A Study on Bio-Fouling Characteristics of Contemporary Trickle and Modular Splash Fills

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Abstract:

The development and marketing of contemporary modular trickle and splash fills has yielded a perception that any "wire frame model" type fill offers similar resistance to fouling as classic splash bar fills. However, laboratory testing and real world experiences have shown that these fills exhibit similar responses to bio-fouling problems as film fills with respect to product design and flute geometry. A systematic laboratory method of evaluating weight gain due to bio-fouling and sediment accumulation illustrates the effects that these different design elements have on the actual fouling resistance of this type of fill.

Introduction

Splash Fills to Film Fills:

There is a vast library written about the evolution of cooling tower fills and the history of splash fills and film fills. The development of film fills in the 1970's and 1980's offered the cooling tower industry a leap forward in cooling efficiencies, and counterflow towers that were originally built with 9m (30ft) air travel depth of splash fills were able to be reduced to only 1.2m (4ft) of a high efficiency cross-fluted film fill. Unfortunately, the great wonder of high efficiency brought with it the specter of fouling, which can totally eliminate any efficiency gains.

The problems and large dollar costs caused by the fouling of high efficiency fills when applied to large electrical generation plant cooling towers provided an impetus for further film fill development. The goal was to find a way to maintain higher thermal efficiencies while trading away some efficiency in order to gain resistance to fouling, with the prize being a fill that is able to maintain a set level of cooling capability over a long period of time.

It is important to realize that this prize can sometimes create difficulties for a tower owner/operator because for a new tower, the decision on what tower to buy is generally driven solely by dollars. A tower built around a more efficient fill will be smaller than or use less fan motor power than a tower built around a less efficient fill; both of which mean less money being spent up front. What needs to be understood is that the long-term operation of the tower and the costs associated with it are heavily influenced by the fill choice. As the power industry learned hard lessons in the 1980's, it does not matter how "efficient" your fill is when it is brand new. What is critical is can you get the required cooling capacity out of your cooling tower months and years after the tower is built?

Film Fill Evolution:

The first film fills were sheets of asbestos cement board, and the invention of the first cross-fluted fills by Munters in the late 1960's revolutionized the cooling capability in a given volume of fill. As noted by other authors including Monjoie (TP11-26), Zelek (TP06-19), Mortensen & Conley (TP94-05, TP98-14, & TP01-02), manufacturers of film fills applied research and development projects into finding ways to attempt to mitigate the highly fouling nature of cross-fluted fills with the result being the rather large and continually evolving variety of counterflow fills that are now available on the market.

Figure 1: Basic Flute Geometries

Cross-fluted fills generally provide the highest cooling capacity per volume along with the highest potential for fouling. The cross-flutes help to slow down the water film velocity in the pack. This increases the time for air-water interaction within the pack and is one reason these designs give the highest efficiencies. However as discussed by Whittemore and Massey the reduction in water film velocity has one of the largest impacts on the biofoulant growth.

Offset fluted and vertical offset fluted fills are a more recent development blending some of the characteristics of cross-fluted fills and fully vertically fluted fills. As a blend, they generally still offer relatively high cooling capacity per volume of fill, but the vertical geometries of these fills provide higher water film velocities which provide much greater resistance to biofouling due to the higher hydrodynamic shear stress. Due to the sheet geometries, these designs also offer fewer mixing and distribution ("cross-over") points within the fill packs, which again helps to keep water film velocities high. Even a highly sloped cross-fluted fill (sometimes also referred to as a "shallow corrugation angle" product), provides these crossover points which reduce water film velocities.

Vertically fluted fills provide the greatest fouling resistance of all film fills since they maximize water film velocities and have no cross-over points. When this design is used in a pack with large sheet pitch (the spacing between individual sheets), fills of this design can be applied to some of the most demanding applications.

Development of "Wire-Frame" fills:

Another path of fill development has been the creation of various "wire-frame" fills that have the appearance of a wire-frame 3D drawing of a fill pack. The intent with these packs has been to provide much less surface area when compared to a film fill, in the hope that this type of product will thus provide greater fouling resistance than a film fill. As with film fills this type of pack design lends itself towards the same types of flute geometries as film fills with cross-fluted, offset flutes, and vertical flute geometries all being offered by various manufacturers.

