GUIDELINES FOR HEAT EXCHANGE PERFORMANCE EVALUATION. A PRACTICAL AND SEMITHEORETICAL APPROACH.

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ABSTRACT

Steam Generators and highly rated heat exchangers, such as feed water preheaters, moderator coolers of PHWRs, etc., are frequently surveyed, as far as heat exchange capability is concerned, by monitoring some of the heat and mass transfer balances variables involved, though they are not necessarily the most proper ones for the best assesment.

Through several years' experience working in the engineering department of a Nuclear Power Plant, it can be concluded that every important component or equipment that has an almost unique design due to its importance, requires a particular treatment for its periodical surveillance.

In the present paper some guiding rules for a better achievement of the aforementioned task are described and illustrated with examples taken from several plant situations.

It can be concluded that, improving process variables measurement, together with data reconciliation and a proper modelling leads to better parameters to survey heat transport in heat exchangers.

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INTRODUCTION

Steam Generators and highly rated heat exchangers, such as feed water preheaters, moderator coolers, etc., are frequently surveyed, as far as heat exchange capability is concerned, by monitoring some of the heat and mass transfer balances of the involved variables, though are not necessarily the most proper ones for the best assesment.

Through the experience of several years working in the engineering department of a Nuclear Power Plant, it can be concluded that every important component or equipment that has an almost unique design due to its importance, requires a particular treatment for its assesment that could be summed up in the following steps:

1. Data collected in the commissioning of the station and in the first 100% power condition have been found extremely valuable for later comparisons and general trends. Then, their collection and recording must be a task of high responsability.
2. Temperatures, flow rates and power should be taken with the highest achivable accuracy, but without jeopardizing the plant availability and safety.
For example, data from spare thermoelements may be directly taken, DP cells can be added in parallel to the main orifice of the flow meter pressure taps, etc.
3. Data should be reconciliated as frequently as possible by performing crosschecking balances. This analysis requires a thorough knowledge of the station systems and their interrelations.
4. Parameters evolution and relationship should be represented in a way that permits immediate response from the control room personnel in order to maintain the availability and safety of the station, but the process engineer must look for variables or group of variables that provide the best representation of the overall equipment performance and/or reveals their anomalous behaviour.
5. Asymmetric behaviour of similar equipments has to be found through the values of the variables defined in (4).
6. Unsteady state phenomena such as the ones underwent in startups or shutdowns or even in abnormal events, are not easily interpreted but they are a source of invaluable information, so they must be carefully recorded.

7. Parameters modification after interventions, such as chemical cleanings, could be a source of contradictory results and a whole reconsideration of the set main variable has to be done. For example, this could be attributed to an uneven removal of the deposits which distorts the external overall heat transfer coefficient observed.
8. In connection to the aforementioned steps, and mainly with point (7), modelling is a powerful tool, but equations or equation systems already solved must be kept as simple as possible and they should always be based on basic laws.

GENERAL REMARKS

1.The importance of the data collected in the comissioning and in the first 100% power state.

1.1 Parameters which are not expected to change during plant life:
Primary heat transport system pumps: if the pumps were well designed and the constitutive materials properly chosen, the pump behaviour should not be expected to change during the plant life. This is due to the fact that the impeller surface should not change its roughness along the time. Then, the pump curve is only dependent on the grid frequency. Nevertheless, as the primary coolant pumps are non-serial components, the pump curve flowrate vs height, should be measured during the commissioning by adding special instrumentation. The importance lies in the fact that most of the nuclear power plants do not have flowmeters in the primary side pipes.
The non-modification condition of the main pumps curve, assuming a constant grid frequency, is a parameter that could be considered robust in the data reconciliation of the plant energy balance. At least three points of the pump curve, height vs. flow rate, could be obtained along the power plant rising level.
1.2 In the commissioning all the variables related to the Heat Exchange Performance and its evolution should be measured with the strictess accuracy, mainly at 100 % power. For that purpose local instrumentation has to be added and/or spare sensors used. For example, ΔP's through the pumps and heat exchangers must be locally measured with externaly verified instrumentation with simultaneous registration of the stability.
1.3 The plant energy balance and local energy balances in equipments are recommended to fit with an error lower than 1 % of accuracy (when the calculations are performed for both, hot and cold fluids).

