TECHNICAL PAPER

Deep Bed Nutshell Filter Evolution

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1.0 ABSTRACT

Since their debut in the Oil & Gas industry in the 1970's deep bed black walnut shell filters have gone through many innovations and stages of evolution. Walnut shell filtration was developed as a higher performance method of filtering free oil and suspended solids in applications where sand and multi-media filters were traditionally used. Success of the early designs and acceptance by industry drove further innovation and multiple vendors entering the market to provide alternatives. Today, walnut shell filtration is widely accepted for polishing of oily water in upstream oilfield, downstream refinery and power plant facilities.

The success of this class of filter and the numerous design variants on the market can make it confusing for a customer with limited 1st hand experience to understand the critical factors that differentiate high performance designs from low performing ones. This paper is intended to help the reader better understand how the technology developed over the last three decades, the various performance challenges encountered and the solutions to these challenges within each generation of the technology. The paper then expands on the latest generation of hydraulic backwashed nutshell filter technology and how it can benefit the industry.

2.0 INTRODUCTION TO DEEP BED FILTRATON

The conventional definition of filtration is a mechanical or physical operation which is used for the separation of solids from fluids (liquids or gases) by interposing a medium through which only the fluid can pass. In this paper we expand this concept to cover filters that also remove free oil particles (droplets) from water.

As this is a paper about the evolution of Deep Bed Walnut Shell filters we must start at the beginning with the filtration of solids. There are two types of filters for separating particulate solids from fluids – Surface filters (sieves), where separation occurs at a single perforated layer (a sieve), and Deep Bed (or Depth) filters, where the granular particulate media (multilayer lattice) retains those particles that are unable to follow the tortuous channels of the filter media.

Depth filters can be operated either with upward- or downward flowing fluids the latter being much more typical. For downward flowing devices the fluid can flow under pressure or by gravity alone. Pressure depth filter tend to be used in industrial applications and often referred to as Depth filters. The Depth filter is the type discussed in this paper.

Depth filter works by providing the particulate solids with many opportunities to be captured on the surface of the media particles. As fluid flows through the porous media along a tortuous route, the particulates come close to media grains. They can be captured by one of the following mechanisms [1]:

- Direct collision
- Van der Waals or London force attraction
- Surface charge attraction/repulsion
- Diffusion

With these variations on mechanisms for removal there are many different factors involved in design of Depth Filters. Like any other process equipment, filters need to be designed so that they are efficient, economical, easy to operate and maintain. Understanding the relationship between filter performance, filtration rate and filter media properties is the key in successful design. Media properties and evolution will be covered in more details later in this paper but to better understand the impacts for media it is necessary to first understand the chemistry role within Depth filtration.

Depth filtration is accomplished by attachment of the particles to the media, which is a completely different mechanism than that of Sieves as the Depth Filters do not primarily work by straining or size exclusion. Virtually all the particles targeted for removal in Depth Filters are negatively charged and so the filter media granules themselves, thus the particles and the media are not attracted to each other, in fact, they are repelled by each other and find it difficult to pass through the filters tortuous path while continuously being repelled. Due to this principle one method of improving performance of this type of filter is to change the surface chemistry of the targeted particles by means of adding positively charged cations or polymers to facilitate the filtration process performance. One of such coagulating agents is filter alum. These cations attract multiple negatively charged particles thus creating larger size clusters which are then easily removed in the depth filters.

Depth filtration systems with particulate media beds are common in many industries for removal of dirt and other contaminants from fluid streams. While it is possible to use particulate bed filters to clean gases, their utilization is more common in the filtration of liquids.

After a filtration cycle has progressed for a period of time, the bed becomes loaded with dirt and contaminants and begins to lose its effectiveness as a filter. It may also begin to clog preventing fluid from passing thereacross. As a remedy, the particle bed is periodically backwashed to remove the dirt and contamination from the filter media and flush the same away from filtration system for disposal and reclamation. Contaminant loading causes a larger pressure drop across the bed and unless the bed is backwashed to remove the trapped materials a fracture will form allowing water to bypass the filter bed matrix.

Almost a century of experience in utilizing Depth Filters has narrowed down most of the design variables such as media bed depth, optimum filtration flux rate, filter media itself etc. However there is one design variable which still experiences endless modifications - the backwash method.

We believe it is the backwash method which predominantly distinguishes the good filters from the bad ones.

3.0 FILTER MEDIA EVOLUTION

There are two distinctive evolution lines in the history of Depth Filters:

- Filter media material;
- Filter media backwash method.

Both are very important design variables and are dependant on each other.

In the 1700s the first water filters for domestic application were applied in Europe. These were made of wool, sponge and charcoal. In 1804 the first actual municipal water treatment plant designed by Robert Thom, was built in Scotland. The water treatment was based on slow sand filtration with horse and cart distributing the water. In the 1890s America started building large sand filters to protect public health. Starting in 1970, public health concerns shifted from waterborne illnesses caused by disease-causing micro organisms, to anthropogenic water pollution such as pesticide residues and industrial sludge and organic chemicals. New regulations were implemented that focused on the industrial waste and industrial water contamination thereby forcing water treatment plants throughout the United States.

