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CLEANING METHOD EFFECTIVENESS AND THE COST OF INCOMPLETE CLEANING

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ABSTRACT

The cost of heat exchanger cleaning has many components, and it is necessary to account for all costs and the economic impact of incomplete cleaning to select the best applicable cleaning method. This paper will outline a methodology to account for all costs related to cleaning, the benefits to be gained by complete cleaning, and how different cleaning methods affect the benefits. Cleaning methods vary in terms of their effectiveness and costs, and quite frequently we settle for an incomplete cleaning for one or more reasons:

1. There is no adequate method to determine the progress of the cleaning and the cleaning activity is "finished" without restoring the unit to 100% clean.
2. Notwithstanding the above, there is insufficient time.
3. The cleaning method is incapable of restoring the unit to 100% clean.
4. The budget allocated for cleaning is insufficient to reach the optimum results with the chosen method.

We will consider a case of a crude preheat heat exchanger where fouling leads to energy losses and increased emissions, and look at the relative economics of chemical cleaning, hydroblasting, and ultrasonic cleaning. We will also present a summary of the different cleaning techniques, how they are carried out, what impacts costs, and the timing. Based on the overview, we will provide insights on how to optimize cleaning methods and schedules to achieve maximum heat exchanger performance.

INTRODUCTION

There are different types of costs involved in the cleaning of a heat exchanger, the cost of the cleaning activity and indirect costs associated with the cleaning. Direct costs include what we pay the cleaning contractor, materials and handling costs such as the cost of disassembly and reassembly, transportation to the cleaning facility, equipment, chemicals, and waste disposal, and sometimes the cost of repeat cleaning needed to reach inspection-level cleanliness. Indirect costs include the loss of production while a unit is shut-down for maintenance, and as we will introduce here, the incurred if an incompletely cleaned heat exchanger is put back in service – the lost heat duty and the added costs of energy, emissions, and process debits. The first kind is always accounted for in a cleaning decision, but the hidden costs can sometimes be much larger and may lead to a different cleaning decision (when to clean, cleaning method) if taken into account.

In this paper we will consider the three most common cleaning methods – high pressure water cleaning (hydroblasting), chemical cleaning, and ultrasonic cleaning. These methods are applicable to both the tube and shell side, and are briefly described below:

Hydroblasting: This is the traditional method of using high pressure water to dislodge foulant off the tube surface. While the tube-side (ID) of some exchangers can be cleaned in-place, cleaning of the shell side requires the extraction of the tube bundle from the shell. A major disadvantage of this method is that in many cases, it is not possible to return the bundle to a zero-fouling condition on either the tube OD, ID or both [1]. Data is presented later in the paper to illustrate this point.

Chemical Cleaning: This method uses circulation of chemicals, oil or water based, to remove foulant partly by dissolution and partly by mechanical force. It has a few advantages over hydroblasting – the bundle doesn't need to be removed from the shell, multiple heat exchangers can be in the circulation loop, and the tube and shell sides can be cleaned concurrently with the same circulation. However, there is a large variation possible in the cleaning process, from a low cost, short duration, low flow process to a high flow, long duration and correspondingly high-cost procedure. Our experience shows that the high-end chemical cleaning matches the cleaning effectiveness of hydroblasting and costs about the same per heat exchanger if multiple heat exchangers are cleaned. This method typically requires piping work and external equipment (such as pumps, filters) to manage the circulation, and the disposal of the used chemical solution.

Ultrasonic Cleaning: The tube bundle is put in a water bath, with added chemicals, and cleaned using the force generated by ultrasonic bubbles on the tube surface [1]. It combines the advantages of hydroblasting and chemical cleaning but with a shorter overall duration, a significant reduction in water use, and less risk to personnel. Data will be presented in this paper showing the much higher cleaning effectiveness of this method compared to the other two.

The most significant disadvantage of the ultrasonic cleaning method is its inability to clean aluminum-finned exchangers due to chemical incompatibility, and a lack of availability of

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equipment for widespread application (both current limitations due to the newness of the technology).

RELATIVE COST AND EFFECTIVENESS OF CLEANING METHODS

Fig. 1 shows the relative costs and cleaning effectiveness of the three methods, based on the Authors' experience. The X-axis shows how close the resultant cleaning comes to a zero-fouling condition, with 100% corresponding to fully clean. The percentage here is defined as the ratio of the actual heat duty right after cleaning (Qa) to the duty that a zero-fouled heat exchanger would provide (Qc). The left Y-axis shows the relative cost, and the right Y-axis shows the duration of cleaning, both referring to just the cleaning activity.