2. The importance of multiple measurements.

It has been often noticed that variables such as temperatures or pressure drops can be taken twofold or threefold by using some spare instrumentation available in the plant.
For example, spare RTD's are directly read and later taken as a reference value.
Another possibility is given by the differential pressure transducers in which it is possible to connect an extra instrument in parallel through the pressure taps.

3. Data reconciliation.

3.1 Data reconciliation at Candu Nuclear Power Plants:

It has to be done by carrying out cross checking balances. A good example is given by the Candu reactor in which the mass flowrate can be estimated twofold. As a matter of fact, the primary side mass flowrate, mp, can be calculated through the data measured in one steam generator and verified in the other one that belongs to the same loop. It is given by the basic equation:

$$ms * (hvs - hls) = mp * (hi - ho) \qquad (1)$$

where ms is obtained from the feed water flow flowmeter, thus being convenient to average several measurements in order to consider stochastic errors due to noise and to the level oscillation of the steam generator. The enthalpies hvs and hls are obtained from data of the steam pressure and boiling feedwater temperature and hi and ho are obtained from the RIHTs. and ROHTs. (Reactor Inlet and Outlet Header Temperatures) and primary side pressure.

Although equation (1) assumes no blowdown, the correction is very simple by introducing the blowdown flow or by a shut off of the blowdown valves when the measurements are performed.

3.2 Data reconciliation in a multiloop PWR:

The most important aspect is to make sure that the power for each steam generator has been properly measured. In the reconciliation equation (1), mp for each pump should keep its value regardless of the power after its correction, as the effects of density have been already taken into account.

4. How to choose a representative parameter.

It has been found that a parameter like the overall heat transfer coefficient reveals better information of the equipment behaviour than, for example, the representation of the temperatures by themselves.

5.Non-symmetric effects.

A non-symmetric behaviour is easily followed by the calculation of a global parameter like the overall heat transfer coefficient,UA , instead of a variable like the temperature.

Examples are given by the different behaviour of steam generators, although they have been operating since the plant's commissioning. For instance, the real operating time and the total energy transferred along their whole life time might be different due to effects such as assymetries of the core neutron flux and/or differences in the pump curves. Then the fouling produced on each steam generator is also different.

EXAMPLES

1.Overall heat transfer coefficient in a PVHWR (Pressurized Vessel Heavy Water Reactor):
Figure 1 shows the representation of UA vs. the logarithmic mean temperature difference, LMTD, for the steam generators of a PVHWR close to the comissioning of the station. In the figure, the calculated points are presented together with the error . It can be seen that the curve reaches a plateau, which would show changes due to fouling with higher sensitivity and accuracy than if temperatures were plotted by themselves.
Changes in the UA coefficients are not shown in the figure but, for both S.Gs., UA had decreased to approximately 21 Mw/°C in the region between 80 % and 108 % power after a chemical cleaning in which they were restored to 24 Mw/°C.

