10 years (2000-2010), this could have been defining the market for this business but a regain over the last 5 years started to see both some new applications from users and multiphase manufacturer companies emerging on the market from different domains.

If it is clearly understood today that none of the technology or meters on the market are capable to handle wide range of fluid types and Gas Volume Fraction (GVF) or Water Cut (WLR) with expected accuracy. Some cannot cope with all environmental conditions (pressure, temperature, H2S, Erosion…) and therefore caution must be applied when contemplating the use of any Multiphase Flow Meter (MPFM) and Wet Gas Flow Meter (WGFM) versus given applications from Topside to Subsea configuration for example.

If multiphase metering has gained significant acceptance from users & regulatory bodies, we are still at the step of understanding how to use them and how does this product work for a given application, and often more expertise needs to be present and generally out of the knowledge of one supplier of metering equipment or a final user. The secrecy or the lack to formulate simply the use of such product has created some large hope and disillusion too.

The paper will highlight and propose some answers to the recurrent questions: Where are they the most suitable? What are the coming needs? Why are we having new comers (products)? Did the main manufacturer companies miss something over the years about the market trend/demand? What multiphase metering users should do? How to operate & use them? How Operators can influence business? Are there some revolution/evolution ongoing wit new comers? What will be the next multiphase generations?

The papers will look at in a broad range the advantages and shortcomings of the technologies already implemented in various commercial meters in terms of operational issues, economic benefit, or advantages/disadvantages from the operator's point of view. It will also highlight new approaches in designing multiphase metering systems. Some lessons learned will be presented such as improvement of reliability and operation, accuracy of some specific measurements but also highlighting the failures/issues to address the true need of the final users with current available technology.

At the end of this paper, we expect that the explanation will provide practical statement and recommendation practices for design and operation to allow moving forward and helping all parties in this domain to understand what their need is and what they should look for.

1. INTRODUCTION

Over the last 160 years, the multiphase flow meter was the separator, this has been a great tool and it is still considered as the most appropriate instrument for well metering & testing wells & looking at the well performance. The main issues stated over the years and sometime forgotten by the end-user is that the technology is based on gravity separation, this means a significant density contrast between the phases is required to be able to split them in a reasonable time (below 1-3minutes).
The horizontal or smart wells development has been becoming more popular with multiple downhole sections and they have led to much larger productivity in the meantime the constraint with separators displacements on road have not changed keeping the overall dimension similar. Then there is less retention time for the fluid inside the separator and then leading to issue about the quality of the phase's separation.
Numerous studies have shown that a gas wetness of few percent can lead to a significant overestimation of single-phase metering device (i.e. 0.5% of liquid loading in gas line may lead to +2 to +8% over reading of gas flowrate versus line pressure). This could lead to wrong statement about well potential, GOR and statements about the reservoir conditions including wrong information to retune a reservoir model. Furthermore, due to deeper well and equipment capable to handle higher pressure, the density contrast between the different phases has been significantly reduced. A lot of new devices have been added inside the separator to help the separation like coalescer for the liquid, demister for gas, or spinning process for the fluid to improve separation.
Also the development of the heavy oil (i.e. which means heavier oil density) and then poor density contrast with water has led to use in some cases the separator in two phases (gas and liquid only) and with a use of manual sampling procedure for water cut measurement or use of equipment like Coriolis not calibrated for such conditions or not made to work accurately with one phase predominant against the other for proper allocation.
As stated by few oil and gas companies, overall going better than ±5%-10% for each phase require a fair involvement of expertise, instrumentation, and maintenance which is not always achievable with the cost of such field operation with a trend to reduce always the OPEX over the years.
Additionally, new needs coming from challenging developments like subsea, HP/HT have shown limitation of separation systems for well & field flow measurements and have generated needs for other type of measurements .
This raises some main questions: Is the oil & gas industry happy with separation system & associated uncertainty? Is it what the market need? Do we need to address the problem in different manners?
The market came up with MPFM & WGFM technologies with another question: Are we satisfied with existing MPFM & WGFM solutions?

2. OVERVIEW OF THE MULTIPHASE AND WET GAS DEVELOPMENT

Starting in mid-80s, the wish to use a new way to address the well performance and measure well rates was initiated with the objective to have a metering solution per new well, the multiphase flow metering business started commercially some years later around mid-90s, this first 10 years of research and development led to solution that were sometime unrealistic to be used in the field (size, weight, cost…) or having technology or interpretation closer to the voodoo than scientific approach. The disappointment introduced by the test and use of such new technology was very big by the end-user (i.e. oil and gas industry) and the fact that the concentration of multiple technologies was requiring such level of expertise and knowledge for this tiny equipment was another significant parameter to reduce further the spread. This legacy about unrealistic statement or vision of MPFM and black box from the end of the 90's is still present today. Difficult to forget the investment in some cases in a business where wells can be flowing for 20 to 40 years. Early adopters in use of technology were burnt and the laggards less keen to use them.

Wet Gas Business

If the multiphase business started chronologically with MPFM for oil fields, Operators have been using orifices or Venturi for wet gas metering since many years. Consequently, for this short document and the point to make it is better starting with wet gas meters.

The core of the development of the wet gas meter is a Venturi for most of the products, extended researches over more than 55 years has shown that the typical use of the equation of the ISO 5167 lead to large over reading of the gas rate following the liquid loading or Lockhart-Martinelli parameter (figure 1).

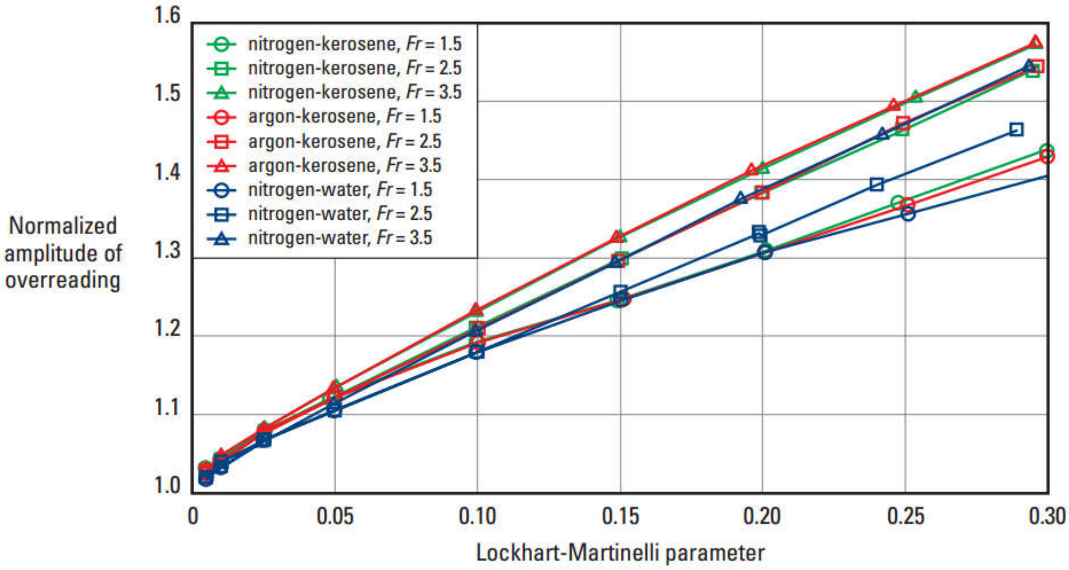

Figure 1: Venturi over reading of the gas rate versus liquid loading [2]

Extensive works were made to provide a correction on this over reading, we could mention as main milestones chronologically the work of Murdock (1962) on orifice plate with the following equations:

$$q_{gas,corr} = \frac{q_{g(tp)}}{\Phi} \quad \text{Or} \quad m_{\text{gas}} = \frac{EA_d C\varepsilon_{\text{wet}}\sqrt{2\rho_{1,\text{gas}}\Delta p_{\text{wet}}}}{\phi} = \frac{m_{\text{gas,apparent}}}{\phi}$$

And

$$\Phi = 1 + 1.26X$$

The work of Chisholm Correction (1967) for orifice plate (NEL):

$$q_{gas,corr} = \frac{q_{g(tp)}}{\Phi} = \frac{q_{g(tp)}}{\sqrt{(1 + CX + X^2)}}$$

And

$$C = \left(\frac{\rho_{liquid,line}}{\rho_{gas,line}}\right)^n + \left(\frac{\rho_{gas,line}}{\rho_{liquid,line}}\right)^n$$

Later De Leeuw Correction (1997) revisited Chisholm for Venturi and with a range of β between 0.4 to 0.6 correcting the fixed value n=0.25, by introducing a dependency versus the Froude number, to:

$$n = 0.41 \quad \text{for} \quad 0.5 \le Fr_{gas} < 1.5$$
$$n = 0.606\left(1 - e^{-0.746 Fr_{gas}}\right) \quad \text{for} \quad Fr_{gas} \ge 1.5$$

The different works both from Stewart et al (NEL 2003), Reader-Harris et al. (2005), Steven et al. (NEL 2006) show how liquid properties can influence the DP over reading.