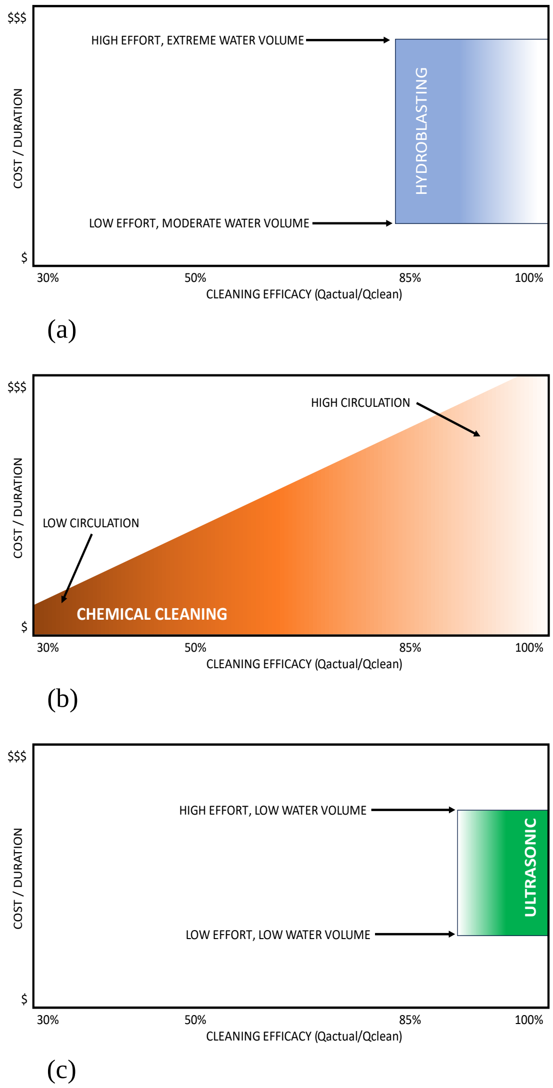

Fig. 1. Cleaning cost vs effectiveness of three cleaning methods - (a) Hydroblasting, (b) Chemical cleaning, (c) Ultrasonic cleaning.

Figure 1 shows how the three methods generally perform in terms of cost/speed and cleaning results:

(a) Hydroblasting: Based on previous studies by the authors, hydroblasting cleans exchangers to a (Qa/Qc) that ranges, based on time and effort, from 65-95%. The variation is based on the type of fouling, shell side cleanability, ability to clean U-bends, time taken for cleaning, and water pressure. Later in this paper, we show that the average cleanliness is <85% for difficult-to-clean services [1].

The relative cost of cleaning also has a large variation, mostly due to the effort applied (time) and location. In some areas of the world, the required labor may be very low cost.

The cleaning duration tracks linearly with costs, and varies widely between 4 and 48 hours, plus mechanical activities, but may well extend beyond that period for heavy fouling or if a repeat cleaning becomes necessary to meet inspection readiness. In extreme cases, week-long durations and water use of over 4 million litres is not uncommon.

(b) Chemical: Chemical cleaning has the widest range of cost, duration, and effectiveness. A low circulation method with small pumps and using small connections on the heat exchanger nozzles is quick but may provide little improvement. A badly fouled heat exchanger may gain only 10-20% in terms of (Qa/Qc). A procedure using larger connections if available and a longer circulation period will provide better results. Lastly, a procedure which requires connections to the main heat exchanger nozzles, larger pumps, and other equipment will cost the most but provide a cleaning equivalent to hydroblasting.

The detailed cleaning procedure corresponding to the right side of the chemical cleaning triangle costs as much as a hydroblast, especially on a per heat exchanger basis. The total cost may be 2X-3X that of hydroblasting, but two or three heat exchangers can be cleaned simultaneously.

The cleaning duration will typically be in the 12-24 hour range (4 days with mechanical), but time is saved because the bundles are not removed from the shell.

(c) Ultrasonic: Ultrasonic cleaning combines the advantages of the removal of foulant with mechanical force and the effective use of ultrasonic cavitation and sonochemistry to loosen and/or dissolve parts of the foulant to achieve a complete cleaning. Cleaned heat exchangers are at or near to zero fouling conditions (Qa/Qc=~100%), which means that where inspection is required, repeat cleaning is never necessary.