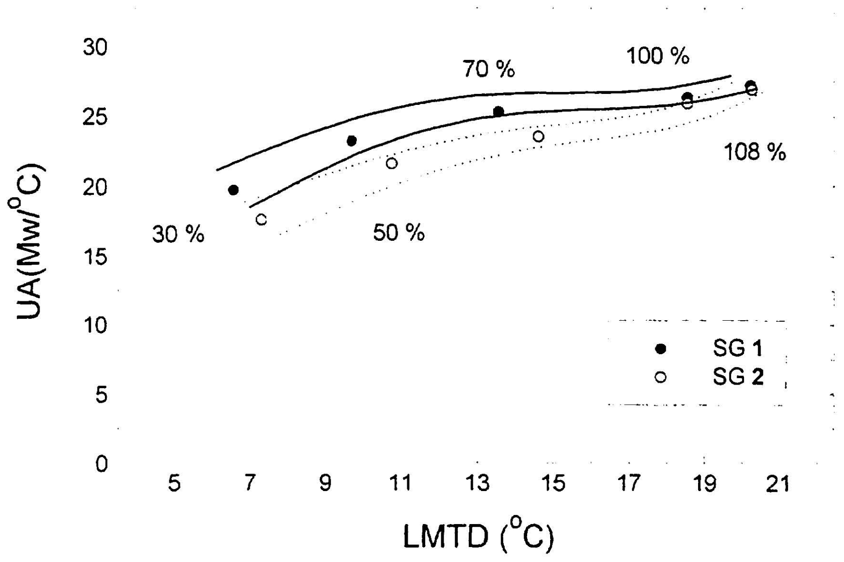


Figure 1
Overall heat transfer coefficient vs. LMTD

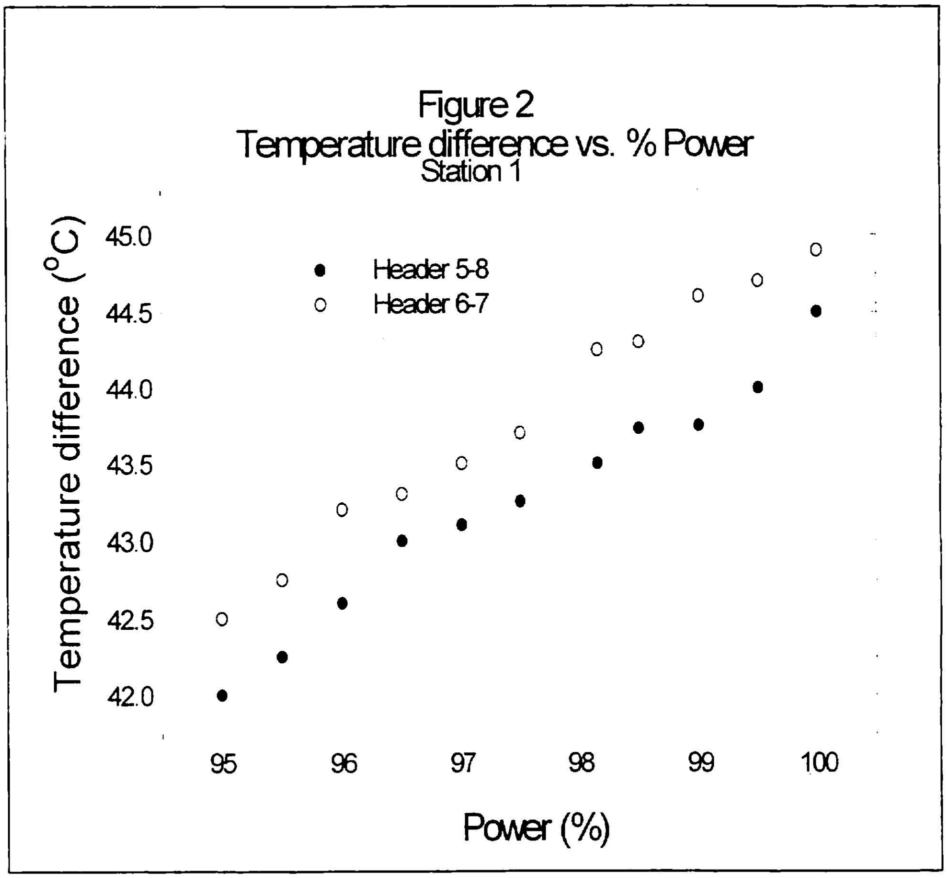
Table I
Steam Generators' Power for Figure 1

% of full Power	S.G. #1 (Mw)	S.G. #2 (Mw)
30	129	128.5
50	225	240
70	343	352
100	488.2	497.6
108	550.5	548