Additionally, Couput, and Gajan (1999) started to show influence of wet gas flow regimes (droplets and films) in DP across Venturi flow meters. Later Salque and al (2008) came up with a new physical model taking account atomisation of films in Venturi geometry to calculate Venturi correction factors in 3 phases wet gas flows with

$$\Delta P_{WG} = \Delta P_{Bernoulli} + \Delta P_{droplets} + \Delta P_{liquid\_film}$$

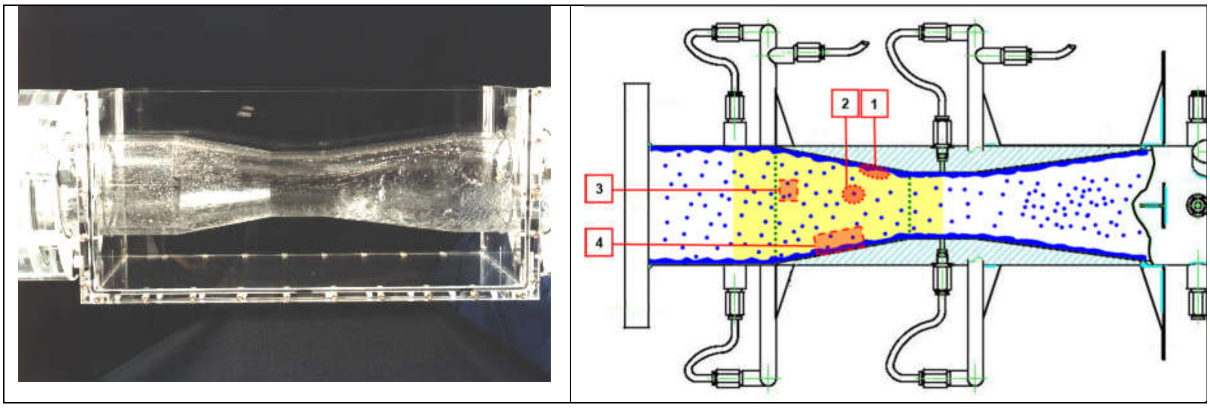

Figure 2: Flow behaviour and droplet analysis for understanding over reading of the Venturi [6]

For wet gas meter technology , mid-2000's has seen a new commercial business coming in with the Wet Gas Business which is a subset of Multiphase Flow but for gassy conditions (GVF > 90%) or gas wells. What is interesting at that time is that demanding fiscal allocation application came up both in Europe & US for wet gas applications [18] which obviously has stimulated market.
Multiple statements or definition exist about what is a WET GAS, and, in a way, this shows the little convergence in this business around some simple concepts. This is sometime driven more by manufacturers (marketing or sales pitch) than science and generic definition.

New or some established manufacturers started different approaches of the problem of metering in this specific flow regimes conditions (figure 3 right side representing the high GVF) by providing either gas & liquids or hydrocarbon & water. For instance, using simple combination of well-established devices demonstrated the capability to access to liquid and gas flow rates. The uncertainty on the gas was established between ±2% and ±6% following the quality of the input parameters and well within the performance mentioned above for separator. This led around 2009 up to 2012 to standardisation initiatives by ISO : ISO/TR 12748 for wet gas flow measurement in general and ISO/ TR 11583 to describe a new correlation for ΔP over readings for differential pressure systems.

Manufacturers have been trying by extensive test to model some typical flow patterns without necessary addressing the entire physics involved in this domain but demonstrating solid result which led to commercial acceptance .The interest in this approach of the wet gas starting from very dry ness conditions was that few manufacturers try to extend it with larger loading of liquid over the years and then the set of equations describes above led to establish performance beyond the initial wet gas business and are capable to address the GVF, today, already down below 90%.

The next step for a full 3-phase wet gas flow meter is to have a water cut (or water volume fraction) or water liquid ratio measurement. Both being related.

$$GVF = \frac{Q_{g\_lc}}{Q_{g\_lc} + Q_{l\_lc}}$$

$$WVF = \frac{Q_{w\_lc}}{Q_{g\_lc} + Q_{l\_lc}} = \frac{Q_{w\_lc}}{Q_{l\_lc}} \frac{Q_{l\_lc}}{Q_{g\_lc} + Q_{l\_lc}} = WLR.(1 - GVF)$$

It should be mentioned that initiative of understanding the physics within meters & modelling meter behaviour is still investigated by some of the main leaders [6], [7], [8], and [9] as an a more efficient way to correct meters in complex 3 phase wet gas flows conditions.

Different techniques are in use from this point of view, either using electromagnetism with a global or local measurement based on the large contrast from a dielectric point of view between the aqueous phase and the hydrocarbons phase with some carefulness given by Van Maanen [10], or the use of optical solution in the near infrared providing at the relevant wavelength a proper signature of the water against the other phases. The use of such type of technology for water cut meter has been well accepted by the end-user because they can be for most of them capable to be used in horizontal way which is one of the easiest ways to find some space to install them on the current or new pipe section.
In general, and beyond the wet gas metering, the less complexity of the assembly of technologies and components including known or adopted equations used inside a multiphase or wet gas meter allows a faster and greater development in this domain.

The differentiation in this domain of flow regimes is obviously the measurement hardware but also the knowhow in the modelling, field & test data, data analytics, and there are already few manufacturers & users going beyond the ISO and capable to provide the better level of information & uncertainty on gas liquid, and obviously with the relevant water cut meter to the 3 phases.

Multiphase Business

The challenge in the multiphase flow business is the presence of unstable flows at the opposite of the wet gas business, this means that the flow structure changes drastically at a given point versus time, the most characteristic ones being the slug and plug flow at the opposite of the pseudo annular, annular and mist flows in wet gas (see figure 3 on the left inside which represents the low GVF versus the right inside with large GVF).

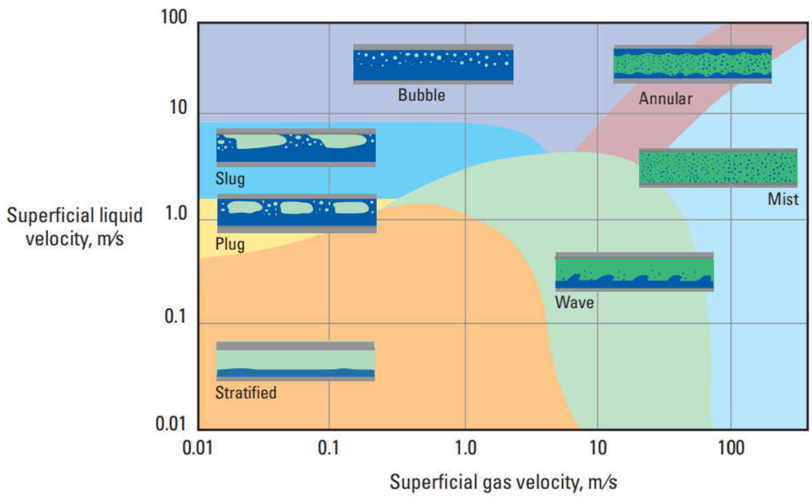

Figure 3: Typical Horizontal Flow Mapping [1]

To address this business in general manufacturers have decided to introduce some conditioners (said or not) and the most common one has been a blind tee, the idea is to make the measurement at the meter conditions (most of them used Venturi like for wet gas) and this means essentially at the Venturi throat, independent of the upstream conditions and be able to provide a compact solution by reducing drastically the upstream pipe upstream of the Venturi. It should be kept in mind that some will require to be as close as possible of the blind tee when other will require a well-defined number of pipe diameter of vertical straight pipe. This quick transition with a sharp 90 direction change allows some relative mixing if the velocity is high enough and then decreases the large slug transition behaviour (a smoothing of the flow, in no case a full mixing process). Additionally, the complexity of the equation with not only the instability of the flow regime but a very strong dependency of the inclination. Figure 4 shows for a stratified flow oil water, with a water cut of 50%, the impact of the deviation on the water holdup measurement in horizontal 90degree and one degree up or down. This shows clearly that expected a multiphase meter in horizontal conditions without a proper mixing is something almost impossible due to the large difference in the water holdup measurement (or water concentration in each section) for a same water cut (water volume fraction). It can be noted that the effect diminishes with larger flow rate (top of the figure with 6,000bpd, versus the bottom 600bpd).