The minimum cost of ultrasonic cleaning is higher than a hydroblast in a low-cost region or

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a low-end chemical cleaning, when only the cost of the cleaning activity is considered. But at least two factors are considered here which make this a more economically attractive method – the cost associated with waste disposal and the process and energy penalties from an incomplete cleaning. The latter is detailed in this paper.

The average cleaning duration is 4-12 hours per tube bundle plus mechanical steps, and because cleaning steps (bath, shell side, tube side) are done in parallel, 6 – 12 tube bundles can be cleaned in a day with a typical setup, based on the authors' experience performing this work in support of refinery turnarounds. This method also uses less than 25% of the water normally used in hydroblasting.

Table 1 shows the various categories and relative direct costs associated with each cleaning method. A blank entry indicates that cost is not applicable for that method. Ultimately, the three methods have comparable costs, so the decision about which method to use must depend on other factors.

Table 1. The direct material and labour components of cleaning cost and their relative magnitudes.

	Chem Cleaning High End	Hydro-blast Cleaning	Ultrasonic Cleaning
Cost Element			
Disassembly & Removal		$	$
Transportation		$	$
Cleaning	$$	$$$	$$$
Piping Equipment	$$$		
Chemistry	$$		$
Reclean for Inspection		$$	
Transportation		$	$
Insertion & Reassembly		$$	$$
Waste Disposal	$$	$$	$
TOTAL PER HX	**$$$**	**$$$**	**$$$**

THE COST OF CLEANING

As illustrated in Table 1, there are many different costs that need to be considered when deciding on the cleaning method that will provide the best economic return.

Table 2 quantifies the costs in Table 1. Costs vary from location to location, and experience-based numbers have been used to arrive at the totals indicated. In the table we see that chemical cleaning has no costs for tube bundle removal, transport, and reinsertion but has added costs for making piping connections and for the chemicals. In It is also possible that chemical cleaning may cost less than shown on a per heat exchanger basis depending on the equipment and procedures used. We have also reduced the cost per HX for chemical cleaning by 50%, recognizing that more than a single exchanger can often be cleaned with one procedure. We note that the cost of waste disposal is low for ultrasonic cleaning because it minimizes the waste produced.

For each method we have included an opportunity cost, which is defined as the value associated with reduced production as a result of an exchanger being taken off-line for cleaning. This notion obviously applies differently for individual cleaning as a part of maintenance, and the "bulk cleaning" that is associated with a shutdown event. For the purpose of our discussion, we are considering only the maintenance case. The value will vary greatly based on the exchanger size and service, so we use a moderate opportunity cost value of $40K USD per day, strictly for illustrative purposes.

CLEANING FOR TUBULAR INSPECTION

The cleaning of a heat exchanger facilitates the inspection of the bundle's tubes. This inspection is used to detect imperfections such as tube thinning, tube pitting, or tube wall cracks. Common inspection methods include Eddy Current Testing (ECT) and Internal Rotary Inspection System (IRIS). These inspection methods require a minimum level of tube cleanliness to provide accurate and reliable results. Our own hands-on experience in the "traditional" hydroblasting services market, and feedback from clients with who we have worked, has shown that between 20-50% of heat exchangers cleaned on a washpad by hydroblasting alone are insufficiently cleaned after the initial attempt to achieve the client's tube inspection targets. This inspection deficiency often results in re-cleanings and re-inspections. This recycle through the hydroblasting cleaning process results in schedule and cost impacts. In some cases, a longer schedule is not possible, resulting in the client accepting a higher uncertainty about the integrity of the exchanger due to abbreviated or compromised test results. In extreme cases, this may even lead to repair work such as retubing, if the tubes cannot be cleaned well enough for inspection.

Based on ten refinery turnarounds performed using ultrasonic cleaning in 2022-2024, with over 600 exchangers cleaned, we have seen that the use of ultrasonic technology in washpad heat exchanger cleanings has increased the probability of a successful tube inspection to 100% as, over all events, not a single heat exchanger was discovered to require a return to the washpad for re-cleaning prior to inspection.

The impact of recleaning on the cost of hydroblasting is shown in Table 2 as the cost of "recleaning", with the cost set to 25% of the cost of the initial cleaning, to account for 25% of the bundles cleaned by hydroblasting requiring a second cleaning attempt to achieve inspection-ready levels of cleanliness.

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THE COST OF INCOMPLETE CLEANING

So far in this discussion we have examined the relative costs of the three cleaning methods in terms of the direct costs and the opportunity costs. We propose now to include in the equation the "cost of incomplete cleaning".