A critical difference between these types of fills lies in the different inherent modes of providing the thermal characteristics. These can be categorized as either "trickle" fills or as "modular splash" fills. As noted by Kröger,

> "Trickle packs or grids are much finer than splash packs and are made up of plastic or metal grids onto which the water is sprayed. It runs down the grid rather than splashing. Because of the much finer mesh than the splash type fill, they tend to clog more easily and have a greater pressure drop."

Since the water is forming a film along the strands of the trickle pack, the cooling occurs such as that in a film fill. Therefore, in order to maximize cooling capacity, reduction in water film velocity is a key to maximizing the cooling capacity of a trickle pack. For this reason, cross-fluted trickle packs with large numbers of fine strands were developed in order to give the highest efficiencies to these types of fill packs.

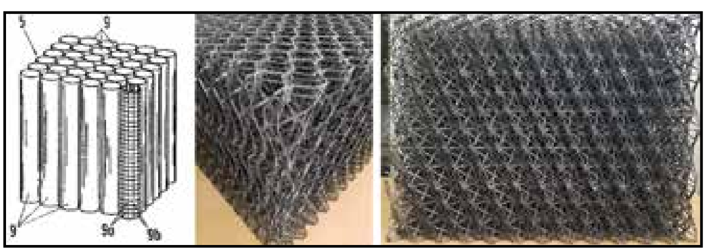

Figure 2: Sample Trickle Fills

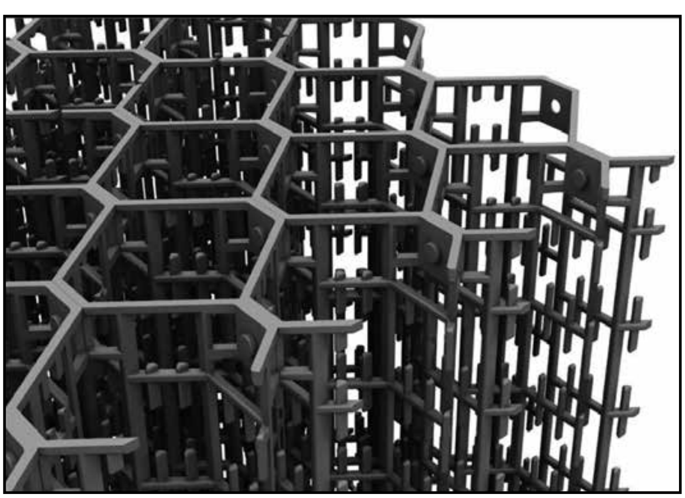

Figure 3: Sample Modular Splash Fill with detail of droplet generating features

In contrast modular splash fills achieve their thermal characteristics via droplet cooling, just like a splash fill. Instead of the water only forming a film along the strands of the "wire frame," a modular splash fill incorporates design features that create droplets, such as those shown in Figure 3. When this feature is combined with a flute geometry that maintains water film velocity such as a vertical-offset flute, there are noticeable gains in fouling resistance.

It is this contrast between contemporary trickle and modular splash fills that is the subject of the tests in this paper.

Introduction to Biofilms and Fouling

How biofilm layers form and grow:

Biofilms are a complex, three-dimensional matrix of organic and inorganic material. A biofilm is more resilient than a single-floating bacteria with its distinguishing characteristic being the extracellular polymeric substance (EPS) created by the bacteria themselves. EPS is a sticky substance that is used to adhere the bacteria to surfaces and to adhere nutrients to the bacteria. The EPS may account for 50-90% of the matrix, and as the age of the biofilm increases, so does the amount of EPS the bacteria secretes. Using this matrix, the bacteria will develop attached communities that can vary in thickness depending on the environmental conditions. Once the biofilm has reached a safe population level they will use the matrix to communicate with other cells to trigger certain genes. Sub-colonies have also been observed within the biofilm and within the bacteria community. The attached layer may be considered one sub-colony, and their only function is to maintain surface attachment and to provide nutrients to the layer above them. The layer above them would be a separate sub-colony which only has the function of reproduction and making the community larger.

