Understanding Hydrostatics:
An Essay of Details, Idiosyncrasies and Easily Misunderstood Concepts

Hydraulic Cleanliness

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Preface

Often when we at Qsine are implementing hydraulic systems we are faced with questions like: “Why do you do that?” “What does this one do that That one won’t?”

In many circumstances the questions arise with the focus on cost differences but in far more circumstances we see that the questions should arise when there are no cost differences. Like many things, high quality hydraulic systems often go unnoticed but poor quality ones get all kinds of attention.

People familiar with hydraulics know from experience that the components span very broad ranges of quality, performance and price. However, creating a high quality system requires more than simply piecing high quality components together. A system’s overall quality results from the mix between understanding basic, fundamental concepts and focusing on intricate details.

Strong knowledge of fundamentals will get to effective solutions but it is only after proper attention has been paid to all of the details that the high quality systems emerge. We have seen many very good (and often expensive) systems crippled by either the lack of attention or misunderstanding of fine details. Performance, reliability and life fell short of expectations even though the system was schematically correct and efficient.

We have helped many of our customers make decisions about hydraulic equipment by sharing our experiences with them over the years. However, we have noticed that our verbal tips and coaching are quickly forgotten. This seems only natural since the client’s primary concerns are what the hydraulic systems are doing and not how they are doing it. Our intention is to write a series of papers, or tips, on both the basic concepts and the details of hydraulic systems that we have found important.

The series “Understanding Hydrostatics: An Essay of Details, Idiosyncrasies and Easily Misunderstood Concepts”, is a reference that focuses on refinements. The techniques are geared towards performance enhancements through craftsmanship more than system functionality and design skills. Hence, information presented in the Series will not generally be recordable in schematic or logic diagrams.

INTRODUCTION

75-85% of all hydraulic failures are due to poor hydraulic fluid conditioning.

The above statement is widely known in the fluid power industry and generally considered a fact. It implies that hydraulic machinery fails only 15-25% of the time due to old age, manufacturer's defects, misapplication etc. The first paper in our series dealt with what fluid condition is and tips on how to maintain good condition.

The other widely known aspect about failures in hydraulic equipment is that many of them occur in the first 6 months of a systems life because they were assembled dirty.

Assuming a system is designed correctly for the application, cleanliness during assembly becomes the single most important factor in life and reliability. System life can be depreciated anywhere from 1-100% in the first hour of operation. Generally it takes large objects in the system flow to kill a system in the first hour. On the other hand, there is a surprisingly subtle difference between the amount of contamination that will reduce system life by 50% in the first hour and the amount that will reduce life by 5% or less in the first hour. This is especially true for high performance systems, using piston pumps and motors.

Any scoring or scuffing on bearing faces or sealing interfaces will lead to an increased rate of wear. On bearing faces the imperfections caused by contamination leads to more friction, which results in heat localized at the imperfection and further wear from the rough interface. At sealing interfaces, scoring results in leakage. A pressure drop and flow always represent power and thus, the leak will consume power, which will generate local heating at the imperfection. Between the heating and the natural fluid erosion from the leak, wear will occur.

Basically, an imperfection on mating surfaces is a spot where wear can occur more easily compared to the "perfect" surrounding surface. If we can minimize the imperfections, wear has fewer places to start and will grow slowly. If there are many imperfections, wear has many places to start and, just by its nature, wear accelerates as it grows.

Contamination that Affects Hydraulics

Generally, particles 40 microns (0.040 mm) or larger will affect component life and reliability in operation. 40 microns is not a hard number that you can say, anything less will not cause problems. It really is a statistics game. Often particles smaller than 40 microns pass through hydraulic components without causing damage. The risk of something jamming or scoring increases significantly as the size grows from 40 microns. Of course a gear pump is not the same beast as a servo valve but gear pumps depreciate from contamination also. The main difference is the application: if the performance of gear pump drops a little bit but is not noticed, it is likely because the output is not being measured that closely. Servo valves are generally in applications where the output is being measured carefully.

A particle that is 40 microns is difficult to see with the bare eye, it is about the limit of human vision. Place it in a drop of oil and most people will not be able to see it all. The point is to understand is that even if it looks clean, it may not be. Of course, there is no practical way to keep all particles 40 microns and bigger out of the system. The skill to practice is to remembering the 40 micron particle and assembling the system in a way that minimizes the entry of these particles into the system.