2. Primary side quality in a Candu 6 Primary Heat Transport System :

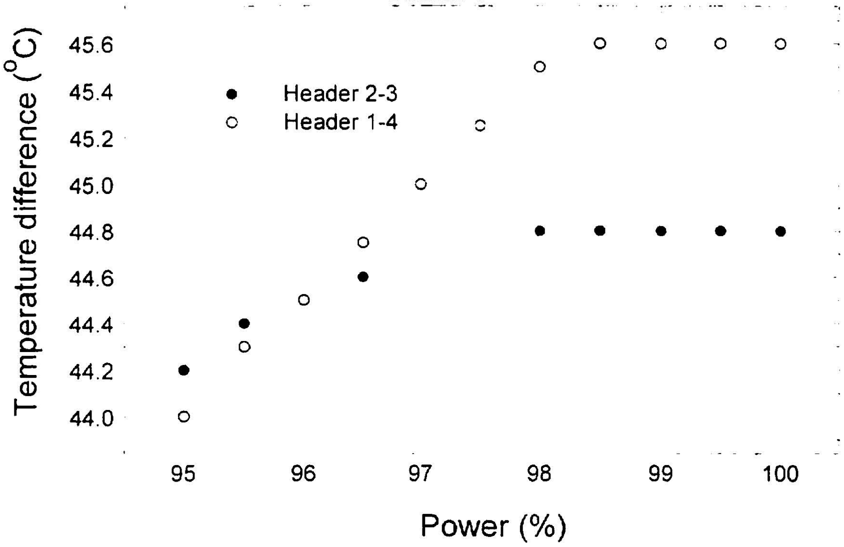
Figures 2 and 3 show temperature differences between the inlet and outlet headers vs. percentage of full power (from 95 % to 100 %) for a set of data provided by a Candu Station #1. In these figures, an assymetric behaviour is observed between loops 1 and 2 .

In the case of ΔT's between inlet and outlet headers 5-8 and 6-7 a straight line (not shown) would fit the measured data thus proving the absence of quality (Figure 2).



On the contrary in Figure 3, it can be appreciated that for ΔT's between inlet and outlet headers 2-3 and 1-4, at a given power, the trend changes and remains constant up to 100 % power, thus showing the existence of quality.

Figure 3
Temperature difference vs. % Power



In this event, its magnitude can be estimated by the following approximation:

$$(1 - x) * hl(Ts) + x * hv(Ts) = hl(Ts + \delta T) \qquad (2)$$

which can be rearranged into :

$$x * [hv(Ts) - hl(Ts)] + hl(Ts) = hl(Ts + \delta T) \qquad (3)$$

where δT comes from the difference of temperatures between the values of the extrapolated straight line and the horizontal line. Both values of temperature are taken at 100 % power and the enthalpies are a function of the PHTS saturation temperature (Ts).
Then, symplifying the right side of equation (3) by ignoring the effect of pressure on the enthalpy hl, we can write:

$$x * [hv(Ts) - hl(Ts)] + hl(Ts) = hl(Ts) + Cp(Ts) * \delta T \qquad (4)$$

Finally from (4) we find:

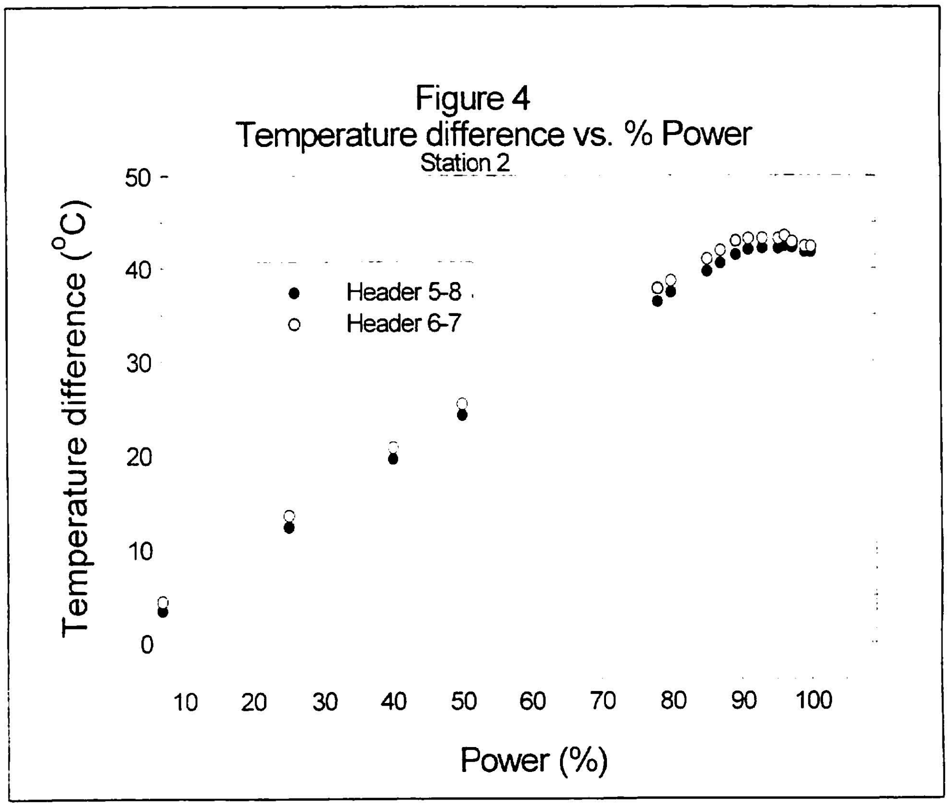
$$x = Cp * \delta T / \lambda \quad (5)$$

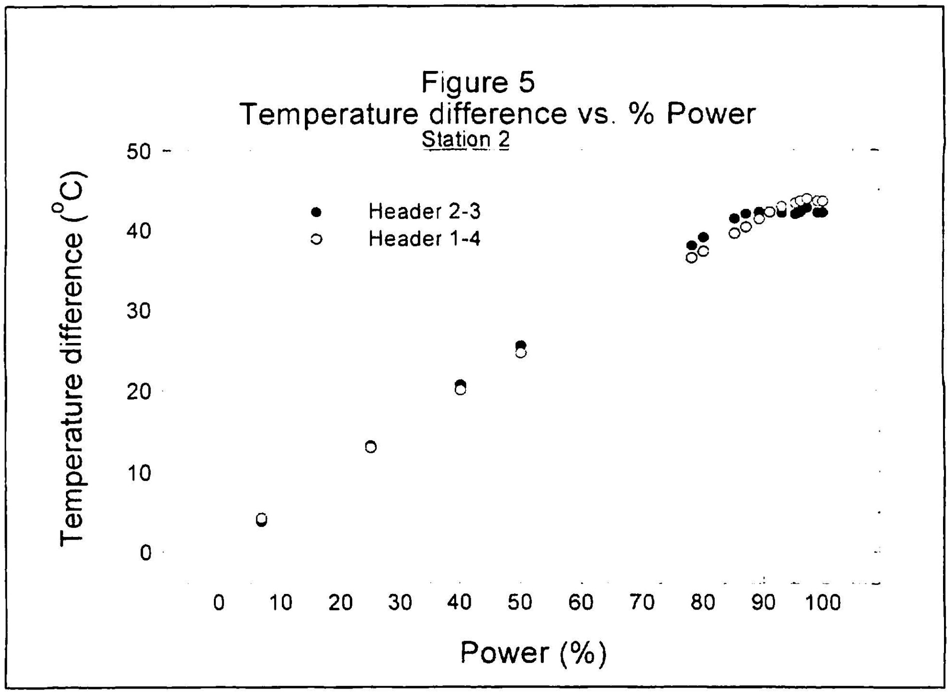
The values of quality from the calculations,are presented in Table II:

Table II
Station # 1

ΔT's between inlet and outlet headers #	quality
1-4	0.004
2-3	0.0075
8-5	-
6-7	-

Similarly, Figures 4 and 5 show the same representation, i.e., ΔT's between inlet and outlet headers vs. percentage of full power for a set of data obtained from Candu Station #2.
It can be seen that in this case both loops present quality and its value can also be estimated from expression (5).