Biofilm life cycles in relation to cooling tower fills:

New PVC and PP fill packs are initially hydrophobic. Therefore, they repel water and cause it to bead up, which is detrimental to achieving the full thermal efficiency potential of the fill. Due to this circumstance fill packs need to be conditioned, a.k.a. "seasoned" or "aged," such that a very thin insulating layer of organic and inorganic materials form on the plastic surface. Once this layer is formed the free-floating bacteria have a surface they can land on and begin the absorption phase. This phase is still reversible, and the length of it will depend on the shear forces and nutrients at the surface of the plastic. Once there are enough bacteria on the surface they will begin to secrete the EPS matrix and develop an irreversible layer which become the foundation of the biofilm. At this point they will use the matrix to signal other cells to begin the growth and division stage which will eventually grow into a mature micro-colony three-dimensional film. This mature micro- colony will be able to send signal molecules within itself in order to signal for dispersion which will allow bacteria to leave the colony, float into the water, and land to form new colonies. They will also be able to send signal molecules to other forms of bacteria in order to form a multispecies colony complete with water channels, bridges, and other microstructures designed for easy communication and travel of nutrients.

It is the combination of the EPS, the water channels, bridges, and other microstructures, and the presence of solids that lead to fouling. The circulating water within the cooling tower flows through the channels, bridges, and microstructures, and the EPS provides the "glue" that holds any solids contained within the circulating water to the biofilm.

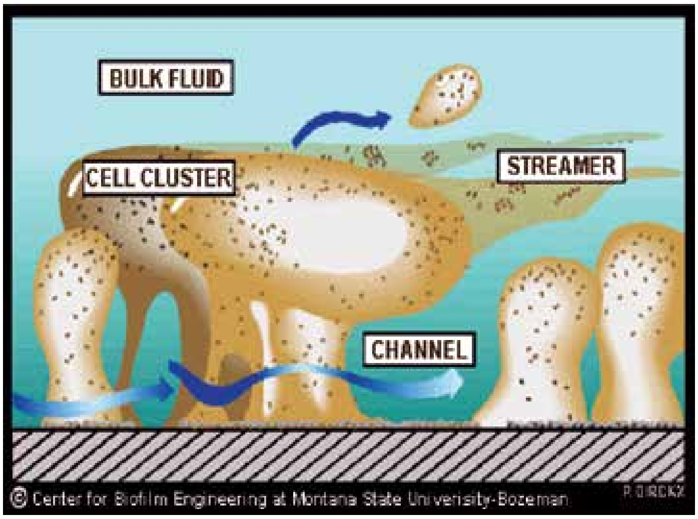

Figure 4: Basic structure of a biofilm

Fouling Tests

Field tests:

There have been numerous field test programs to measure fouling tendencies of fills throughout the years. In some instances, fill has been installed directly into operating cooling towers in "test bays," and in other instances small test towers have been installed onsite that use a side-stream of the circulating water loop. The goal in either scenario is to monitor and gain data on the fouling potential of a particular fill based on the water quality of a specific operating condition – that of the test site itself. Refer to sources Whittemore & Massey; Monjoie, Noble, & Mirsky; Mortensen & Michell; and Mabrouk, Azarou, & Marconnet for further details.

The usual monitoring criterion is weight gain since that provides a measureable data set and is somewhat more readily achievable than other methods such as visual inspections. The basic premise is that the higher the weight gain, the greater the fouling. Research presented by Whittemore & Massy, Monjoie, Noble, & Mirsky, and Southern Company provided data that related the weight gain values of different fills to the thermal performance (degradation) of the fill. The test data proved that higher weight gain of the fill packs resulted in lowered cooling capabilities.

Laboratory tests:

Research has also been performed in laboratory environments by multiple entities where fills were exposed to artificially enhanced fouling environments in an effort to provide comparative results between different fill designs. It is acknowledged that the specific test environment in a laboratory setting is not equal to a field installation, if only for the fact that every field installation will have its own unique parameters that set it apart from any other site. The benefit of a laboratory test is that the fouling parameters can be controlled and different fill designs can be evaluated and compared based on the same conditions and at the same time. Laboratory tests also provide the opportunity to accelerate the fouling process, if wanted, so that a process that might take months or years in the field can be observed in a much shorter period of time. As such, results from laboratory fouling testing must be considered as relative results and not absolute results. However, they still provide an important evaluation tool for fill choice.

Brentwood Laboratory Fouling Test Program:

Fouling Test Rig Description:

Brentwood's fouling test rig is designed to concurrently evaluate six (6) fills with each fill bay being suspended from its own individual load cell. Each fill bay measures 305mm W x 610mm L x 1829mm H (12in W x 24in L x 72in H). A variable frequency pump pulls the water up from a pump basin to a gravity feed nozzle basin where the nozzles are evenly distributed across the top of the bays. A feed system is injected into the upward flow of water to allow for a gradual addition of nutrients and solids.