For reference, here are some typical objects measured in microns:

- Grain of table salt: 100 μ
- Width of a human hair: 70 μ
- Talcum Powder: 10 μ
- Bacteria: 2 μ

Myths about Shortcuts to Cleaning up Systems

One fallacy that we have seen tried many times in the past is the "let it get assembled dirty and we will circulate the crud out when it is done, it will be faster". While the process seems sound and logical, I have never seen it work successfully. When people think, "I don't have to be careful" things go out of control. There are several cases I have been called into where, cigarette butts, plastic bags, muffin cups and other unbelievable things showed up in the filters. One was a food processing plant where the so-called "circulation" took years, not hours, to clean the system up.

Even if reasonable care is taken it is impossible to setup a process. I have been at circulation session and people stand around while the pumps hums, and no matter how many hours or days have passed, everyone looks at everyone else and asks "Can we stop yet? Did we get it all yet?"

Others yet have hooked up very expensive particle counting, flow analyzers and circulated until the reading became less than some chosen value. They could show the charts to the customer and say, “Your system was cleaned to this level.” Which was great except as soon as the customer started bouncing his truck down the road, all of the “ribbon” drill chips that were stuck in the corner of the reservoir became dislodged and took down the pump and valves.

Similar things have happened to other customers that were circulating to clean their products. They found that the contamination was coming free inside their product while it was in transit to the customer.

The truth is that circulating before startup can be helpful for clean up, but only if the system is very clean to start with. The intention for using it should only be to get out the unavoidable contamination. In this case, whether the circulation runs for 2 minutes or 2 months, there should be less than a 1% difference in cleanliness.

Do it Carefully, Be Certain

The most common mistake we see with cleanliness is that people confuse an innocent problem with a simple one.

Cleanliness seems trivial so it is seldom a priority from the onset of a project or the development of a product. When the problems related to poor cleanliness do surface however, people realize that it is a difficult thing to control because it is hard to quantify. Anything that cannot be measured cannot be controlled. If there were a “cleanliness meter” that could analyze the inside of a system and list the particle sizes and counts of each size, quality control would be a snap.

But there is no such device. The best that current technology can do is test a sampling of oil and tell us how dirty the sample is. The sample is either drained from the system or measured real time through a flow stream. Either way, the oil sample is rarely a good indication of the cleanliness of the system as a whole, particularly in new systems where the oil is fresh.

The result is that cleanliness as a measurement, is the sole judgement of an assembler. Unfortunately, it is often time consuming and boring to be meticulous about cleanliness and this can skew the judgement. And herein lies the problem of quality control, to which we have no recommendations other than: trust people who really care about what they do and understand the consequences of dirty hydraulics.

The only way to be certain that the system is clean inside is to know that at every step, things were assembled clean and if anything got in or was left in, it was not much. It may be a tedious process but having to troubleshoot contaminated systems is worse. A stuck valve or a damaged pump is relatively easy problem to diagnose and fix, even if it is expensive and intermittent. Cleaning up a fully assembled system to prevent the catastrophe from happening again is by far the greater headache because again, there is never certainty that the system is clean.

Do it and do it carefully. The reward comes in the form of silence because customers are seldom silent when a system is causing trouble and they think you are at fault.

Helpful Hints

Things you can do to help control the amount of contamination entering a system are:

- Sweep up the work area before assembly starts.
- Change into clean coveralls before you start.
- Keep the outside doors closed to prevent the wind from stirring things up.
- Avoid assembling in the proximity of welding and grinding that may be going on.

During assembly, the visible contamination is not the problem. If a part is plugged and capped, washing it in solvent and/or blowing it off with compressed air will clean it up. The major problem occurs when components are left uncapped. The contamination gets into the part, where it is likely unseen, and using compressed air only drives the crud deeper into the component. So it is simple:

- Keep any open connection capped or plugged.
- Blow the part off before uncapping it.
- Connect thing up as soon as they are uncapped.

Hoses and fittings should all be blown out before installing, even if they are capped and even if they were cleaned at the supplier. If hoses are being shipped from your supplier uncapped, ream out your salesperson, as there is no excuse for this. If they don't have caps, they should be shrink wrapping the ends. Confirm with your salesperson that the hoses are being cleaned during and after assembling. The cutting wheel creates rubber and steel dust inside the hose. They should be blowing the ends of the hose out after it is cut and before they crimp on the ends. They should also be blowing a foam "pig" through the hose to clean the finished assembly.