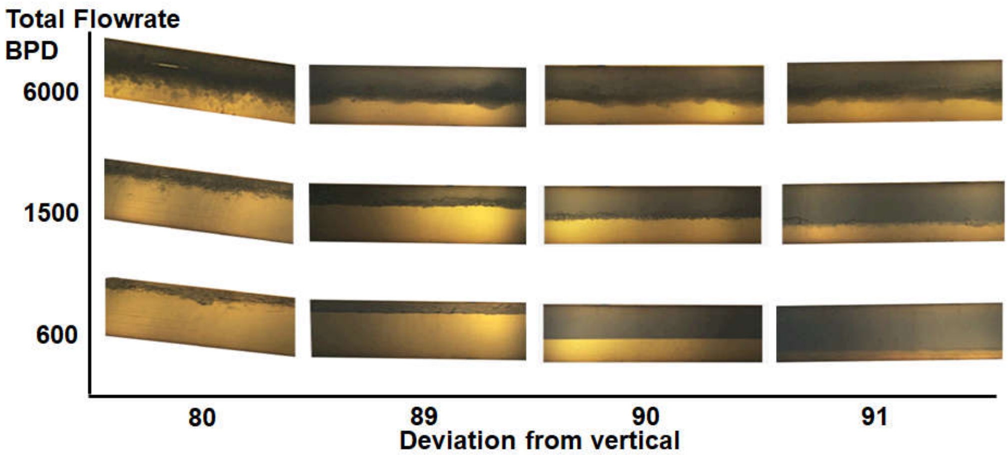

Figure 4: Influence of the deviation on the liquid flow rate versus flow rate [5]

The selected and generic vertical position coupled with a Venturi led to large slippage effect between the phases (for example, this can be apprehended by the density) and it is discussed later. The Vertical solution will reduce the 4D problem (3 axis and temporal issue) to a 2D and a less prominent temporal effect. This will allow using in the simpler manner the nonlinear equation and then some averaging techniques could be applied for some meters in such configuration. The type of flow rates faced in multiphase will be bubble and fine dispersed bubble, slug, and plug and in some cases high GVF case the transition pseudo annular between churn and annular (but here the competition with the wet gas solution is evident). To make it clear the multiphase meter is a device handling liquid phases at low GVF and trying to cope with the presence of larger quantity of gas, when in the wet gas business, it is the presence of the liquid which is used for correction on the high accurate gas rate.
Obviously without going inside the technologies used by manufacturers, this configuration blind-tee and Venturi has a cost requiring additionally a vertical structure and as indicated very often some requirements about the distance between the blind tee and the meter, furthermore a down leg part with some additional instrumentations or not is necessary to be connected on a horizontal pipe.

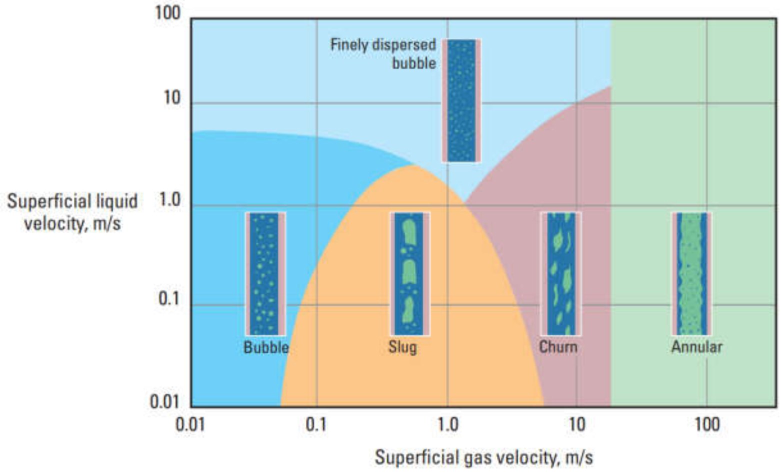

Figure 5: Typical Vertical Flow Mapping on the left inside up to 20m/s for the superficial gas velocity the largest part of the multiphase regimes [1]

As indicated earlier, most of the multiphase meters are built with the same technique than the wet gas with the use of a Venturi allowing in a way or another to address the total mass rate or the density of the bulk mixture but all are based on the Bernoulli's equation as introduced before for wet gas with some specific corrections and often proprietary and not divulged leading to reinforce the statement made earlier about the black box.
Where the divergence will start it is to measure the volume fraction of each phase, some will go with modelling of the slippage, some will use multiple correlation techniques to identify gas and liquid slippage, and some will use multiple sensors to address the same problematic. It becomes very quickly apparent that the data processing is complex and being proprietary, this is not communicated or explained in a way that the potential end-user will understand. The cost due to the large concentration of multiple techniques not necessarily comprehensible in simple words lead even after 20 years to consider most of them not economical yet to be installed on each well and require some careful evaluation for manifold and allocation due to the uncertainty dependency versus the flow conditions. The lack of joint industrial project (JIP) and probably also engagement of oil companies and independent laboratories to rank them and defined the sweet spot for each of them add some doubts or uncertainties on the capability to use them for some new field developments. The lack at this stage of standard like in the Wet Gas is also another issue even if some efforts are undergoing (API or ISO).

To sum up, the wet gas business started from simple concepts, with well accepted technologies and some modelling which were reviewed by the community in a way or another. This led to some serious basis for development of solutions albeit it could be said that more science should/could be introduced, this is working. The gas flow rate uncertainty is today well within 2-5% and the liquid is in a reasonable value. Some efforts are ongoing in parallel in this wet gas domain from the modelling side (Azzopardi et al.), or some oil and gas companies (TOTAL, SHELL) and finally from the metering side (Van Maanen et al.) and they are publishing the way forward. The activity in the development of water volume fraction or water cut over the last 5 years shows a regain and large interest to provide a 3-phase solution for wet gas cost effective being one of the main parameters. Finally, the trend is to be able to access the larger liquid loading and way above 10% (or GVF<90%) is an indicator of healthy product which could address a larger size of the market over the coming years.

At contrary the multiphase domain with the complexity of the flow, the use of technology 20 years old or legacy associated with that led this domain with solution up to 5 years ago quite cumbersome and difficult to understand for most of the end user. Few "new kids in the court", and the modular solutions proposed by some manufacturers are bringing a new way of addressing the problematic. If it is now well accepted that one architecture cannot address the entire multiphase flow regimes business and then there are some sweet spots for each technology and this needs to be well identified by impartial and independent laboratory in line with some ISO standard like the ISO 17025. We have seen some initiative taken by individual oil and gas companies or group of them and it should be more structured to address larger number of products on the market. The unrealistic statement of some manufacturers with no access to the true processing are keeping the end-user confused and overall affecting the entire multiphase business growth.

3. WHERE ARE WE TODAY WITH WET GAS AND MULTIPHASE BUSINESS

With right now more than two million wells around the world (Figure 12), the penetration of the multiphase/wet gas meters is less than 0.5%. We crossed the 8,000 meters sales of MPFM and WGM last year which over 20 years of presence on the market shows a very small business penetration. It should be indicated that the wet gas business is growing much faster in % than the multiphase business. Even if we were only looking the number of wells drilled over the last 30 years the market penetration stays lower than 1%. The review is much better subsea with a market penetration closer to 20% and these statements needs to be explained.

From the 1980 to 2015, some significant changes have been happening in the oil production with new players or with established players getting larger market shares like Kazakhstan, Angola, Norway, Qatar, Colombia, Brazil, Canada, UAE… If oil production of some countries like Saudi has been larger, the percentage against the overall production was not significantly different. Looking closer the list of countries mentioned above, it can be noticed that they have been either a new contributor thru gas business (with LNG technology) or then by subsea or deep offshore installations (figure 10). These are the two revolutions that have been happening with first the crossing of the 1,000m water depth by mid-90's which means access to reservoir deeper and usually with more light oil or often gas wells. The second, with the LNG carrier with today more than 450 commercially used and more than 50% more in construction/order.