Test Protocol:

1. Install the fill packs into the fill support assemblies that are suspended from the load cells and record the weight of each individual fill pack.
2. Fill weights are to be calculated as the sum of the individual fill packs that are installed onto the fill support assemblies.
3. Start the water flow at 16m^3/hr (70 gal/min).
4. The biological feed consists of 30:4:4 (nitrogen:phosphate:potassium) fertilizer and sucrose sugar to accelerate weight gain.
5. Bentonite clay is added to act as the silt inorganic substrate.
6. Through the use of a PLC, several conditions are monitored every five (5) minutes. These conditions include: date, time, flow rate, dissolved oxygen, pH, total suspended solids (TSS), weight from each load cell, air temperature, and water temperature.
7. Values that are monitored on a daily basis include: COD (Chemical Oxygen Demand), Total Nitrogen, and also TSS as calculated via a secondary method.
8. When COD levels fall below 350mg/L more sucrose is added. When nitrogen levels fall below 30mg/L more fertilizer is added, and when TSS levels fall below 375mg/L more bentonite clay is added.
9. On a weekly basis the water flow is turned off, all water is allowed to drip off the packs, and a dry weight is recorded. This is listed as the "drip dry" weight, and it is used as the comparison to the original dry weight of the packs since it provides the best comparison with minimized water hold-up weight.
10. Weight gain is also monitored on a daily basis by subtracting the water hold-up weight measured at the beginning of the test before any bacterial growth has started.
11. The pH probe is calibrated on a weekly basis.

Contemporary Trickle Fill vs Modular Splash Fill Fouling Test:

Since extensive research has been performed on a large variety of film fill products over the years, as detailed in the referenced documents in the bibliography, the authors wanted to perform a similar study on the more recently developed trickle and modular splash fills currently available to the cooling tower industry. Of particular concern was the notion that all of these fills are non-fouling fills, without regard to geometrical differences between competing products. Since geometrical differences yield different fouling potentials in film fills, the theory is that the same trend would apply to wire-frame type fills.

Test Program:

The test program involved the selection of two (2) competing wire-frame type fills: a cross-fluted trickle fill (CFTF) and a vertical-off-set modular splash fill (VOMSF). Both products were made of PP. Three (3) bays of CFTF alternated with three (3) bays of VOMSF to fill the six (6) total bays in the fouling test rig.

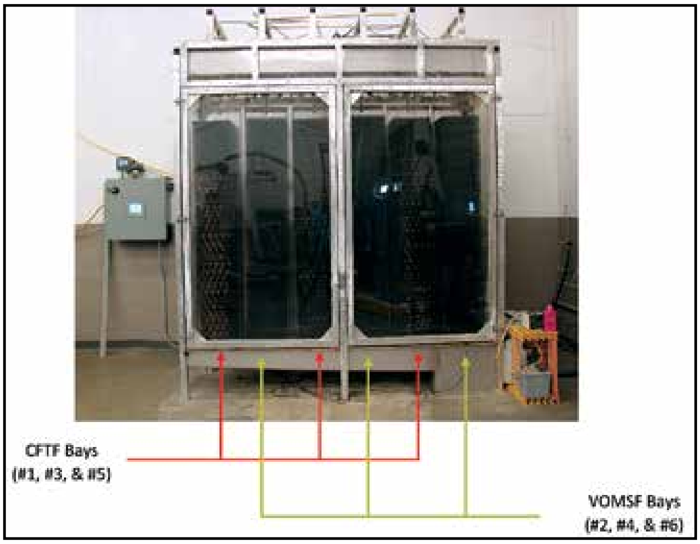

Figure 5: Fouling Test Rig Set-up

The fill packs were placed into fouling rig and data was collected for a period of slightly over 22 weeks. This was an extended duration test which provided a view into the nature of the biofilm life cycles. Initial heavy growth periods are followed by plateaus that reflect the limit of a colony's ability to sustain itself. At that point the colony sends out danger signals which cause the organisms to conserve energy and cause dying members to slough off. Once the colony has retracted enough to survive within the available nutrients, the cycle starts again.

Test Results

Initial Observations:

One of the most startling observations of this test was the initial rapid biofilm growth on the CFTF fill packs, and this was very unexpected since the general perception of these products is that they are low-fouling or even "anti-fouling" fills. The following pictures shows the biofilm growth of the six (6) test bays at the three-week drip-dry weighing.