When filling or topping up a system, clean and blow off the area surrounding the filler breather before removing the breather. Use a filter cart to add oil to the system or pour directly from the original oil container. Never use an open container, even it is supposedly dedicated to oil transfer. At Qsine, we prefer to run everything through a filter cart. Even pouring direct from the original oil container is quite dirty.

You will find mill scale from the refinery's pumps and plumbing in the oil containers. Not that many years ago, a lot of oil companies put motor oil into white 1 liter jugs. Take a look some time and you will notice that almost all oil containers are black or a very opaque gray now. It makes it difficult to see the crud at the bottom of the container.

Maintenance

The same tips apply for maintenance:

- Keep things capped and plugged.
- Clean off the area surrounding the filler breather before removing the breather.
- Use a filter cart to add oil to the system or pour directly from the original oil container.
- Never use an open container, even it is supposedly dedicated to oil transfer.

Tips specifically for maintenance:

- Check fluid levels daily or installed a level warning indicator.
- Change filters regularly (more on this below) and keep track of the filter changes.
- If a filler breather or other item that exposes the system to the outside environment gets lost, do not let the “make-shift” solution operate forever, get a replacement.
- When you get a replacement, buy a spare or two to prevent the “make-shift” from going into service again.
- Look for and repair leaky seals and fittings. These are entry points into the system.
- Inspect your oil for indications of water on a weekly basis, or daily in humid conditions. While the system is cold, drain a small sample of oil from the bottom of the reservoir. Look for water if the system has been sitting or for milky oil if it has been running. Replace the oil if either of these conditions exist. Water is generally more prevalent in systems with cylinders, which cause air to be ingested into the tank, and where ambient conditions are prone to making condensation.
- Water removing filters can be used in humid environments where condensation is a problem. However, care must be used with these filters as the desiccant, which binds the water also binds many additives that are important for lubricity and viscosity stability. The desiccant also expands as it absorbs water and, as a result, these filters clog very rapidly.

Maintaining Fluid Condition

One of the most common questions we get is: “How often should the oil and filter be changed?”

There are many rules of thumb about this subject and like all rules of all thumbs, they will get you into trouble unless you think about your situation. In general we recommend:

- Change the first filter on a new system after 50 hours of operation.
- Regular filter changes should be made on 400-500 hour intervals or twice a year.

Notice that there are no general recommendations about changing oil. We suggest sending a hydraulic oil sample to a testing laboratory on 500 hour intervals to test the fluid for the following:

1. Particle size, counts and content.
2. Chemical content (ie. fluid additive condition) including water.
3. Viscosity check @ 100 ℉ and @ 210 ℉

The test results will indicate when fluid changes are necessary and if filter change intervals should be altered.

There are many exotic and expensive filters available and they can be used but most often, they are unnecessary. From our experience, regular filter changes are more important to system life that the type of filter you use. If the system goes together clean and maintenance practices keep it clean, almost any nominal 10 micron filter can perform adequate cleaning, even on servo systems. The truth that the filter companies prefer not to talk about is that if the system goes together dirty or gets dirty during maintenance, no filter has much chance of salvaging system life anyway.

Our experience has shown us that using an inexpensive filter that our customers can buy in the case loads without feeling a crimp for money is helpful in that they do buy filters by the case, and the filters get used. If the filter is expensive, they buy them one at a time so right away it becomes a chore. And when the spare gets used, often it is not replaced right away and the next time a filter change gets missed.

High capacity filters can be used on high capacity systems with extreme duty cycles. To use high capacity filters in hopes that they will prevent problems if maintenance is ignored for years is wrong thinking.

Technical Reference & Cleanliness Jargon

As stated earlier, cleanliness is a difficult thing to measure and we can only measure a sample. The results from the sample are assumed to be indicative of the whole system. The cleaner the system is and the longer a system runs, the better this assumption is because the fluid commingles with all of the components and picks up the contamination.

When we look at fluid cleanliness from a technical standpoint, the first thing to remember is that a particle that is considered to be contamination is measured in microns (millionths of a meter). Drilling chips, weld spatter, remnants of Teflon tape and small mammals are out of the scope of technical hydraulic cleanliness. The cleanliness technician assumes that any item large enough to see at reading distance will never be present in a system. Only if this assumption holds true can it be assumed that the oil sample will truly be indicative of the whole system cleanliness after many hours of operation.