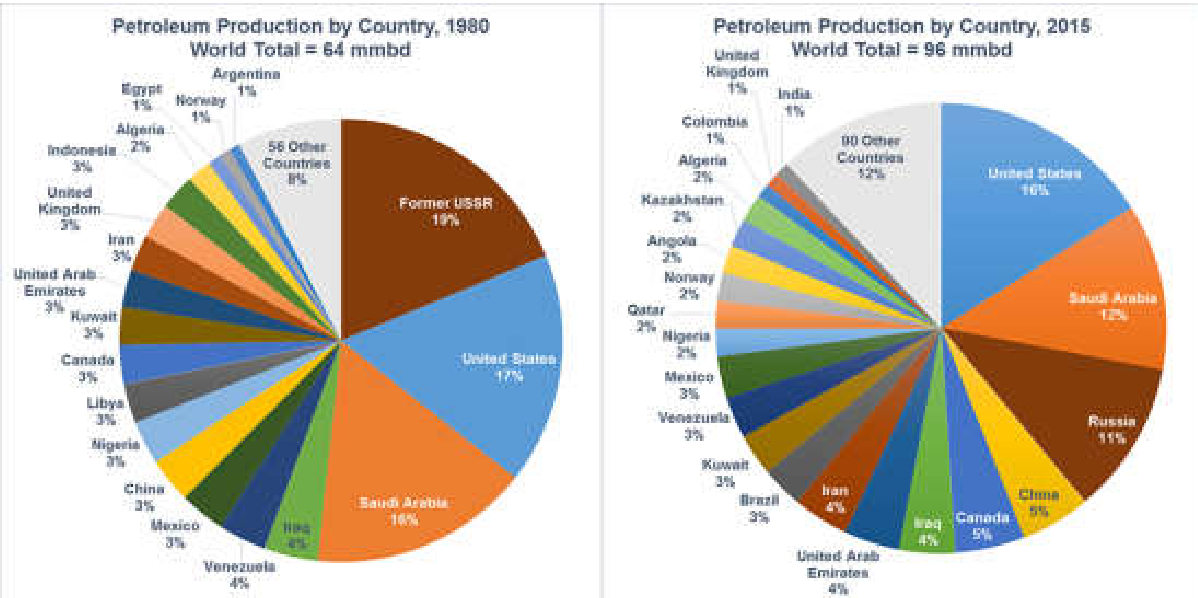

Figure 6: Production of the main country in 1980 and 2015 with the associated changes [3]

This leads us to the following point, if the need of energy has been significantly growing and then will continue the ratio over the last 10 years (from 2005) stays the same with 75% of the production land and 25% offshore (figure 7). What is interesting to mention is around 6% of the production is coming from deep-water and more than 10% of the liquid hydrocarbon is coming from condensate? This indicates that a change with better oil quality and more challenging conditions to get access to the oil have been faced by oil operators.

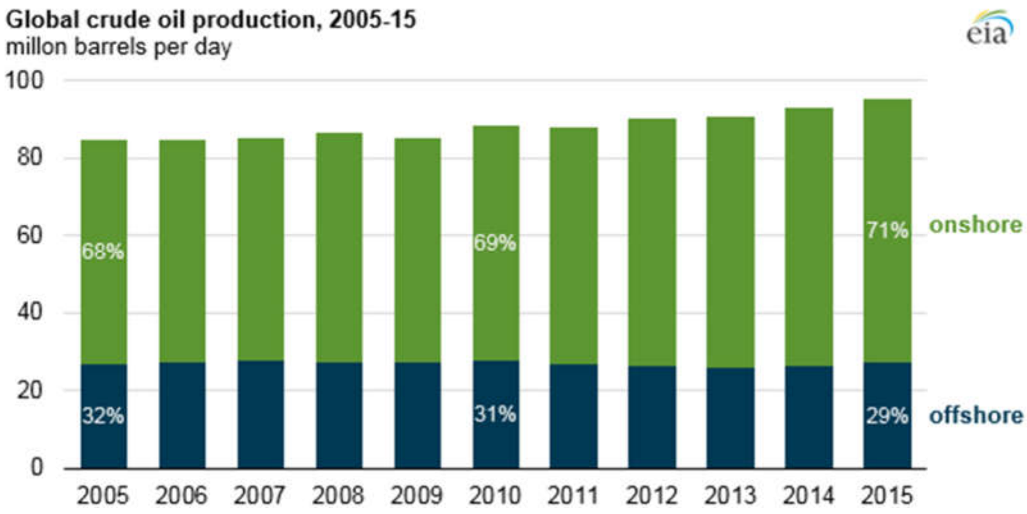

Figure 7: Global production split between onshore and offshore over the years from 2005 to 2015 (include condensate and gas liquid hydrocarbon) [4]

Let's recognize for example that during the second part of the 80's the deepest offshore well was around 500m. The oil industry crossed the 2,000m depth by second part of 2000's. The floating system with the largest water depth is today the FPSO Pioneer with a water depth of 2,690 m in the Chinoock and Cascade fields, Gulf of Mexico [USA]. The deepest subsea tree is in the Tobago field with a water depth of 2,934 m, Gulf of Mexico [USA]. The deepest system for separation and bombing is in the Period field with a water depth of 2,480 m; Gulf of Mexico [USA].

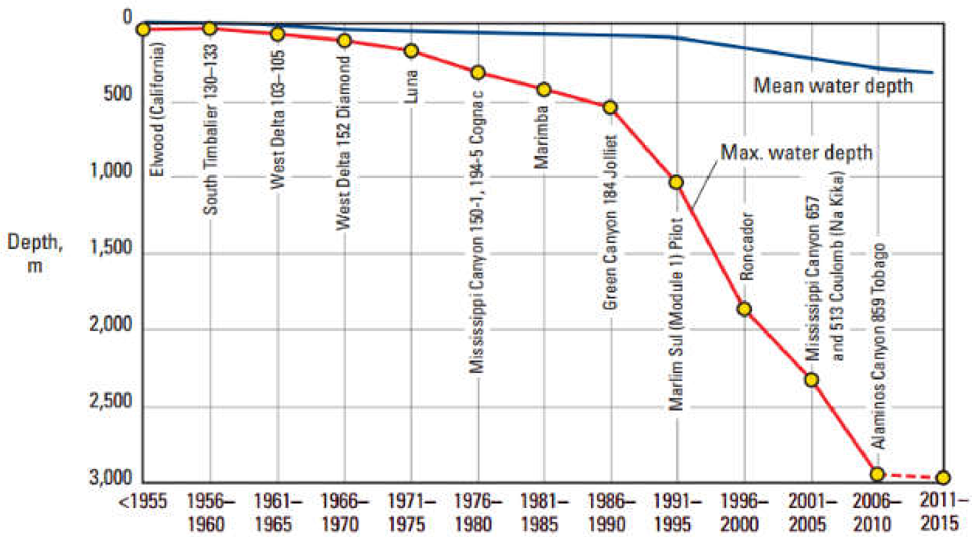

Figure 8: Trend of water depth versus time for subsea exploration and production activity [5]

What an adventure and to see that even separation process are back in subsea business. On the other side the number of large discoveries (conventional oil and gas) is significantly down, and with a generic natural decline of 3-4% on yearly basis it is the production of USA, Russia or Saudi that is expected to be found each 4 years just to balance the current production. Obviously, the oil business found a solution with a large effort came thru the production of the unconventional oil and gas (Heavy Oil, Oil Sand, Tight Oil (shale oil), shale gas, and Oil shale…). Altogether, it is more than 8 trillion of barrel of oil additional accessible. It should be kept in mind that today the primary recoverable factor is, in some of these applications, lower than 10% but improvement of technology could make them much higher in the coming years. A quick review of the recovery factor for oil and gas shows clearly an advantage for the latter. In 2007 [12] the average recovery factor worldwide was 22%, with a value around 39% in USA and 23% in Saudi Arabia. Today, the RF is reaching ultimate average recovery factor for oilfields, on a worldwide basis, of 35%. This means that about two-thirds of the oil that has been discovered is left within the reservoir. In the case of unconventional oil reservoirs, the average recovery factor is between only 5% and 10%, meaning there is enormous potential for producing more oil from conventional and shale oil reservoirs around the world. There is, and of course in well-known locations, enormous prospects for booking new reserves. A quick estimate shows that a 10% in the recovery factor from 35% to 45% would bring about 1 trillion barrels of oil. This contrasts with a typical RF from gas fields of between 80% and 90%.