In this case the qualities found are shown in Table III:

Table III
Station # 2

ΔT's between inlet and outlet heaters #	quality
1-4	0.0078
2-3	0.0187
8-5	0.0152
6-7	0.0156

It is necessary to remark that Station # 2 , at the time the data were collected, had been operating for more EFPY (Effective Full Power Years) than Station #1.
It is recommended to record both carefully, the primary and secondary side pressures for periodical comparisons. Also, the plots can be normalized to a given pressure (primary and secondary side) for a better verification of the Steam Generators' behaviour.

3.Uneven distribution of fouling on a heat exchange surface.

For the following development the next assumptions are considered: (i) local fouling resistance is in all cases proportional to the local thickness of the deposit, which also implies constant thermal conductivity. (ii) internal and external heat transfer coefficients are independent of the fouling. (iii) Although the conclusions are for an equipment with a constant secondary side temperature, they are also valid for a heat exchanger with different temperatures at the inlet and outlet sides of both streams. (iv) the total amount of deposit is a constant given by :

$$\int_0^L e(z)*dz = K_1 \qquad (6)$$

(v) Variation of physical properties due to temperature are neglected.
Then, if we consider a heat exchanger for which the inlet and outlet temperatures for the heating fluid are T1 and T2 respectively while the outer fluid is boiling at tb, the usual energy transport and energy conservation equation integrated in one dimension is valid:

$$K_2 * \mathrm{Ln}\frac{(T2 - tb)}{(T1 - tb)} = \int_0^L U(z) * dz \qquad (7)$$

and :

$$\frac{1}{U(z)} = \frac{1}{Uo} + \frac{e(z)}{k} \qquad (8)$$

The overall heat transfer coefficient U could be expanded in series, if it is considered that the fouling resistance is kept low enough in order to the series expansion to be valid, it is found that:

$$U(z) = Uo - Uo^2\frac{e(z)}{k} + Uo^3\frac{e(z)^2}{k^2} \qquad (9)$$

If the expansion (9) is replaced on the right hand side of the energy balance (7), we have :

$$\int_0^L U(z) * dz = Uo * L - Uo^2\int_0^L \frac{e(z)}{k} * dz + Uo^3\int_0^L \frac{e(z)^2}{k^2} *dz \qquad (10)$$

When different functions of e(z) are substituted in eq. (10) and the result compared to the one with the homogeneous distribution, it can be concluded that the latter gives the lowest value for the overall heat transfer coefficient.
Because of that, not always the same amount of fouling (when it is constituted by a mixture of the same physical properties, e.g. thermal conductivity) produces the same effect. The worst distribution would be the even distribution and/or a given amount of deposits could produce

different performances of the heat exchanger not easy enough to be interpreted by the ordinary methodology.

CONCLUSIONS

As it was stated in the title, the present paper presents a set of sensible rules based on the experience gained in the field, through which the surveillance of heat exchangers can be improved. Also, some exemplifications have been given with the aim of highlighting that proper combination of a good recollection of data, without dismissing those coming from the startup or abnormal conditions, together with redundancy of measurements and their proper interpretation and representation will improve the results obtained by the process engineer making them more understandable and easy to foresee. Also, some of the mentioned techniques are capable of anticipating instrumentation failures.

NOTATION

A: heat exchange area
Cp: specific heat of the primary side liquid evaluated at Ts
e(z): fouling thickness
k: thermal conductivity
K_1: constant in equation (6)
K_2: constant in equation (7)
hi: primary side inlet liquid enthalpy
ho: primary side outlet liquid enthalpy
hvs: secondary side steam enthalpy
hls: feedwater enthalpy
hv: primary side outlet steam enthalpy
hl: primary side outlet liquid enthalpy
L : heat exchanger total length
LMTD: logarithmic mean temperature difference
mp: primary side mass flow rate
ms: feedwater mass flow rate
T1, T2, tb: temperatures in equation (7)
Ts: PHTS saturation temperature
U: overall heat transfer coefficient.
Uo: clean overall heat transfer coefficient.
x : steam quality

Greek letters
λ: primary coolant latent heat of vaporization (hv(Ts) - hl(Ts))

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