Even though silica sand was the most commonly used filter media, there were other media used in Depth Filters such as polyvinylchloride (PVC), granular glass, anthracite etc. PVC was capable of holding more oil per unit of media volume than sand or anthracite, but at the same time was a lot harder to clean during backwash. Over the years there were multiple attempts to modify these media to improve their filtration/ backwashing characteristics. One of such modifications was a chemical treatment [3] of the media to change surface properties but it was not long lasting improvement. This type of chemically modified media never found significant commercial success due to the limited effective life of the product.

Black Walnut Shells (BWS) as a filter media was first introduced to Depth Filters in the early 1970-s. BWS outperformed Silica sand and all other materials in all the physical characteristics. BWS are light in weight, with a specific gravity of about 1.3 to 1.4; the shells are relatively strong, having a modulus of elasticity of 170,000; and the shells are relatively non-abrasive when compared to sand or anthracite coal. This last property is somewhat surprising in view of the common use of walnut shells as a blasting grit of metal finishing. It was found [2] that a very specific “nutshells”, i.e. granulated black walnut shells, possess a capability of coalescing oil from contaminated liquid flow and accumulating the coalesced oil in the interstices of the filter media bed.

Black walnut shells (when water saturated) also exhibit a relatively weak affinity for oil enabling rejuvenation of the bed by conventional backwash cycles. The economic benefits flowing from that discovery were apparent in view of:

- The commercial availability of Black Walnut Shell media;
- The monetary savings from elimination of medium treatment with solvents or surfactants;
- The relative ease of removing accumulated oil and solids from the medium;
- The ability to reuse the filter media; and
- Low attrition rate.

3.1 Black Walnut Shells Wettability

A measure for a material's affinity for oil may be expressed in terms of an "oil affinity quotient". A series of tests were conducted by others to evaluate and compare an oil affinity quotient of PVC, anthracite, sand and black walnut shells [2]. Equal weight portions of each of four media were first soaked in light mineral oil (i.e. kerosene), then media was dried in vacuum. The oily medias were then re-weighed to calculate the oil affinity quotient which is expressed in terms of oil retention per unit of volume of media.

The results represented in Table 3-1 show that black walnut shells have an oil affinity of only about 16% of that of PVC. Even though sand and anthracite have close performance results to those of BWS, they have the following disadvantages:

- Sand is relatively heavy (requires higher backwash energy) and abrasive (reduces the lifetime of the media and filter components);
- Anthracite is easily fractured into relatively flat flaky particles (blinds off the filter prematurely)
- Sand particles are of smaller size than the optimal desired (limits the maximum allowed filtration flux rate due to elevated pressure loss across the bed of fine sand particles. BWS can be crushed and sieved into any size granules).

Table 3-1: Grams of Oil retained per cubic centimeter of media

Media	Test 1	Test 2	Test 3	Test 4	Oil affinity Quotient Average
Polyvinyl chloride	0.192	0.240	0.244	0.172	0.212
Anthracite	0.032	0.044	0.052	0.040	0.042
Silica Sand	0.032	0.048	0.052	0.040	0.043
Black walnut shells	0.020	0.044	0.036	0.032	0.033

However, it should be noted that in produced water treatment application of Depth Filters it should never be the case where media gets initially coated with oil as was performed in these tests. Instead Black Walnut Shell media is initially washed with water and loaded into the filter vessels being completely saturated with water. Given that BWS media is water wet comparing to sand which is oil wet, the first being initially coated with film of water will never have the same oil affinity quotient of 0.033 as was shown above. Oil droplets will always be repelled from water wet BWS particles. This is the biggest advancement over all the other Depth Filter media alternatives.

With almost forty years of operation history Black Walnut Shells have proved to be so far the best fit media material for simultaneous oil and solids removal from water.

4.0 BACKWASH THEORY

While oil does not directly adsorb to the BWS media particles it can act to agglomerate media particles together if media is constantly being incompletely fluidized and backwashed. It's what is referred to as "Mud Balling". Therefore a frequent and thorough backwashing of the media bed is required.

Backwash as a part of the filtration cycle is automated and can be triggered by one of the following:

- Clean filtered water outlet quality falls below a set point;
- Predetermined pressure drop across the filter bed is achieved; and
- Pre-set time for filtration stage.

Backwash is either performed inside the same vessel where the main filtration stage takes place or in a separate scrubber vessel with a media being fluidized and pumped back and forth every cycle between two vessels – main filter and external scrubber.

A properly designed backwash system should achieve the following:

- Complete fluidization of the filter media bed;
- Removal of trapped oil and solid particles;
- Low stress and shear to the media granules;
- Low water throughput;
- Short cycle time;
- Low energy input; and
- Limit or eliminate rotating equipment or elements.