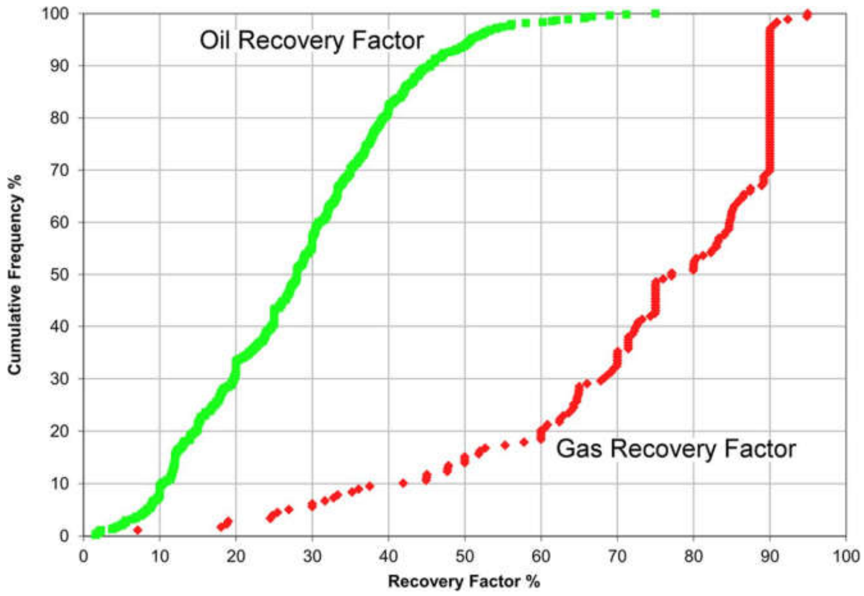

Figure 9: The cumulative frequency versus recovery factor, rend of water depth versus time for subsea exploration and production activity [13]

<u>What makes this multiphase metering business more successful subsea than topside?</u>

We are coming to the cornerstone and where the multiphase business could be instrumental to the oil industry, it is by improving the knowledge of the reservoir thru the well performance and the GOR monitoring, WLR, Quality of water, and overall by looking the Recovery Factor. The EOR (Enhanced Oil Recovery) can drastically improve the economics of a field from an average of 15% (solution gas drive) to more than 50-60% (gravity drainage drive). The maths is a killer, 1% global Recovery Factor improvement is 10MMbpd additional over 100MMbpd which is close to the current daily production right now (to make the calculation easier). This is where the MPFM and WGM could be playing a role thru a proper reservoir knowledge and the use of MPFM but also additional technology (drilling, pump, lifting method, and so on).

As example, the recovery factor in North Sea (a place for adoption of new technology) has been increasing from ~35% in 90's to 46% in 2015 [14]. OGA and NPD have number from 43 to 46% for 2016-2017. There is a goal by the main players in this North Sea offshore business to get in average recovery factor in the range of 55% for subsea field, and 65% as an average for platform. This can be put in perspective with Petronas for example and a recovery factor of 26% in 2009 [15]. The Brazil offshore was around 20% in 2010 [16]. There is a factor 2 in recovery by proper techniques from drilling to production.

This achievement was possible because the oil operators are working in these very harsh conditions and they have clear and challenging procedure to follow. The productivity or production of the wells are very high with completion way above 4-6in and a loss of one well thru mismanagement will be catastrophic or could seriously impact the economics. This is one of the main drivers. If a MPFM or WGM is not capable to increase the production, it is an enabler to understand the reservoir behavior with measurement as close as possible of the reservoir (waiting for the MPFM to be inside the well).
The other driver which has been growing over the last 4 years, will be the tie back of production of some marginal fields to main pipeline or platform and either custody transfer or fiscal allocation which involve a proper understanding of the quality of the oil and the quantity of the oil produced.

Finally and not the least, the financial exposure and the cost of development of a field subsea is such that the cost of a multiphase flowmeter or wet gas meter per well is considered acceptable, the price of them from our understanding is usually 3 to 4 times bigger than topside but they provide usually a redundancy to allow a statistical mean time between failure (MPFM) beyond the life of a given well. Unfortunately, this number being statistic approach if you multiply by 10 the number of units you divide by the same amount the MTBF. It is not a domain where the failure rate will come close to 0 quickly. Meanwhile, this configuration and high-quality leads to justify that the pricing is not a showstopper overall for the deployment of a technology and then corroborate the statement mentioned on the wet gas earlier. The market stays relatively modest and it can be checked against the number of subsea Christmas tree installations (figure 10). Assuming a penetration factor of 50%, this stays in the range of 125 units per year with the current estimation with Europe, North America, and Africa the main 3 players.

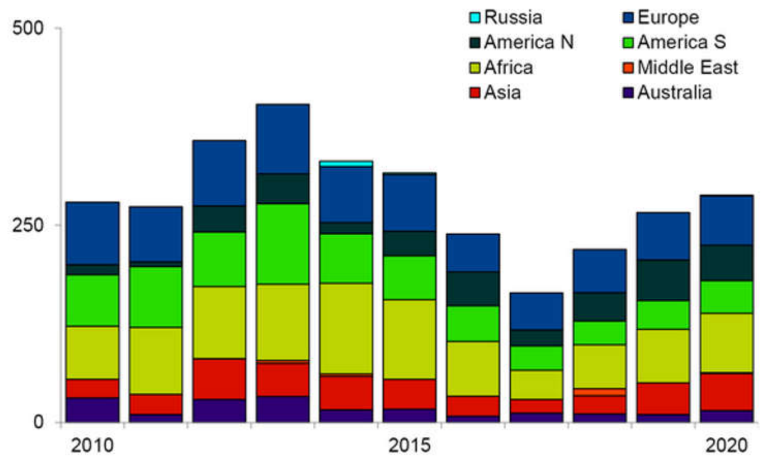

Figure 10: Number of subsea Christmas tree Installation by region versus the years [17]

Topside, the pricing cannot be excluded of the equation for early technology adoption, and even if the product seems more compact with the inline meter there is no clear step change in the uncertainty of the multiphase meters (opposite to wet gas) against some separation solutions and if a separation is very costly subsea this can be done with reasonable price topside.
Business decision is always a balance between product cost and risk exposure versus uncertainty on the statement in our case the flow measurement. A low-cost meter was usually referring to lower quality when a high-cost meter was expecting to be associated with better performance. Better performance is leading to better decision making and less exposure in the risk taken. This is summarized (figure 11) by the blue line for the uncertainty and the red one for the decision. On the x-axis is represented the uncertainty from good to poor, and the price willingness (for the end-user) for multiphase and wet gas flow meters versus uncertainty.

There is no scale on the figure because price is different, but the trend is the same. The risk exposure is presented by red line (right y-axis) versus uncertainty. It is represented by a blue area where the typical and established multiphase flowmeters are in price and uncertainty today versus the expectation of the market (end-user). No price is indicated just a guideline to represent the effort to be done for adoption. Price being a perception following the type of application. The price is perceived to be way too high and the meter uncertainty is not to the targeted or expected level by the end-user. In green, the wet gas meter subsea or topside and subsea multiphase meter are represented together, and they are much closer to the adoption area in yellow.
In orange is presented the modular option which usually are cheaper than the standalone one. Few manufacturers have been able to revisit, and tailor-made their offer for the end-user. The new comers have been also able to enter on the market due to price competitiveness but also gaining some advantage in uncertainty in some areas which makes them adopted much quicker having no legacy.
Overall and this should not be a fundamental news the price of the meter is still considered above the expectation fair price but also an improvement in terms of uncertainty is still required. This being again relative to the expected market.

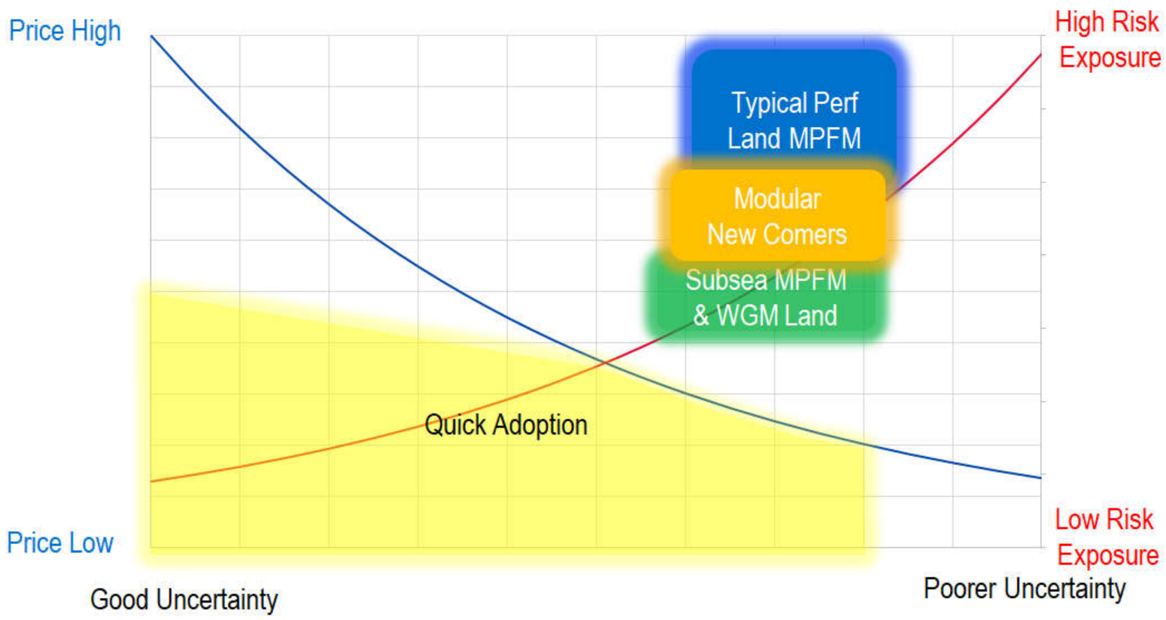

Figure 11: Price expectation and risk exposure versus uncertainty allowing to define the technology adoption following the market subsea, land, wet gas and multiphase