Figure 6a: Bays 1 - 2 - 3 at Week 3 (CFTF / VOMSF / CFTF)

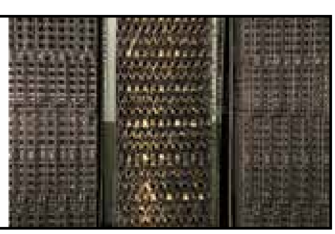

Figure 6b: Bays 3 - 4 - 5 at Week 3 (VOMSF / CFTF / VOMSF)

1. The CFTF bays (#1, #3, & #5) all had significant biofilm growth compared to the VOMSF bays (#2, #4, &# 6) which had almost negligible growth.
2. Bay 1 showed an appreciably greater amount of growth compared to Bays 3 & 5. Upon an investigation, it was learned that the local environment at that bay had a slightly elevated temperature which provided a more hospitable climate for the bacteria, and they were able to multiply more rapidly than in the other bays. A means to moderate the temperature to match the other bays was enacted.

As the test period continued it was interesting to note how the life cycle process brought the weight gain on Bay 1 back to amounts comparable to Bays 3 & 5 by approximately Week 10. Due to the larger colonies, there was a much greater sloughing off of dead bacteria in Bay 1 so that by Week 10, the biomass matched the available nutrients similarly to Bays 3 & 5.

Weight Gain Data:

Total Weight Gain

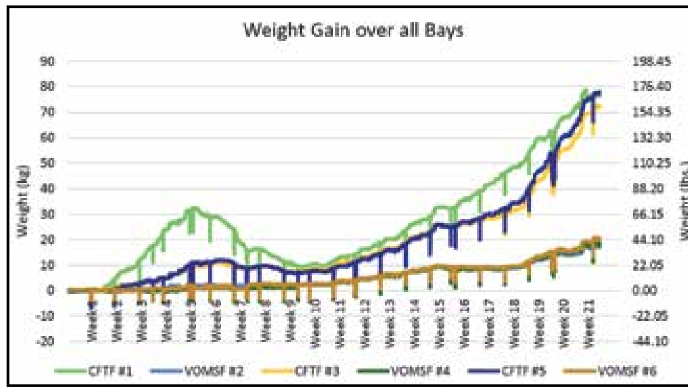

Figure 7: Overall Weight Gain

Average Weight Gain/Volume

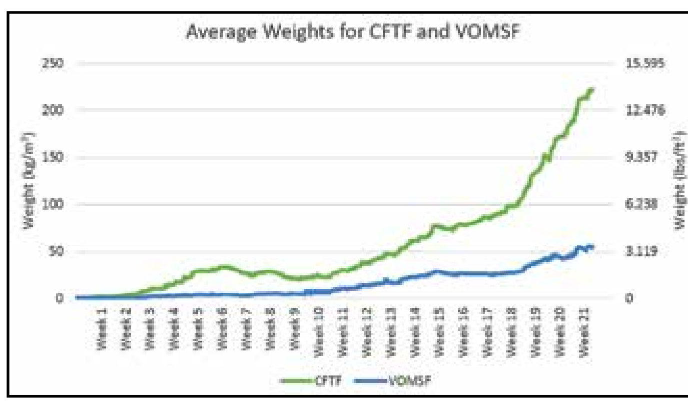

Figure 8: Average Weight Gain / Volume
***NOTE: CFTF Bays 3 & 5 and VOMSF Bays 2 & 6 Only**

Failure of Fill CFTF Fill in Bay 1

Between Weeks 20-21 the fill in Bay 1 gained so much weight that the fill collapsed around the fill supports, shifted, and fell out of the rack. At that point further data collection for that tower was invalidated. This is the reason that Figure 7 only shows average weight gain per volume for two (2) each of the CFTF and VOMSF bays instead of three (3) each. The middle weight gain VOMSF bay (# 4) was excluded from the calculation of the averages in order to keep each fill type to an average of two values.

Effect of Fouling on Tower Cooling Capability:

At the end of the day, the overarching impact of fouling relates to how that fouling degrades a cooling tower's cooling capability. If the purpose of a low-fouling fill is to minimize the reduction in cooling capability, then a tower designer or the owner/operator that purchases a cooling tower can make an informed decision to possibly spend a little more money up front on a slightly larger tower or a tower that uses more energy for air movement knowing that the extended duration of relatively constant colder water will provide a return on investment in a reasonable period of time. In order to illustrate the effects of fouling on performance, both un-fouled and fouled packs of each fill type above (CFTF and VOMSF) were tested in Brentwood Industries' Counterflow Cooling Tower Test Cell. This test cell provides a means to test a 610mm W x 610mm L x 1829mm D (2ft W x 2ft L x 6ft D) fill section in a fully instrumented fashion and yield the KaV/L vs L/G heat transfer and the pressure drop vs air velocity characteristics of a fill.