We define incomplete cleaning as a cleaning result which provides less than 100% of the originally clean thermal and hydraulic performance upon return-to-service. In terms of heat duty this means that the actual heat duty right after cleaning is less than expected from a heat exchanger with zero fouling, that is (Qa/Qc) < 1.0. Table 3 shows the results from a previous study [1] in which the before and after performance of operating heat exchangers was examined, contrasting the results obtained by hydroblasting to those obtained using ultrasonic cleaning. Each row is for the same heat exchanger, and results were calculated using operating data provided by the clients after each type of cleaning. The performance difference is evident, with average cleanliness better by about 15% for ultrasonic cleaning.

Table 2. The cost of cleaning (USD).

	Chem Cleaning High End	Hydro-blast Cleaning	Ultrasonic Cleaning
Cost Element			
Disassembly & Removal		$2,000	$2,000
Transportation		$500	$500
Cleaning	$5,000	$10,000	$15,000
Piping Equipment	$30,000		
Chemistry	$5,000		$2,000
Reclean for Inspection		$2,500	
Transportation		$500	$500
Insertion & Reassembly		$2,000	$2,000
Waste Disposal	$5,000	$5,000	$2,000
BASE Cleaning Cost	**$22,500***	**$22,500**	**$24,000**
Total Cleaning Duration	4 days	5 days	3 days
Opportunity Cost ($40K/day)	$160,000	$200,000	$80,000
TOTAL CLEANING COST	**$182,500**	**$222,500**	**$104,000**

*** Cost is cut in half considering that on average, 2 HX's may be cleaned at once.**

To further illustrate the impact of incomplete cleaning for the purposes of our discussion here, we simulated two heat exchangers, assuming a high fouling crude as the fouling fluid. To do the simulation we used HTRI's Xist® software to simulate the fouled performance under two different starting conditions over a 1-year period. Fig. 2 shows a heat exchanger with a surface area of 500 m^2, and Fig. 3 of 875 m^2. Fouling resistances were applied in each case in order to simulate typical performance of shell and tube exchangers in a refinery application. The figures show the simulated heat duty degradation due to fouling over a one-year period. Qa is the heat duty starting with 100% clean, Qa' is starting at 85% clean, and the area between the two curves is the loss of potential heat duty due to incomplete cleaning. The loss in Fig. 2 equals 3,781 MWh and in Fig. 3 the loss is 11,800 MWh. Using $10.22/MWh for energy, with a furnace efficiency of 90%, the reduced heat duty results in an increased energy cost of $43K and $134K respectively. Using the US EPA's CO_2 equivalents calculator, the energy savings would correspond to a reduction in emissions of approximately 2,500 and 8,000 tons of CO_2.

Table 3. Data for cleaning effectiveness [1].

Service	Shell Side	Tube Side	Hydroblast (Qa/Qc)	Ultrasonic (Qa/Qc)
CPHT	Vac Resid	Crude	86%	97%
FCC Slurry	BFW	FCC Slurry	78%	91%
CPHT	HGO	Crude	62%	100%
CPHT	Vac Resid	Crude	75%	100%
CPHT	HGO	Crude	91%	100%
CPHT	HGO	Crude	78%	93%
CPHT	Vac Resid	Crude	80%	100%
CPHT	Vac Resid	Crude	80%	93%
L/R DEA	Lean Amine	Rich Amine	90%	100%
CPHT	ABPA	Crude	92%	98%
CVDU	Flash Crude	Vac Resid	86%	100%
		Average	**82%**	**97%**

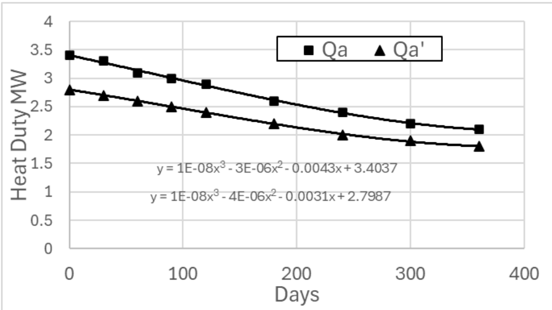

Fig. 2. Heat duty degradation due to fouling, Case 1 - 500 m^2 heat exchanger.