<u>What did we miss to get a same success topside?</u>
We have been mentioning the pricing and performance as differentiators between the topside and subsea business. But are there any other factors?
As indicated earlier the population of well is much bigger topside meanwhile let's looked at in details (figure 12). There are less than 1,000 wells producing above 10,000 bpd, where probably a solution with MPFM of 8inch or above will be required with the associated gas production. There are roughly 30,000 wells with flow rates above 2,000bpd and a requirement for 6in or above. Less than 70,000 wells with flowrate above 500bpd and a 3 or 4inch solution. There are more than 200,000 wells with a flowrate in the 200-500bpd range and an optimal cost effective 2inch solution could work. They are almost 1million wells below 200, and before falling in the stripper well category where a small tank could be the best solution with a donkey pump. The largest number of well is then with small pipes solutions or low flowrates. The issue is then the meter cost versus the accuracy proposed or risk exposure for the producer. The latter point will be important following the country where the government or a private person owns the

underground. It is obvious that today none of the meter on the market are capable to address the uncertainty (being fair) and the cost (being low) required by end-user. As indicated, there is a significant effort made by some manufacturers to approach the problem with a modular MPFM and then being able to reduce the cost and proposed an optimal solution to the end-user.

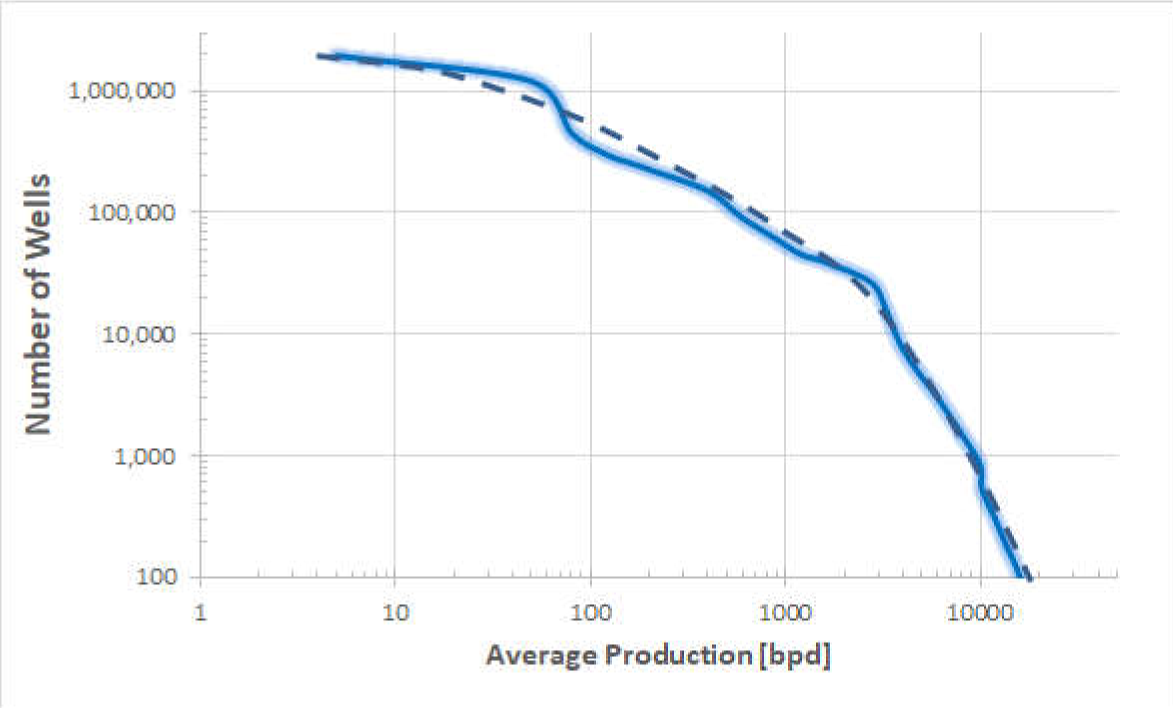

Figure 12: Consolidation of the number of gas and oil wells active around the world versus the production

It has been seen that large quantity of meters ordered in once can lead to significant cost reduction and then be closer to the end-user expectations. An additional issue or enable to lack of market penetration has been associated with some technologies used, for example the Nuclear Magnetic Resonance techniques requires a heavy and costly equipment which probably has as a niche market with the trunk line or large production at low speed. The accuracy can be within the expectation in this domain of application but difficult to imagine today this can be used at the wellhead one day, but this should be extended to radioactive meters.

4. MPFM and WGFM WITHOUT RADIOACTIVE SOURCES

Oil and gas industry since the early days has been using nuclear measurement; usually such techniques of measurement were used downhole, the goal being to measure essentially the density of the rock at the early stage and combined with other measurement being capable to give some information about the lithology. Mastering such measurement and then knowing the fact that some of the radioactive element have the capability to be used thru a pipe (i.e. clamp on solution) this was customized for topside application and for the density measurement but also for welding inspection. This was most of the time portable solutions and used as a service. The natural move to the use in multiphase flow meters subsea was very relevant in the sense that these radionuclides act like a clock with no electronics and then failure is almost impossible except lost of material due to loss of container integrity. Being under water and not accessible this was safe. By end of the previous millennium most of the multiphase flow meters topside had also a radioactive active source against an early trend with manufacturers going without radioactive source. Some companies have developed solution based on gamma ray interaction with the fluid for composition measurement of the oil, water and gas. Such equipment will require a more complex mechanical setting with some transparent windows to allow the low energy gamma ray to interact with the relevant electrons' layers. The simplicity of installation as a clamp on is gone in such case but a more compactness can be gained. Whatever the type if radionuclide, they are all rated versus toxicity, strength/energy penetration thru body/material, and activity (i.e. how long before this source could be considered harmless we talk here usually in 10 years or 100 years as a unit).

The trend has been lately to propose solutions either to use radionuclide specifically to some applications or more drastically without any nuclear measurement. This latter statement fits with the vision for the use of more and more multiphase flow meters and with the current awareness to be greener, safer. In the same type with the oilfield being in unsafe or area close to unstable regions, it is believed that for land application this cannot be the correct solution. The capability to use these nuclides in a way or another for dirty bomb whatever their types will be a showstopper to further development. It can be seen also from another point of view, if the acceptance level with radical cost efficiency reach let's say only 5% penetration rate of the entire population of wells, this leads to more than 100,000 radioactive sources spread everywhere around the world. How a company could, on yearly basis, handle, control, report, ensure the safety associated with thousands of meters using such equipment with such toxicity and unsafe worldwide conditions we are facing now. The OPEX associated with such equipment cannot be disregarded and purely from a safety point of view.
What is clear, it is that such type of meters is currently filling the gap between the separator and then the future non-radioactive meters. But this will not be the solution for the long term, we are probably close to the edge of technology rupture like this happen in mid-2000s with the iPhone coming to the market and then the collapse of the other manufacturers and an entire redistribution (Nokia being out over the following 8 years, or Sony-Ericson over the last 2 coming years). Obviously, the oil and gas energy are more reliance and conservative and then the shift will be much smaller in terms of amplitude, but it is true that even with an optimistic pace to make tenfold the number of multiphase flow meter today, the land business will need way more than 50 years whatever the acceptance rate selected, and this is still way below the subsea acceptance. As conclusion, the right multiphase flowmeter for oil wells was not on the market in the last years and there is large expectation with newcomers.
Over the past few years, new clamp-on technologies have emerged that allow retrofitting and temporary installations, including subsea multiphase meters which can be retrieved by remotely operated vehicles. If this is proved to be reliable, this could be a new generation of multiphase flow meters.