Heat Transfer Characteristic Results

CFTF Packs

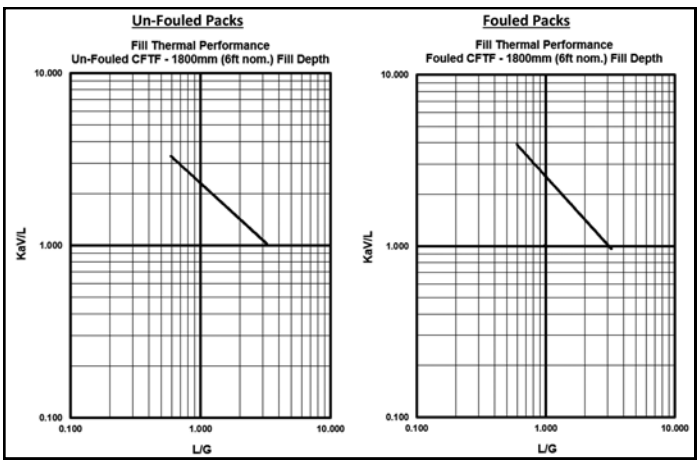

Figure 9: Heat Transfer Characteristics of Un-Fouled & Fouled CFTF

VOMSF Packs

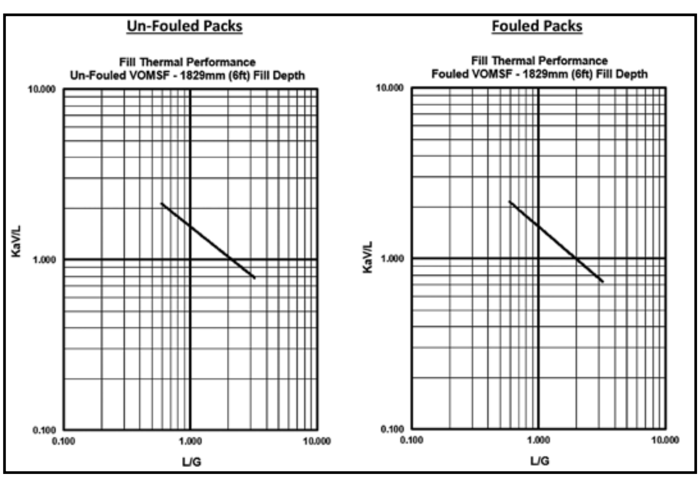

Figure 10: Heat Transfer Characteristics of Un-Fouled & Fouled VOMSF

Pressure Drop Characteristic Results

CFTF Packs

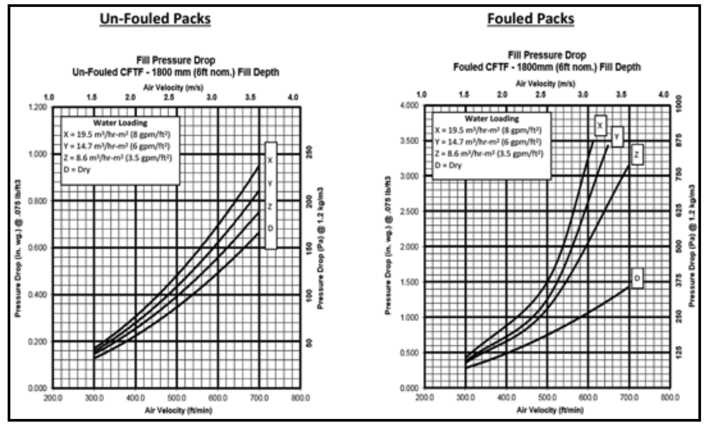

Figure 11: Pressure Drop Characteristics of Un-Fouled & Fouled CFTF

VOMSF Packs

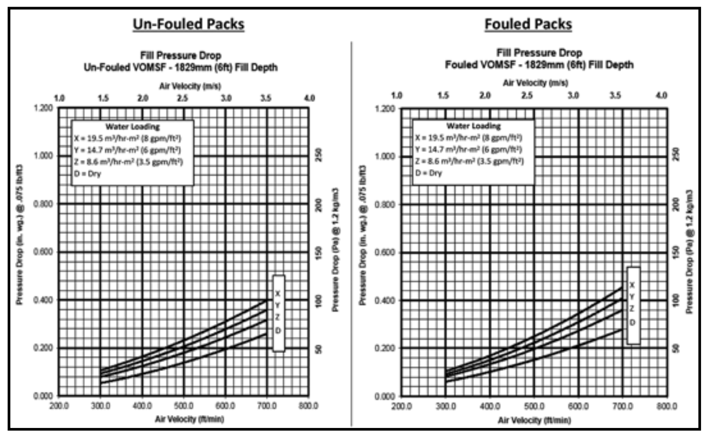

Figure 12: Pressure Drop Characteristics of Un-Fouled & Fouled VOMSF

Comments on Fill Performance Data

Heat Transfer Characteristics:

The heat transfer characteristics do not change much at all between the un-fouled and the fouled packs. The CFTF product actually shows a very slight gain in heat transfer at low L/G values, but the slope of the line is slightly steeper such that there is a very slight decrease in heat transfer at high L/G ratios. The VOMSF product also reflects a very slight increase in the slope of the line with all heat transfer values being very slightly lower at all L/G values except for the lowest L/G value tested which were virtually identical.

Pressure Drop Characteristics:

It is in the realm of pressure drop that the influence of the fouling stands out. The pressure drop of the VOMSF product showed a small increase in pressure drop, and this correlates well with the visual inspection of the packs where only a small amount of foulant is seen adhered to the fill. The pressure drop of the CFTF product, however, exhibits a massive increase in resistance to