So far you should feel like the science of cleanliness is vague and based on some fairly stretching assumptions. If not, re-read the last two paragraphs because it is. Regardless, what the science should tell you is that if you think there may be even a few drilling chips, weld spatter, grinding dust, Teflon tape, silicone… (the list goes on and on) in your system, do not believe the measured cleanliness numbers.

If your systems are suitably clean and you trust the numbers, what do the numbers mean? Filter ratings and fluid cleanliness measurements are often confusing to look at because they contain a lot of information. The assumptions and vagueness of the science means that any number given as a measurement has to be qualified so people can compare apples to apples if possible.

The ISO organization has come up with some standards to try and move cleanliness to a repeatable science. Unfortunately, they keep changing the standards so that the ratings, which were already confusing, become more confusing because you need to know the vintage of your numbers as well.

Hydraulics cleanliness measurements come down to 2 standards for the operator or assembler:

- Filter ratings are by ISO 16889
- Fluid ratings are by ISO 4406

Keep in mind ISO 16889 supersedes the old standard ISO 4572 and ISO 4406 changed in 1999. The differences will be discussed later.

The standard filter ratings are a measurement of filter efficiency and filter companies will publish these numbers for you. The standard fluid ratings are how hydraulic component manufactures communicate to you, the cleanliness level that is required for their components to perform reliably.

When the filter ratings are given in the form:

$Beta_x$: 2/20/75
4µ/10µ/13µ

And hydraulic fluid ratings are given in the form:

22/18/13

You would think that a person could take one set of numbers and determine what they need or will get with the other set but that is not the case. Let us take a closer look.

Filter Ratings

First we will look at how to read the numbers starting with the filter:

$Beta_x$: 2/20/75
4μ/10μ/13μ

This is called the Beta rating and is the old ISO 4572 style. It is in two parts. The "$Beta_{(x)}$: 2/20/75" is the Beta standard to which the filter manufacturer is rating to. The three numbers in slashes are called Beta numbers and are a measure of filter efficiency:

$$\text{Beta number} = \frac{\text{Number of Particles Upstream of the Filter}}{\text{Number of Particles Downstream of the Filter}}$$

So a if we counted 200 particles in the sample before we put it though the filter and 100 after it went through the filter:

$$\text{Beta number} = \frac{200}{100} = 2$$

We would have a Beta number equal to 2, which means we filtered half of the particles. To me, this is not a very practical number but it is what the intelligent people on the ISO committee decided to use. With my peanut sized brain, I prefer:

$$\text{Efficiency} = \frac{\text{Beta number-1}}{\text{Beta number}} *100\%$$

$$= \frac{2-1}{2} * 100\% = 50\%$$

Similarly a Beta number of 20:

$$\text{Efficiency} = \frac{20-1}{20} * 100\% = 95\%$$

and a Beta number of 75:

$$\text{Efficiency} = \frac{75-1}{75} * 100\% = 98.67\%$$

The "x" in the $Beta_x$ signifies the particle size. So when a manufacturer says:

$Beta_x$: 2/20/75

It means; "I am going to tell you the particle sizes that the filter will trap 50% of the time, 95% of the time and 98.67% of the time." And when you see this:

4μ/10μ/13μ

It means the filter element catches 4 μ particles 50% of the time,10 μ 95% of the time and 13 μ 98.67% of the time.

Now remember that this is the old ISO 4572 standard, which is a single pass through the filter. The new ISO 16889 standard is for multiple passes through the filter so for the same filter you will see more impressive numbers but that is not the intention of the change. The new standard is apparently more reproducible and is supposed to keep the filter companies "more honest" (whatever that means!).

Beta numbers under the ISO 16889 standard are designated with a $Beta_{x(c)}$. You can watch for the "c" or you will note impressive Beta numbers such as:

$Beta_{5(c)}$ = 200

Which means for 5 μ particles, the filter will catch a 99.5% of them. What is interesting to note here, where we have a huge Beta number and a question about filter maker's honesty, is to decide how much Beta number is enough. Manufacturer's can publish Beta numbers of any magnitude.

The debate has been over what Beta number do we call "absolute" or close enough to 100% to call it 100%. Some manufacturers use 75 (98.67%), others use 100 (99.0%), other use 200 (99.5%) and others still use 1000 (99.9%).