As all vendors generally use the same media and the same bed depth with similar flux rates it is this backwash feature that distinguishes high performance filters from everything else. A close study of the patent history for this type of filters outlined in this paper show that the one overwhelming differentiator is the design of the backwash system.

High energy is required during the backwash stage of the filtration cycle to fully agitate the complete bed of the media in a violent turbulent fashion and clean the bed as much as possible. It was found from early experiences that simply flowing water in a direction opposite to that of the filtration stage even with such a light weight media as Black Walnut Shells is not sufficient. Section 5 of this paper expands on the patented techniques used to enhance fluidization.

5.0 NUTSHELL FILTER EVOLUTION

With 40 years of development there were numerous different designs emerging and disappearing on the depth filtration market, however in the authors' opinion there are five generations that all designs can be categorized into. Figure 5-1 below is a simplified view of the Black Walnut Shell Filter design evolution.

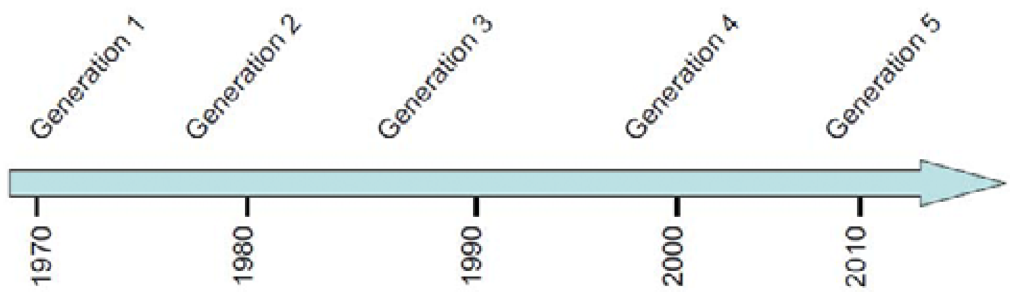

Figure 5-1: Nutshell Filter Evolution Timeline

As can be seen from Figure 5-1 the authors distinguish 5 different generations of Black Walnut Shell Filter designs. The following section expands on each of them in more detail.

5.1 Generation 1

See References 4, 5 and 7

Figure 5-2 below is a simplified drawing of the very first generation of BWS Filters.