airflow as detailed below. This too correlates with the visual inspection of the packs where large amounts of foulant are seen clinging and growing to the many fine-strands of the wire-frame type product. (Refer to Figure 13 for a visual comparison of the fouled packs at the time of the thermal tests.) As you can see in the following table, whereas the Fouled VOMSF increases in pressure drop by about only 11-12%, the Fouled CFTF increases in pressure drop an average of over 375%!

Pressure Drop Comparisons

Water Loading	Air Velocity	CCTF Un-Fouled	CCTF Fouled	Ratio		VOMSF Un-Fouled	VOMSF Fouled	Ratio
8.6 m³/hr-m² (3.5 gpm/ft²)	2.5 (500)	97 (0.39)	274 (1.1)	2.82		45 (0.18)	50 (0.2)	1.11
	3.0 (700)	189 (0.76)	772 (3.1)	4.08		80 (0.32)	90 (0.36)	1.13
14.7 m³/hr-m² (6 gpm/ft²)	2.5 (500)	105 (0.42)	324 (1.3)	3.10		50 (0.2)	55 (0.22)	1.10
	3.3 (650)	184 (0.74)	847 (3.4)	4.59		80 (0.32)	90 (0.36)	1.13
	3.0 (700)	212 (0.85)	N/A N/A	N/A		90 (0.36)	102 (0.41)	1.14
19.5 m³/hr-m² (8 gpm/ft²)	2.5 (500)	115 (0.46)	374 (1.5)	3.26		57 (0.23)	60 (0.24)	1.04
	3.1 (615)	187 (0.75)	872 (3.5)	4.67		82 (0.33)	92 (0.37)	1.12
	3.0 (700)	239 (0.96)	N/A N/A	N/A		100 (0.4)	115 (0.46)	1.15
*Key: SI Units (IP Units)	m/s (ft/min)	Pa (in W.G.)	Pa (in W.G.)			Pa (in W.G.)	Pa (in W.G.)	

Table 1: Pressure Drop Comparisons

It is important to note that the pressure drop on the fouled CFTF fill was so great that it exceeded the capability of the fan power on the test cell to increase air velocity any higher than 3.3 m/s (650 ft/min) at the middle water loading and 3.1 m/s (615 ft/min) at the high water loading.