People using the lower numbers claim that the people using the high numbers have no technical advantage and are just using the big Beta number for marketing purposes. Vise versa, the high end group claim the lower numbers give the filters a better micron rating than they deserve and are using the micron numbers for marketing. As for who is telling the truth, I can only say that from my experience, I don't know if anyone is actually right but neither group seems to be doing anything overly wrong. Considering that the difference between 75 and 200 is less than 1% they are all close enough that the arguing is not warranted. Furthermore, the whole thing is nothing more than a statistics game anyway: if one particle of any size gets through the filter and scores the pump, does it matter that 99.9% of the others were trapped?

Fluid Ratings

Most hydraulic component manufacturers publish the fluid cleanliness that they want the assemblers and operators of their equipment to maintain in order for their parts to run reliably. A typical fluid cleanliness statement will look something like this:

Maintain fluid cleanliness to ISO 4406 Class 22/18/13 or better.

Often you will see the class given as two numbers such as "Class 18/13" instead. The "Class" is a classification code that states the permissible number of particles in a 1 ml sample of oil.

The particle counts for the old ISO 4406 and the new ISO 4406:1999 codes are as follows:

ISO 4406 **Number of Particles per ml**				***ISO 4406:1999*** **Number of Particles per ml**		
More Than	Up to & Including	Scale Number		More Than	Up to & Including	Scale Number
				1,300,000	2,500,000	28
				640,000	1,300,000	27
				320,000	640,000	26
				160,000	320,000	25
8,000,000	16,000,000	24		80,000	160,000	24
4,000,000	8,000,000	23		40,000	80,000	23
2,000,000	4,000,000	22		20,000	40,000	22
1,000,000	2,000,000	21		10,000	20,000	21
500,000	1,000,000	20		5,000	10,000	20
250,000	500,000	19		2,500	5,000	19
130,000	250,000	18		1,300	2,500	18
64,000	130,000	17		640	1,300	17
32,000	64,000	16		320	640	16
16,000	32,000	15		160	320	15
8,000	16,000	14		80	160	14
4,000	8,000	13		40	80	13
2,000	4,000	12		20	40	12
1,000	2,000	11		10	20	11
500	1,000	10		5	10	10
250	500	9		2.5	5	9
130	250	8		1.3	2.5	8
64	130	7		0.64	1.3	7
32	64	6		0.32	0.64	6
16	32	5		0.16	0.32	5
8	16	4		0.08	0.16	4
4	8	3		0.04	0.08	3
2	4	2		0.02	0.04	2
1	2	1		0.01	0.02	1
				0.005	0.01	0
				0.0025	0.005	00

By the old ISO 4406 standard a three Class code number was given as the count of:

- 2 micron or greater particles
- 5 micron or greater particles
- 15 micron or greater particles.

If it is given as two Class code numbers, then the counts are of:

- 5 micron or greater particles
- 15 micron or greater particles.

In the new ISO 4406:1999 standard, a three number code should always be given and it is the count of:

- 4 micron or greater particles
- 6 micron or greater particles
- 14 micron or greater particles.

Thus, if we interpret the example code:

Maintain fluid cleanliness to ISO 4406 Class 22/18/13 or better.

The manufacturer is saying: "Keep the 2 μ and larger particles between 2,000,000 and 4,000,000 counts per ml, the 5 μ and larger particles between 130,000 and 250,000 counts and the 15 μ and larger particles between 4,000 and 8,000 counts and your system will run fine, from the standpoint of contamination."

If the code were:

Maintain fluid cleanliness to ISO 4406:1999 Class 22/18/13 or better.

Then the manufacturer is saying: "Keep the 4 μ and larger particles between 20,000 and 40,000 counts per ml, the 6 μ and larger particles between 1,300 and 2,500 counts and the 14 μ and larger particles between 40 and 80 counts and your system will run fine, from the standpoint of contamination."

Notice that there is a large100 times difference in counts for the same code numbers depending on what standard is called. Make certain that you read the specification carefully and go to the correct table.

Many manufacturers neglect the 2 μ code in the old standard because the particles are generally not harmful to hydraulic systems. Remember that 2 μ's is the size of a bacteria.

Using the Numbers

So now we have all these numbers floating around in our heads. We know what the manufacturers want and we know what the filters can do. How do we link the two together so we can get the appropriate match in an application?