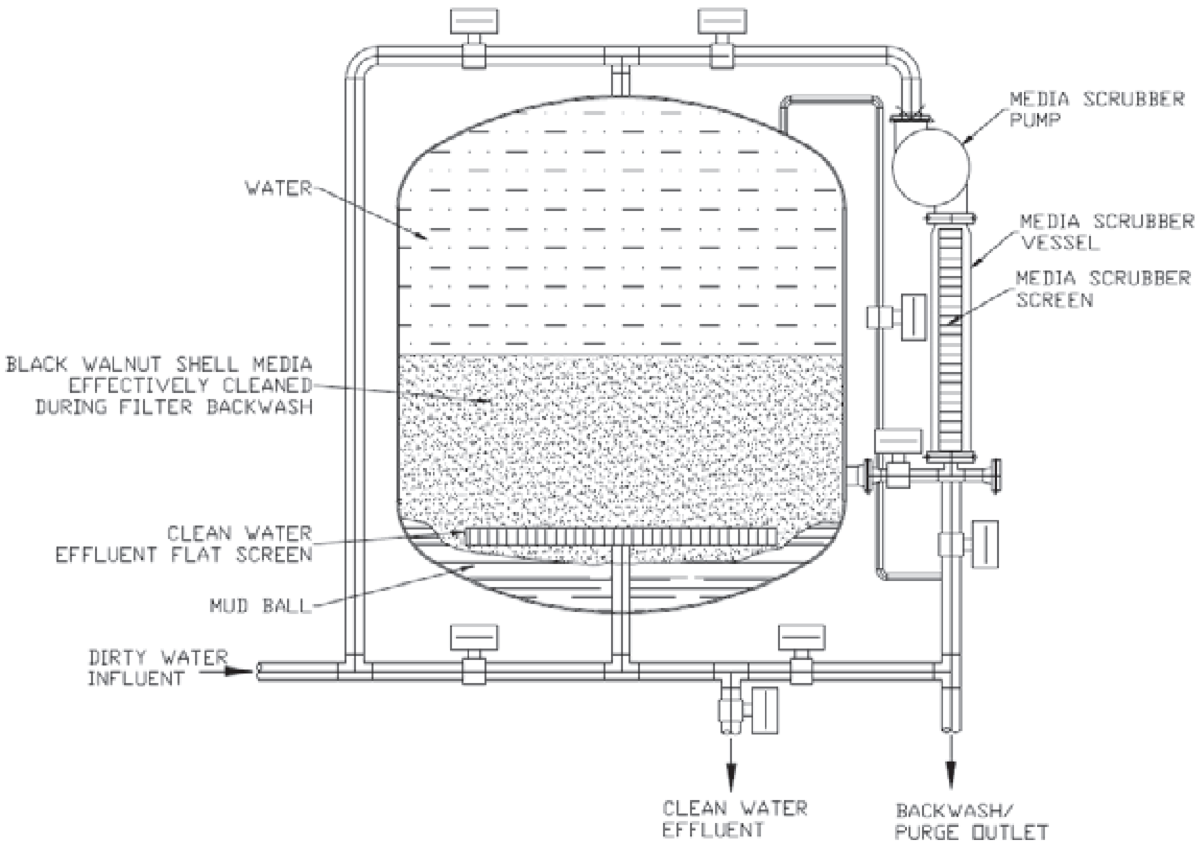

Figure 5-2: Generation 1 BWS Filter

The design features specific to the first generation are as follow:

- External scrubber with pump;
- Single backwash entry nozzle;
- Backwash nozzle is Bed submerged (within bed) and side entry; and
- Non-mechanical liquid fluidization.

Being very first generation and opening an era of BWS Filters in produced water treatment in early 1970s these filters had many design limitations including:

- External equipment requires additional space – bigger foot print;
- Additional cost of an external scrubber vessel, piping; pump, valves;
- Rotating equipment – additional maintenance;
- It is impossible to check whether all of the filter media been removed / scrubbed and returned to filter vessel;
- Costly high HP motors required to pump the slurry through scrubber vessel;
- Specialty slurry pump required
- Rapid attrition of the filter media resulting in excessive rate of media replacement required;
- Stagnant zone below the filter bottom screen results in “mud balling” effect;
- Design is only effective for a vertically oriented filter, therefore not applicable to flows above ~ 50,000 bwpd; and
- Bed-submerged cleaned media nozzle with side entry creates unfavorable settling hydraulics (uneven bed depth after backwash)

During backwashing stage slurry of agitated media is pumped out of the main filter vessel from a top nozzle and sent through an externally located scrubber vessel where shell particles experience a very intensive scrubbing along the scrubber screen tube. Contaminant-rich water stream flows through this screen and cleaned BWS particles are pumped back to the main filter vessel.

Given that the filter media is removed from the main vessel for cleaning, inevitably a portion of it is left in the external scrubber vessel and associated piping at the end of each backwash stage thus causing “mud balls”. It is also noted that this design reduces the media bed height in the filtration vessel increasing a potential of “breakthrough” when during forward filtration flow an untreated water finds the least resistant path and short circuits the media bed leading to contamination of clean water at the filter outlet. Another negative of this design is that the media settling in the scrubber vessel blocks the piping making it problematic to start the scrubber pump during the following backwash stage [8]. This problem was addressed in the next filter generation.

5.2 Generation 2

See References 6 and 8.

Figure 5-3 below is a simplified drawing of the second generation of BWS Filters. The design features specific to the second generation are as follow:

- External scrubber with pump;
- Single backwash entry nozzle
- Backwash nozzle is non-bed submerged (above bed) and side entry; and
- Non-mechanical liquid fluidization.