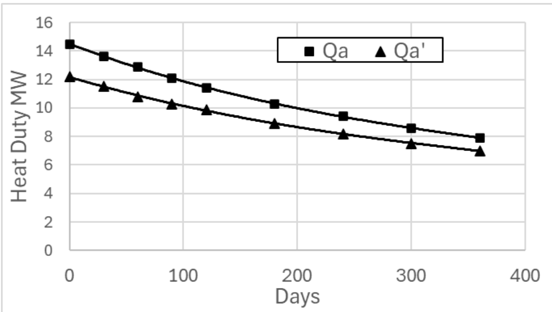

Fig. 3. Heat duty degradation due to fouling, Case 2 - 875 m^2 heat exchanger.

In addition to the apparent loss of potential heat transfer capacity caused by the remaining fouling after an incomplete cleaning, there is an additional consideration which may apply in many, if not most, cases. That is the increase in maintenance interval which may be realized by reinstalling a zero-fouling level bundle after cleaning. In our studies of client results using ultrasonic cleaning, we have noted a

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general trend towards longer maintenance intervals and have seen intervals doubled in some cases. This increase in availability not only reduces maintenance costs but improves the ability to capitalize on market conditions.

THE NET COST OF CLEANING

We now can combine the information about the direct and indirect costs of cleaning for the three methods, with our understanding of the potential costs of incomplete cleaning to arrive at a true "net" cost for cleaning a heat exchanger by each of the three methods.

Table 4 shows that by considering not only the immediate financial costs of cleaning, but also the impacts of residual fouling, a more robust estimate of the 'Net Cost of Cleaning" can be determined. In order to account for the potential increase in service interval offered by complete cleaning, an interval factor is introduced as a cost multiplier, with 1 being the factor used for complete cleaning, i.e. the interval is optimized and the cleaning cost is simply the cost of a single cleaning. An interval factor of greater than 1 is applied for incomplete cleaning. For example, incomplete cleaning may shorten the interval to the next cleaning, thus increasing the maintenance cost over the same time period by the stated factor. Based on feedback from clients, we have set an interval factor of 1.25 for chemical and hydroblasting cleaning, which we assume produce similar results in terms of incomplete fouling removal.

Table 4. The Net Cost of Cleaning

	Chem Cleaning High End	Hydro-blast Cleaning	Ultrasonic Cleaning
TOTAL CLEANING COST	$182,500	$222,500	$104,000
Interval Factor	1.25	1.25	1.00
Potential Energy Cost of Incomplete Cleaning (500m2, 5.5Pa)	$43,000	$43,000	$0
NET COST PER HX	**$271,125**	**$321,125**	**$104,000**
Potential Energy Cost of Incomplete Cleaning (875m2, 5.5Pa)	$134,000	$134,000	$0
NET COST PER HX	**$362,125**	**$412,125**	**$104,000**

It should be noted that the comparison of relative costs does not take into account other maintenance scheduling factors that may be important to the overall cost.

CONCLUSIONS

Cleaning of heat exchangers can be done by several methods, but the selection of the best method should consider all the associated costs, direct and indirect.

The three methods considered have similar "base cleaning costs" however when a holistic approach to understanding the "Total Cost" and "Net Cost" is taken, there appears a clear advantage to ensuring that cleaning leaves no fouling behind.

A minimal-effort chemical cleaning can be very inexpensive but results in small improvements to the performance. Hydroblasting and high-quality chemical cleaning cost about the same and result in a cleanliness of 85% on average. Ultrasonic cleaning, which also has similar costs, has been shown to result in 100%, or near 100% performance recovery.

Cleaning time plays a complex role in the value calculation, particularly in turnarounds, where a reduction in overall cleaning time can significantly reduce adjacent costs for things like cranes, staffed inspection capacity, washpad utilities, labor, etc. These costs have not been considered in this analysis but could also play a significant role in the overall net cost analysis. As previously reported by others, ultrasonic cleaning has been demonstrated to reduce the required washpad cleaning time by more than 50%, when compared to washpad hydroblasting [2].

The impact of complete cleaning to a zero-fouling condition can have a significant impact on the overall economics of cleaning heat exchangers. Until the advent of ultrasonic cleaning, operators had the typical choice of two similar performance and cost techniques – hydroblasting or chemical cleaning. A complete return to zero-fouling operating condition has previously only been available through replacement for many of the challenging fouling service bundles we encounter in our daily cleaning operations. The addition of ultrasonic cleaning as an option changes the economics significantly, as the method not only allows better cleaning results, shorter cleaning durations and more reliable testing results, but can also have a significant impact on carbon intensity by reducing heat energy inputs to the refining process and the associated carbon emissions.

NOMENCLATURE

Qa Actual heat duty, MW
Qa' Actual heat duty, incomplete cleaning, MW
Qc Clean heat duty, MW

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