Like I stated earlier, even though the format of the numbers for filters and fluids look like they should correlate into a simple equation to calculate fluid numbers from filter numbers or filter numbers from fluid numbers, there is no such relationship.

In fact, look at many component catalogs and right after they say: "Maintain fluid cleanliness to ISO 4406 Class 18/13 or better." They will add "A Beta_{10}=10 filter will generally be sufficient".

So let us see at: 10 μ's the filter is $\frac{10-1}{10} = 90\%$ efficient.

Huh??? After all this, they are saying use a nominal 10 μ filter. You are thinking: "Must be a gear pump, right?" But, believe it or not, this is from the Sauer-Danfoss's 45 Series, 4,490 psi rated, open loop, piston pump catalog. This same filter recommendation is found in the catalogs of Sauer-Danfoss's 51 Series hydrostatic motors and 90 Series pumps. These are high-speed speed components rated at 6,000 to 7,000 psi. The 90 Series pumps are also servo controlled.

The "ISO 4406 Class 18/13 or better" cleanliness requirements will satisfy most pumps, proportional controls and many servo controls. And many times it can be done with a nominal 10 μ filter. Our experience at Qsine leads us to believe the same thing. The vast majority of our systems have spin-on, nominal 10 μ filters. We have seen many of these systems operate trouble free for more than 20 years without component replacement. Our education over the years taught us that cleanliness during assembly and maintenance and regular service are generally far more important than the filter selection.

So if everything can be done with a nominal 10 μ filter, why all the discussion? Simple, it cannot all be done with a nominal 10 μ filter – you knew that answer was coming. But how can a person calculate or decide what filter to use?

This question postponed the writing of this paper for years because I never found a reasonable way to present the analysis. Every technical article I read on the subject started with: "Assume X number of particles of Y size are being ingested from the filler breather and this much is coming from pump wear…" etc.

This always reminded me of the joke about the physicist who designed a chicken plucker that could process an unbelievable number of chickens. When presenting the design to an audience his first statement was: "First we assume the chicken is spherical…"

But there are some general rules that apply: The type of contamination in the surrounding environment is important. Some things are worse for getting into systems than others and some things are just harder to filter out than others. Experience is the only thing that will help make a decision in this case. Another factor is the actuators: cylinders always introduce more contamination than motors. Cylinders draw contamination in on the rods and they generally make the reservoir breathe: the fluid level falls when the cylinder is extended and it rises when the cylinder is retracted.

You can try and calculate contamination generation but the answer will only be as good as the assumptions you make. Hence, I will not even attempt to tell you how to filter a spherical chicken out of your system. So eventually, I gave up on the idea of presenting the theory and decided to just tell people what we do.

The "Keep It Simple Stupid" (KISS) philosophy comes into play but you will not get an immediate answer. First try the nominal 10 μ filter and if it is insufficient, then advance the filter technology to something better.

This advice should not be interpreted as "risk destroying your system and try again if something fails". The fluid testing that was recommended earlier in the maintenance tips is a very valuable tool. If the filter is insufficient, it will quickly show in the particle counts of the fluid analysis. If certain materials are showing up, then you know the media is not suitable for the application. Fluid tests do one thing that no analysis can do and that is build experience.

Fluid cleanliness with all of the jargon and strange ratings, looks like complicated wizardry when first tackled as a study subject. As you look more carefully, you will realize that the complication comes mostly because there are so many factors that are hard to quantify which affect cleanliness.

I think the truth is that people at the filter and hydraulics companies and ISO also know that cleanliness is not complex but defining cleanliness is. However, there is a need for a way to communicate cleanliness to assemblers and maintainers so that systems do run reliably. If there is any magic involved, it comes down to do you trust the numbers when you get a measurement? Dissolving the magic and gaining trust comes from the knowledge that the system went together clean.

As far as system life goes, it is very simple: think in terms of microns, use care and attention to keep things clean at the micron level, keep things clean at every step and never take a short cut. With a new product or piece of equipment, use fluid testing. Testing and test results make the subject easier to understand and helps you develop a feel for what is really happening before a failure. The problem is that it takes time to develop the experience and that never helps when you need the answers right now.

One other thing I would recommend is to use advice of people with experience as a guideline to steer you into your own experiences. Never take what they say as an absolute truth. Their knowledge was developed in the applications they worked on and their advice can easily be wrong because of a solitary factor in your application.

Learn what works and use that knowledge to learn more or learn better… I guess that applies to anything.