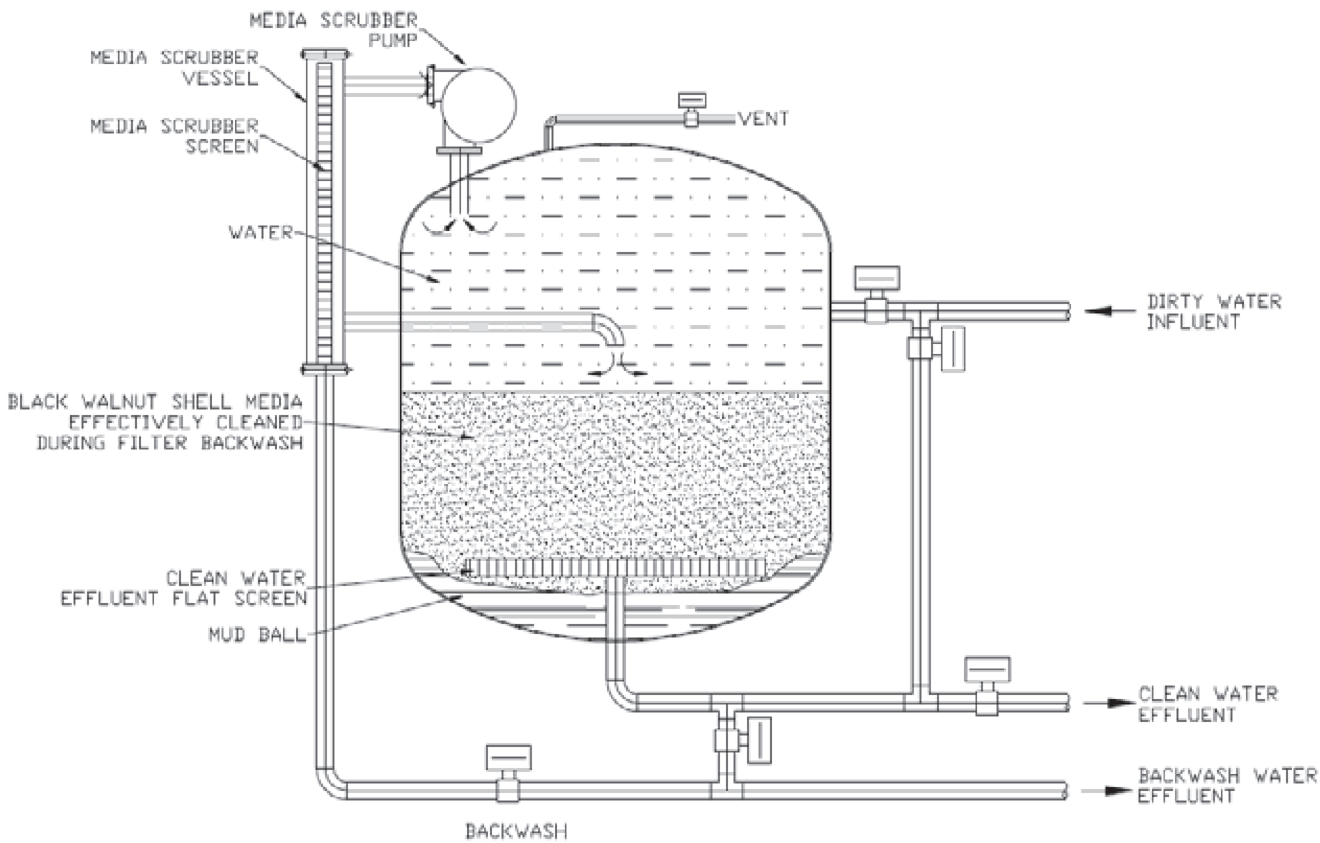

Figure 5-3: Generation 2 BWS Filter

The only design change to the first generation was the placement of the clean media return nozzle above the media bed level in the filter vessel. This was done to prevent unnecessary media bed agitation during the media settling stage while still circulating the slurry through the scrubber vessel. This resolved the uneven settling that was observed when Generation 1's bed was brought back into its filtration stage.

This design change also allowed the Generation 2 filter to partially reduce amount of nutshell media particles being trapped in the external scrubber thus easing piping plugging issues. However, this design still had a number of disadvantages such as:

- External equipment required additional space;
- additional cost of an external scrubber vessel, piping; pump, valves;
- Rotating equipment – additional maintenance;
- Costly high HP motors required to pump the slurry through scrubber vessel;
- Specialty Slurry Pump required
- Rapid attrition of the filter media resulting in excessive rate of media replacement;
- Stagnant zone below the filter bottom screen results in “mud balling” effect; and
- Design is only effective for a vertically oriented filter, therefore not applicable to flows above ~ 50,000 bwpd.

5.3 Generation 3

See References 9 and 10

Figure 5-4 below is a simplified drawing of the third generation of BWS Filters:

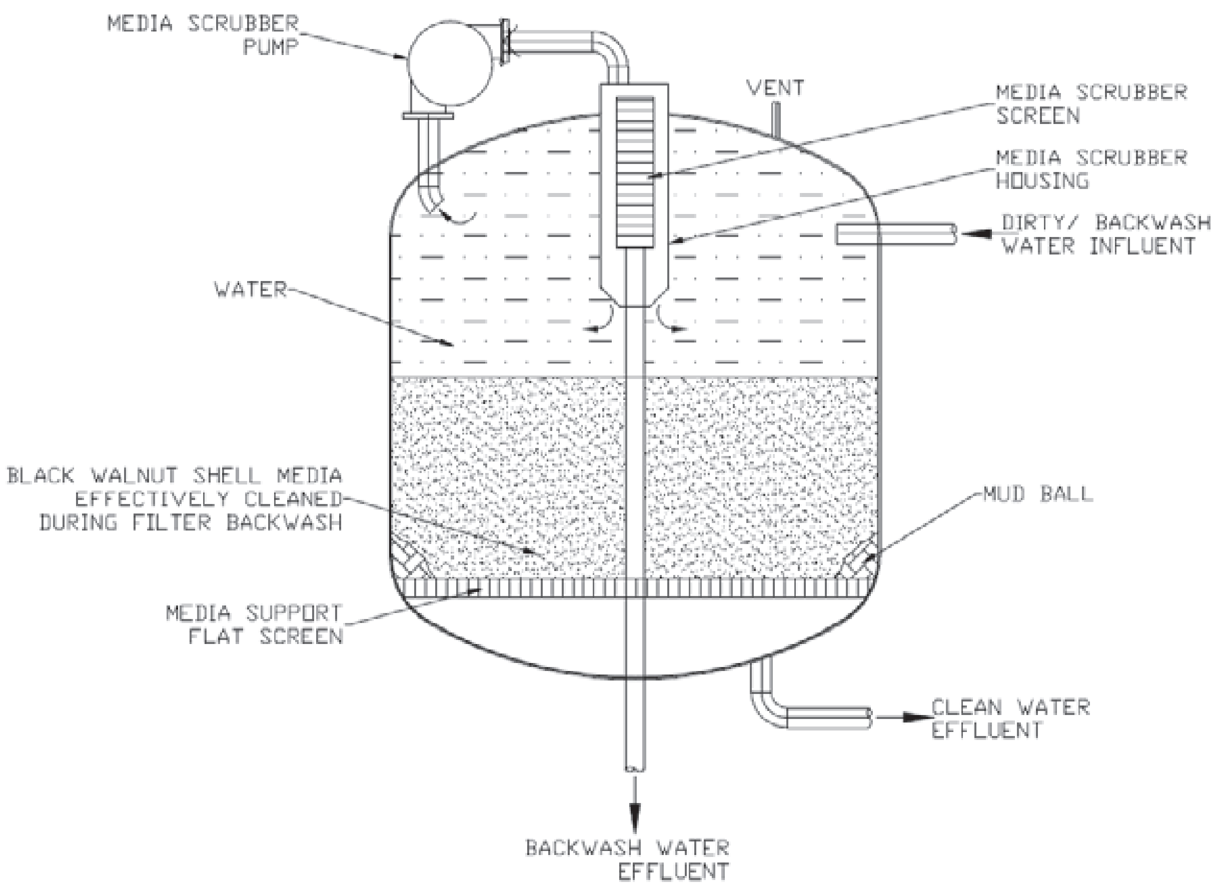

Figure 5-4: Generation 3 BWS Filter

The design features specific to the third generation are as follow:
- Internal scrubber with pump;
- Single backwash entry nozzle
- Backwash nozzle is non-bed submerged (above bed) and top entry; and
- Non-mechanical liquid fluidization;

Scrubber vessel was eliminated and scrubber element (screen) was placed inside the main filter vessel reducing the overall foot print of the unit. As a result of this change all the cleaned media is now returned to the filter vessel and not trapped in scrubber vessel/piping thus completely solving the design problem of the previous filter generations 1 and 2.

The following disadvantages of this design are still apparent:
- requires additional space;
- Rotating equipment - additional maintenance;
- costly high HP motors required to pump the slurry through scrubber vessel;
- Specialty Slurry Pump required
- rapid attrition of the filter media resulting in excessive rate of media replacement;
- Stagnant zone at the filter bottom and adjacent to the vessel shell results in "mud balling" effect; and
- Design is only effective for a vertically oriented filter, therefore not applicable to flows above ~ 50,000 bwpd

5.4 Generation 4

See Reference 12

Generation 4 was the 1st radical leap ahead in backwash design concept and for the 1st time eliminated the need for media to leave the vessel and to pass through the slurry pump. Energy for fluidization would now come from a motor external to the filter that drives a shaft mounted mixer (impeller) that is internal to the filter. This single change dramatically reduced the media attrition rates and the volume of water required to fluidize the bed. Generation 4 also abandons the idea of a conventional fixed scrubber element and instead implements a separator tube made of wedge wire screen which is attached to the same mixer shaft and is rotated at the same time. Due to the enhanced energy for fluidization coming primarily from a mechanical rather than fluid source this design has eliminated the mud balling stagnant zones from prior designs while simultaneously reducing the volume of water required for a backwash.

Figure 5-5 below is a simplified drawing of the fourth generation of BWS Filters. The design features specific to the fourth generation are as follow:

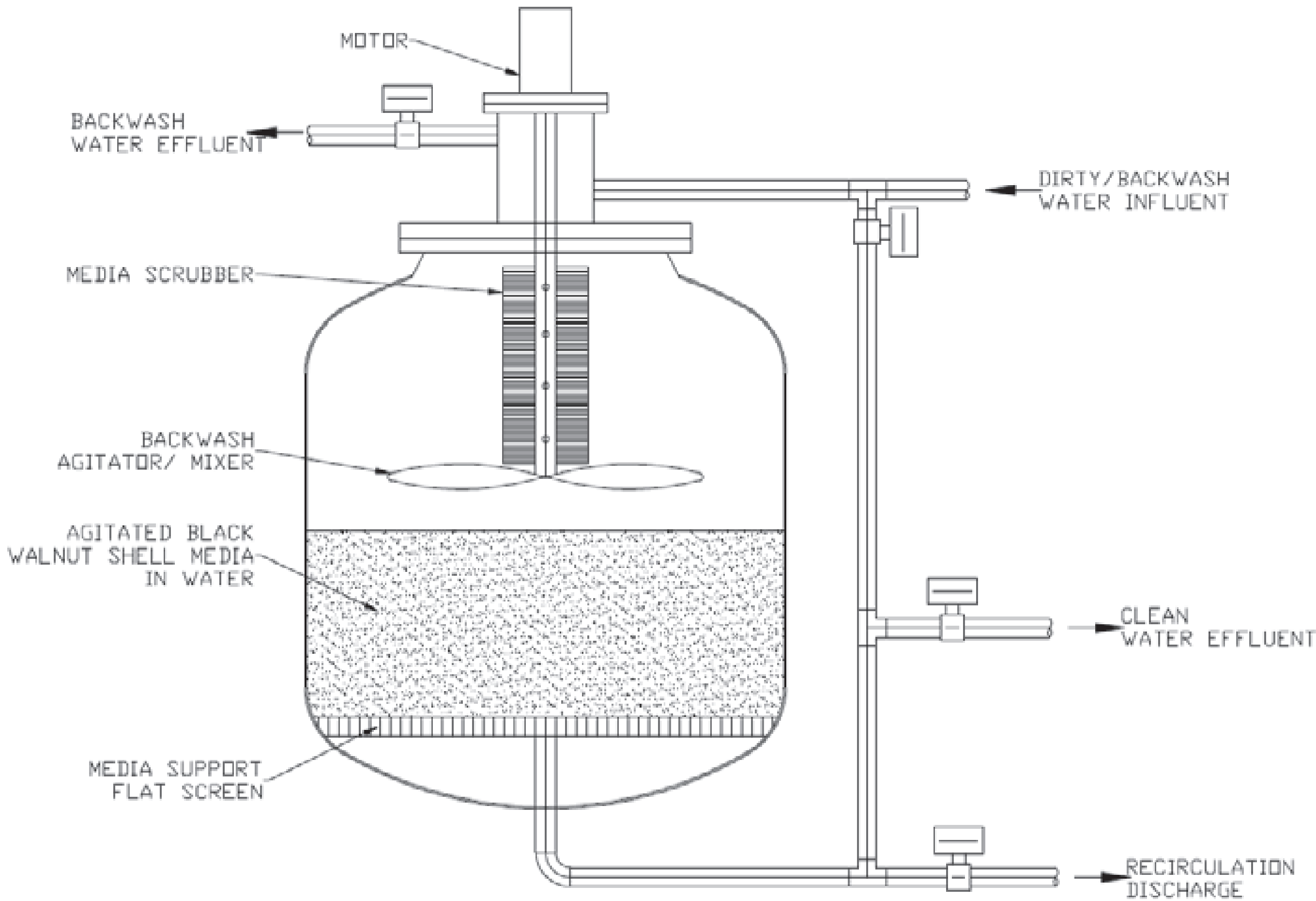

Figure 5-5: Generation 4 BWS Filter

- Internal scrubber
- Mechanical mixer with impeller;
- Backwash nozzle is non-bed submerged (above bed) and top entry; and
- Mechanical and liquid fluidization;

Nutshell media is not removed from the main filter vessel for cleaning any more. Backwashing takes place inside the main vessel which reduces the capital costs of the unit as well as footprint. Added mixer satisfactorily agitates the media during backwash stage requiring less amount of water comparing to the previous design generations.

The following are the problems still accompanied fourth generation filter design:

- Rotating equipment - in particular the mechanical seals for the rotating shaft through the vessel;
- High HP motors required to drive shaft and mixing impeller;
- Limited applicability to a horizontal filter configuration (filters larger than 50,000 bwpd). Larger filters require multiple internal mixers and fluid dynamics are no longer as efficient at filter heads and in between mixing devices

5.5 Generation 5 – Sabian Filters

See Reference 13.

While Generation 5 is used in both vertical and horizontal vessel orientations it was primarily developed to address the issues of performance in high flow applications where the filter is horizontally oriented. The major leap in this design is to eliminate all rotating equipment internal and external through the use of a multi-phase (Gas/Liquid) backwash feed. Use of gas alone was not a new concept for filter bed fluidization as this has been done on conventional sand and multimedia filter beds for over 100 years. This design however addressed the historical problem of gas fluidized filter beds where only a narrow column of bed immediately surrounding the gas sparging nozzle would fluidize. By entraining gas into a header network of backwash nozzles with high velocity water jet the water carries the gas tangentially dramatically further than a single phase gas nozzle. The buoyancy of the gas carried on the high velocity water jet creates a powerful fluidization force on the media while at the same time utilizing very little water in comparison to Generation 1-3 filters (equal to Generation 4.

Each multiphase backwash jet fluidizes a 4 foot diameter zone of bed and by networking into a header very large filters are efficiently fluidized with no dead zones and no rotating equipment or mechanical seals.