5. WHAT IS THE FUTURE? HOW TO ANWER THE CUSTOMER NEEDS?

Beyond that, as explained at the beginning the technology used downstream of the Christmas tree came from downhole, and the oil and gas industry is keen to implement downhole measurement technology as soon as the reliability will be demonstrated. This is the relevant pace to have a meter in front of each production zone. Some downhole deployment of MPFM have been made but this is in an infancy and the road will be very long without any technology leap. The key is to get robust downhole instrumentation and continuous improvement on the data transmission methods. The effort on the fluid behaviour model including the traceability and the uncertainty of the associated fluid behaviour thru the tuning of the EOS should not be disregard in such conditions. Overall, innovation and research are still required to develop robust and integrated multiphase systems.

6. FROM MULTIPHASE METER HARDWARE TO MULTIPHASE FLOW METERING COMPONENTS (MPFC)

Up to now, market offer has been mainly focusing on full MPFM hardware package solutions covering all flow ranges with an associated complexity and significant costs. One architecture cannot address the entire multiphase flow regimes business and it is also possible to use and rely on individual multiphase flow measuring components to build customized multiphase metering solutions suited for application. A multiphase flow metering component (MPFC) is a component able to give relevant multiphase flow information from a multiphase stream.
Venturi primary elements is by definition the most popular MPFC as it is used in most of multiphase & wet gas meters.

Some system for measuring water fraction are already marketed or in development. Other measurements giving liquid, oil or condensate measurements in multiphase or wet gas flow will also allow either to upgrade existing installations or to build optimal multiphase metering solutions.

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Design of future Multiphase metering architectures will not be only based on duplicating MPFM/WGFM complete packages on each stream but will select & combine flow component as well as models together in order to come up to suitable set up in term of performance & robustness.

7. DIGITAL SOLUTIONS & DOWNHOLE SOLUTIONS TO ANSWER CUSTOMER NEEDS

It could be argued that there are some limits in the capability to develop a multiphase flow meter due the hardware element and associated price, and the MPFM will not continue to come down and end-user should be ready for that. Two objections to that, first the price of the meter thru some manufacturing efforts by selecting the relevant place of low wages and high quality, introducing some very lean process, reducing the management structure, is now landing well within the 5 digits number including some European manufacturers. Second, we think that there are some alternatives not well considered by the market, but it will be coming with the ongoing digitalization process in the oil and gas industry and it is the use of “digitalized meter solution” (i.e. preferred to virtual metering). This software solution is an add-on usually to multiple measurements already collected and then with a relevant modelling this can provide robust measurement and even self-redundancy. The market is progressing very well in this domain, there are some solutions that do not require anymore a Ph.D. to run some simulations and there is a trend to make it accessible to mobile devices. Some innovative solutions with the iCloud have been seen or others are in development. The digitalization in oil and gas industry is bringing something that we faced all each day, and which is now to rely more or more on solution not entirely based on physics but with some strong data analytics (i.e. or for some can be named Artificial Intelligence) leading to define robust tailor-made solution. Most of them required some learning curves (based on human or not) and large database. It is believed that the use of combine information from Pressure, Differential Pressure, Temperature and some additional spot check measurement or local measurement can provide a solution viable. This will be very cost effective, the “digitalized meter solution” (DMS) will benefit in real-time of updates, including remote access and then allowing the capability to identify issue from a desk. The benefit is that these systems can be easily integrated into existing infrastructure and they may eliminate the need for additional hardware in the future. In the past some case studies have shown that DMS have also been used to tune faulty multiphase flow meters, when they were initially used as back-ups in case of issues with multiphase flow meters and they have the capability to diagnose potential changes in fluid properties or issues in well management. This is not to say that the physics of the multiphase will be fading out, but they will be complementary efforts and interaction to improve models and use such smart solution.

Beyond that, as explained at the beginning the technology used downstream of the Christmas tree came from downhole, and the oil and gas industry is keen to implement downhole measurement technology as soon as the reliability will be demonstrated. This is the relevant pace to have a meter in front of each production zone. Some downhole deployment of MPFM have been made but this is in an infancy and the road will be very long without any technology leap. The key is to get robust downhole instrumentation and continuous improvement on the data transmission methods. The effort on the fluid behaviour model including the traceability and the uncertainty of the associated fluid behaviour thru the tuning of the EOS should not be disregard in such conditions. Overall, innovation and research are still required to develop robust and integrated multiphase systems.

8. MPFM OPERATION & USERS: TOWARDS A NEW EQUILIBRIUM

Standard operation and maintenance practices applicable to conventional instrumentation has been found inappropriate to operate MPFM & WGFM technologies and systems which require some degree of expertise as well as an integration of various competences addressing fluid behaviour, multiphase flow and specific instrumentation systems.
Up to now, Operating MPFM & WGFM has been found quite expensive due to costs to specialist mobilization specialists all around but also due to time spent to convince & argue about data quality and validity. Remote operation of MPFM & WGFM systems is certainly the way forward like implementation of Remote Metering Monitoring (RMM) carried out by some Company [19]. Basically, RMM is a surveillance system which consists of monitoring continuously flow data as well as raw data and all relevant sensor data to follow and troubleshoot metering. Data is acquired through real time field data made accessible in Environment Information System (EIS) through historical data base like historian systems. Data is transferred and made available to Support entity of Operational Assets or to Company headquarters. In addition to routine tools and simple calculations, RMM may take advantage of advanced tools and software to calculate fluid property calculations or for data validation like Data Validation & Reconciliation (DVR) software which is using information redundancy and input data uncertainty to :

- Detect sensor & meter failure
- Calculate uncertainty
- To calculate back up data

DVR models are used to monitor, and trouble shoot specific equipment at the sensor level or on a larger scale to identify inconsistent meters. DVR can also bring a backup for multiphase flow meters using other sensors like choke valve opening, pressure and temperature combined with flow models. The next step for MPFM/WGFM solutions successful deployment & cost-effective operation consists in taking advantage of digital technology (communication, data sharing, and visualization...) to work in a collaborative way to increase efficiency. After flow data is captured and analyzed, specialists, experts and data users are sharing information locally or remotely to make diagnostics and solve metering issues.Collaborative work between users & suppliers is the key for future success of MPFM & WGFM solutions as their operation involves several E&P disciplines including operations, reservoir, well performance, instrumentation and HSE.

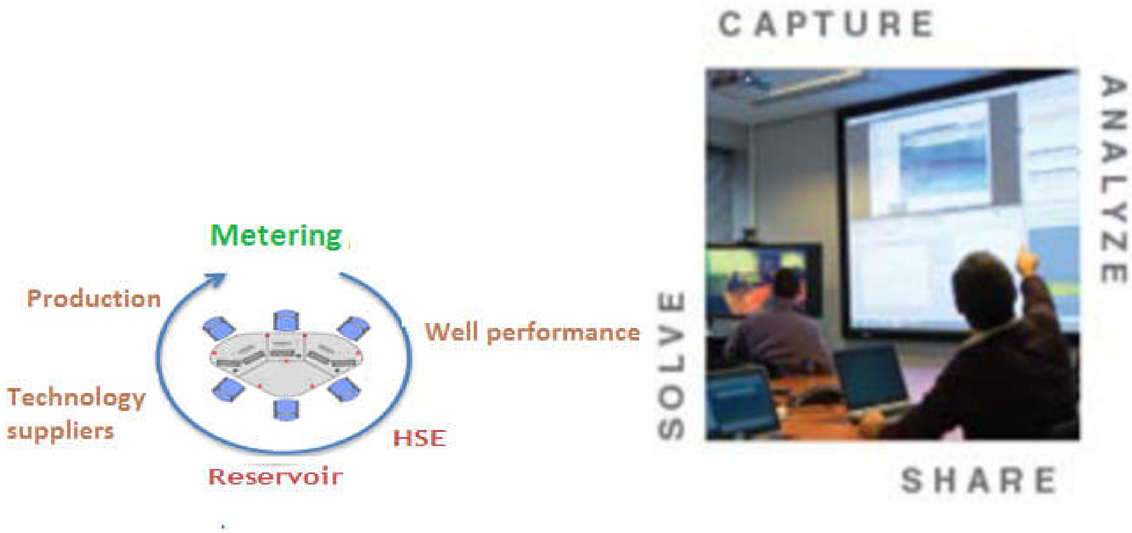

Figure 13: Synergy and Impact of the Digitalization in data communication

<u>What kind of involvement for MPFM/WGFM users & operators?</u>

A larger involvement of MPFM/WGFM users/operators is expected but also needed to facilitate acceptance & further deployment of solutions. What is obviously clear and valid for subsea developments is ready to be extended for on shore & offshore assets.
Further deployment of technology will require users to find out optimal ways of surveillance, validation & operation is a safe & secure way. Environmentally friendly systems will also be preferred for acceptance. Users/operators will have to some extend to be clear on their needs in term of product & also servicing and suppliers should understand Operation constraints.
Up to know, some kind of disequilibria in knowledge has been present between users & manufacturers which may have generated some difficulty in communications and mutual understanding. This will not be the case and this is not for future as Users have now access to a lot of data which allow a better understanding of MPFM behaviour in real life.
Additionally, we think Operators will work more and more together as they start to do with International Standard Organization to standardise best practices. Operators may share same views regarding improvement of technology and agree to initiate Joint testing program. Such initiatives may cover blind test of technologies in third party multiphase loops but also common RD program.