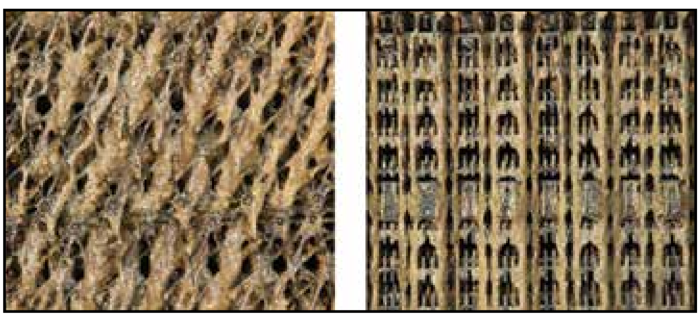

Figure 13: CFTF (left) & VOMSF (right) fill packs showing fouling amounts at the time of the thermal testing in the Brentwood Industries Counterflow Cooling Tower Test Cell. The CFTF fill had a weight gain of 222 kg/m³ (13.8 lbs/ft³) and the VOMSF a weight gain of 54.8 kg/m³ (3.42 lbs/ft³) at the time of testing.

Resulting Effect of Heat Transfer & Pressure Drop Characteristics on Tower Cooling Capability:

In order to analyze the net effect of the above changes in heat transfer and pressure drop characteristics on the cooling capability of a tower, Brentwood Industries' S.T.A.R. rating software was used to model a "typical" field-erected industrial application type counterflow cooling tower as follows:

Example Field-Erected Tower Information:

1. Cell Size: 14.6m x 14.6m (48ft x 48ft)
2. Fan Diameter: 9.1m (30ft)
3. Air Inlet Height: 4.9m (16ft)
4. Fan Deck Height: 11.9m (39ft)
5. Water Flow: 3139m³/hr (13,824gpm)
6. Range: 11°C (20°F)
7. Wet Bulb Temperature: 26.7°C (80°F)

The tower was modeled such that the Un-Fouled VOMSF fill yielded 100% tower capability. The other fills were compared to that based on the fill performance information provided above, and yielded the following results:

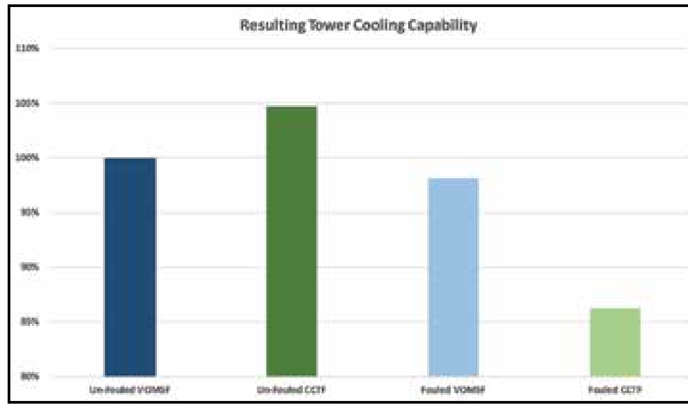

Figure 14: Comparison of Un-Fouled & Fouled CFTF & VOMSF Effects on Total Tower Cooling Capability

Conclusions:

As fill designs evolve in the constant quest to meet new challenges and improve on known deficiencies, there are opportunities to meet those challenges and also opportunities to create new problems. As the advent of film fills and the initial application of them into dirty water towers in the 1970's and 1980's showed that a misapplication could turn a "magical" fill into a "nightmare" fill, there is evidence that not all wire-frame fill designs are the "low-fouling" products that they are largely perceived to be.

Unfortunately, even though trickle packs resemble a modular splash fill and the lack of surface area leads to a misconception that trickle packs offer much greater fouling resistance than film fills, real world and laboratory experiences show that they offer the same pitfalls of the "magical" film fills of yesteryear if they are not applied properly.

The "prize" to be won is a long-term resistance to fouling so that the cooling capability achieved on the day the cooling tower is initially turned on is maintained for many years into the future. That choice provides the greatest overall cost benefit and highest level of reliability for a tower owner/operator.

Figure 15: A Vertical Offset Modular Splash Fill pack still in service in a field installation.

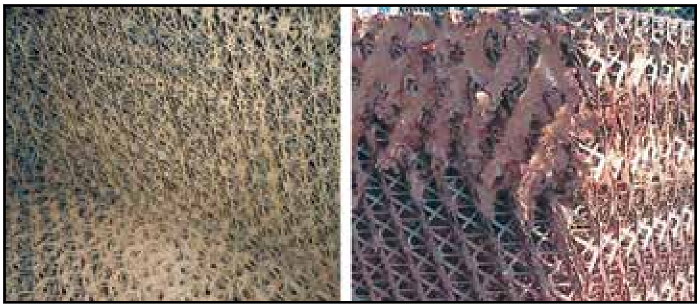

Figure 16: Two different fouled CFTF packs from field installations.

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