Figure 5-6 below is a simplified drawing of the fifth generation of BWS Filters:

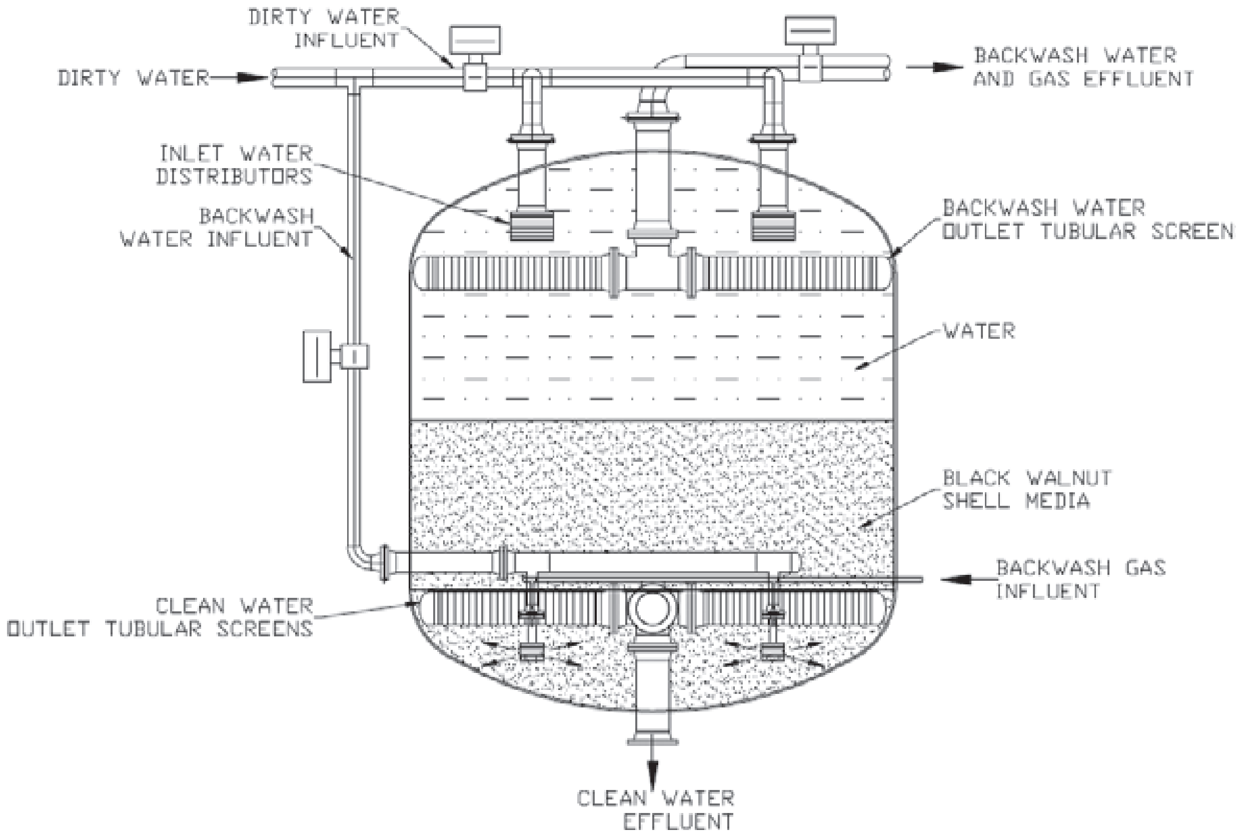

Figure 5-6: Generation 5 BWS Filter

The design features specific to the Fifth generation are as follow:

- Internal scrubber;
- Multiple backwash nozzles (applicable to large filters)
- Backwash nozzles are bed submerged (within bed) and bottom entry; and
- Non-mechanical (gas + liquid) fluidization;

This latest generation resolves all of the above mentioned design disadvantages of the previous generations. Characteristics of the fifth generation filters include:

- Removal of rotating equipment (motor with mixer) provides reduced maintenance requirements and no risk of mechanical failure;
- Elimination of mechanical seal(s);
- Reduced backwash water volumes required to satisfactorily clean the media bed (in comparison to Generations 1–3);
- Simple control philosophy – easy to operate with high reliability;
- Filter is of a robust design with low life cycle cost;
- Longer media life due to lower attrition rates (in comparison to Generations 1–3); and
- Surge capacity required upstream is lower due to the use of inlet feed (oily) water to complete backwash.

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6.0 CONCLUSION

40 years of Development and commercial implementation has resulted in a high performance filter unique to the rigorous demands of industry. The fact that the industry continues to strive to improve on the design of the Black Walnut Shell Filter now into its 5th generation is strong evidence that the market enthusiastically accepts this technology and we can expect to see more nutshell filters in operation throughout the world's oilfield facilities.

While the development cycle times have not been short it is evident how refined the current generation of nutshell filter designs now are in comparison to those that industry struggled with in the early years of development.

Produced water volumes have dramatically increased over the last decade and are expected to keep rising for the foreseeable future. Industry now has a need to recycle this water for use in stimulation of production (water floods, steam floods, polymer floods, etc.) where there is an increased requirement for oil removal filters capable of high performance at unprecedented flow rates. With such a rich history of innovation and evolution the BWS Filter design will surely continue to see developments and improvements to meet the needs of industry.

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