9. SYSTEM PERFORMANCE & DEVELOPMENT AXES

Performance of MPFM/WGFM systems & solutions will not be limited to uncertainty and costs (CAPEX , OPEX). Users are going to look after acceptability of Multiphase Metering solutions in term of environment & safety . In term of applications, they will still be specific niches like pre-salt fields, high pressure high temperature, high CO2, EOR…

Due to the market growth towards gas & cleaner hydrocarbon, it is expected needs & demand for wet gas metering solutions will increase versus time .The applications may cover high accuracy 3-phase wet gas meters potentially used for custody transfer which means 1% on gas but also low-cost wet gas metering components for individual well monitoring with water and/or condensate measurement capability. Clearly fluid property like water salinity or gas composition (CO2 content) may also be a must for coming years.

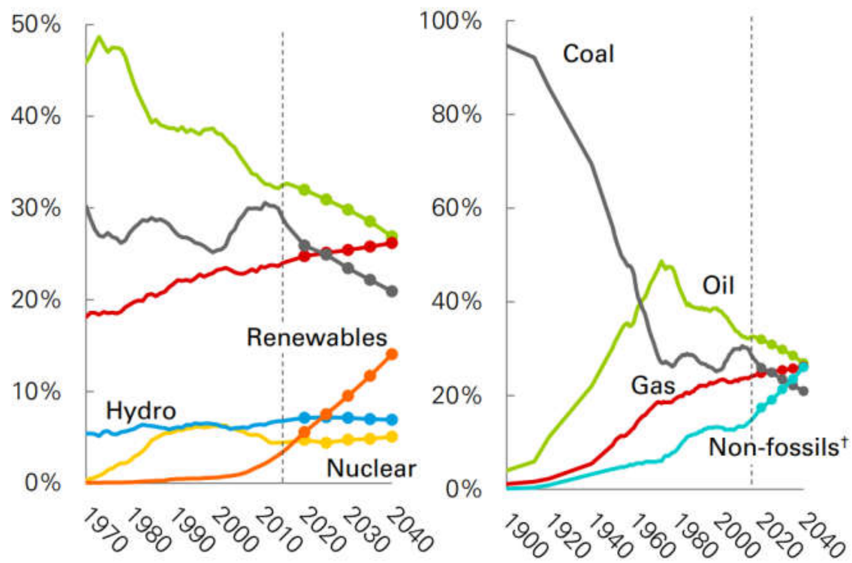

Figure 14: Shares of primary energy past, present and anticipated. † includes renewables, nuclear, and hydro a clear decline for oil can be seen in % when gas is steadily increasing. [10]

For oil applications, one of the key drivers may be cost efficient monitoring of well using low cost multiphase technology without gamma sources. Couple of initiatives have been launched by some operators to evaluate and test such technologies [20]. Possibility to retrofit & upgrade existing installations with clamp on system will be looked at. For both oil & gas application, one tendency will also be to develop individual well metering as an alternative to well testing.

10. STANDARDISATION & REGULATIONS

Clearly, users & suppliers should joint efforts to standardise good design & operation practices both for multiphase and wet gas metering. Several ISO (ISO TR 12748 and ISO TR 11583) & API RP's document are already available for wet gas. New documents are prepared for multiphase metering like ISO TR 21354. In parallel, standards dealing with allocation will refer to multiphase technology use as this is often the case.

Regulatory body are more and more open to MPFM/WGFM technology use, but they will set up some key requirements to users. In this domain, strong cooperation between all parties will be needed. If North Sea regulatory bodies (Norway, UK, Denmark) as well as US regulations have been supporting use of MPFM/WGFM for well measurement but also for field measurements for fiscal application, significant number of new oil countries are also considering MPFM as well metering solutions

11. CONCLUSION:

The manufacturers of MPFM are not fulfilling or answering the need of the end-users with the robust, not a black box concept, and cost-effective solution. The full commitment or adoption is not there and there is an expectation with the newcomers which have no legacy to manage. More critical, looking the overall topside multiphase sales, there is a large bias in the use of MPFM technology to Middle East and specifically to one oil company for land application. This should be the signal for the well-established ones to start to accept the limitation of their current product and come with innovative solution. They should have acquired expertise over the years that could be instrumental for their business and the entire topside multiphase community. Others have been able to provide modular solution to fulfil the specific need. Manufacturers

have also sometimes forgotten that if the use of MPFM is instrumental for the recovery factor and reservoir management, the overall cost (usually 3 time's minimum the price of the meter), is for sure a major issue. This is usually coming from the requirement for vertical solution and if this was not allocated in the early stage of the development of the field then it becomes non-economical.
At the contrary, there is a better fit with the market need in Wet Gas and Subsea business. The spread is much homogenous for the subsea and wet gas business around the world. This indicates that the market is accepting such subsea technology.

End-users should understand that there is not a universal multiphase meter on the market today capable to address the entire multiphase and wet gas business albeit the sales pitch from some company will try to demonstrate the opposite. There are different solutions robust following the fluid properties changes that multiphase flow meters are monitoring to distinguish the oil, water and gas in viscous or not conditions and at low or high pressure. In simple work some may be more susceptible to salinity change, other to H2S change, and all have their own characteristics. On the other hand, the lack of standard and continuous review in depth of the performance by independent regulatory agency/third party (Joint Industrial Project) are also leading end-user to listen the manufacturers with sometime bias in their explanation or true performance by lack of time or condensed message passed to them in some cases.

The opening of the technology and the data processing to third party or to the expert's community will be an enabler for the manufacturers and bringing some clarity to the market. Let's be sure we do not duplicate what happen lately in the car industry with tuning of engine for special test or certification. It is believed when it is time for validation of a technology or meter that most of the tests should be blind, and third-party facility and not on a manufacturer flow loop used to tune the model and, by definition, the meter has been trained on it. For such blind tests, the manufacturer should only know the range of pressure, temperature, flow rate expected.
It is believed that the community of end-users should be careful about extrapolation of results, and the result obtained with small size meter (2-3in) should not be extrapolated to large size (6-8in). It is believed that meter should be tested in conditions as close to the field conditions (pressure, flowrates) when it is possible, and using well defined parameters (Reynolds, Froude…) when it is not possible to match the field conditions. The improvements in software or electronics should lead to gain in uncertainty and robustness but this should be documented and traceable by third party test. By complying with this common sense, this will be pushing even further and quicker the adoption of the MPFM and WGM.

Additionally , it is clear now Operator/user should be more involved in the design & operation of multiphase metering systems. They know their installations and tanks to their knowledge, they can really participate to MPFM/WGFM business development. Doing that with counterbalance Supplier/Manufacturer influence & benefits to all stakeholders including regulatory body.

As final statement, there is today space on the market for the MPFM of the 21st century and this may be something not yet available or coming soon. It will for sure not be with nuclear measurement top side, and it will be cost effective, easily operable, and addressing low flow rate and low pressure. The access to the 3 phases will be compulsory and following the price the uncertainty statement will be established based on the minimization of exposure for decision maker (good or bad), meter price, installation cost, easiness to operate, low capex, and an overall uncertainty which includes meter performance at line conditions and PVT correction or fluid behaviour including traceability from line to standard conditions.

12. ACKNOWLEDGMENTS:

The authors had the opportunity over the years to work on visions and strategies for Multiphase and Wet Gas Businesses either from a manufacturer, independent company, and research or from operator point of view. This work has been achievable thank to the capability given by NEL and TOTAL to support this idea and providing continuous encouragement.
An alteration of some previous works or information have been made to ensure a consistent and sometime simplified message was provided to the readers. This (simplified) document summarizes the main ideas and give a fair statement; there is not enough room in the concept of a conference to provide the entire landscape and summarize more than 60years of cumulated expertise. We hope the road is clearly paved. Beyond the science, the commercial and adoption aspect have been also addressed and should give clarity for future development.

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