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CONSIDERATION OF DYNAMIC UNCERTAINTY IN FOULING EXPERIMENTATION
(EXTENDED ABSTRACT)

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1. INTRODUCTION

Fouling of heat transfer surfaces is a complex process which involves many parameters with poorly understood interaction. The ultimate deposit build-up, therefore, is the outcome of a sequence of various events on the surface, including competition between deposition and removal forces at micro- and macro-scales. All this would result in highly unstable processes with frequently significant fluctuation, if one plots heat transfer coefficient or fouling resistance versus time. Fig. 1 exemplifies such a situation for pool boiling of $CaSO_4$ solutions. It is obvious that the fluctuation is particularly high at the early stage of the experiment, when the crystals are still loosely attached and can be removed easily from the surface by a small shear force.

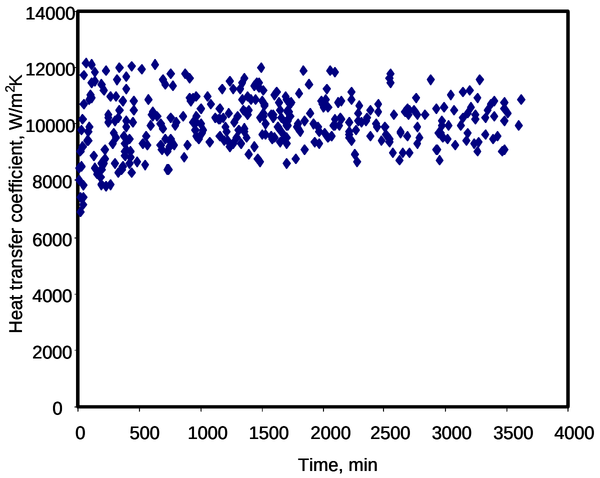

Fig. 1 Raw data for heat transfer coefficient as a function of time during pool boiling of $CaSO_4$ solutions (1.6 g/L and 200 kW/m^2), Bartlett (1995).

Under such unstable circumstances, careful consideration of the experimental error analysis is essential for correct interpretation of experimental results. Nevertheless, a substantial survey of the fouling literature reveals that in fouling experimental research:

- only systematic errors associated with individual components of the experimentation, e.g. thermocouples, pressure transducers or heaters are reported while the inherent instability of the process is largely ignored,
- the experimental results are presented by smooth curves obtained by using mathematical filters or averaging codes (see Fig. 2 as example).

While these practices are useful to derive a meaningful fouling trend, the reliability of the reported experimental results is questionable. This study highlights that the combination of systematic and precision errors should better considered in terms of uncertainty. Two case studies of fouling during convective heat transfer and the more complex process of pool boiling will be presented. The determination of uncertainty reveals that it is not constant and can vary by up to a factor of 4 over the course of fouling runs within the range of operating conditions studied in this investigation.

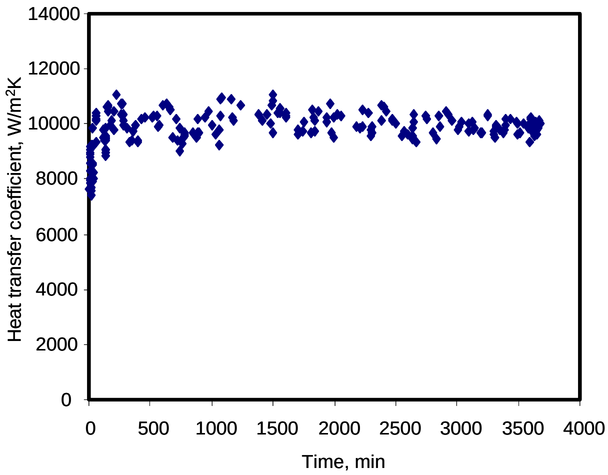

Fig. 2 Filtered data for experiment presented in Fig. 1.

2. FORMULATION

Measured quantities are generally not absolutely accurate since they are all subject to systematic errors of the measuring devices. Thus, it is important to know to what extent the measured quantity is likely to deviate from its actual value. On the other hand, while the determination of systematic error is imperative, it cannot alone reflect the cumulative error associated with a certain quantity. The missing error here is the precision error which depends on the fluctuation of a quantity at a single point of measurement. The deposition processes depicted in Fig. 1 may represent a good example for this. One may easily see that at or close to time zero the heat transfer coefficient under fouling conditions varies by up to 4000 W/m^{2}K. To consider such fluctuation, it is indeed uncertainty rather than systematic error that determines the order of magnitude of the overall error.

Uncertainty of a measured quantity is a combination of the fixed error (Bias error, B) and the random error (precision error, P) depending on whether the error is steady or changes during the time of an experiment (Kline and McClintock, 1953). The uncertainty of the experimental results in this study is estimated for either 95% or 99% confidence as given by Eqs. (1) and (2):

$$U = \left[B^2 + P^2\right]^{1/2}. \qquad \text{95\% confidence} \qquad (1)$$

$$U = B+P \qquad \text{99\% confidence} \qquad (2)$$

The bias limit (B) is due to the systematic error, while the precision limit (P) depends on instability and complexity.

For the determination of uncertainty, consider "Y" as an objective function (here for instance fouling resistance) which has to be calculated from a set of measurements as:

$$Y = f(X_1, X_2, X_3, \ldots\ldots, X_N) \qquad (3)$$

The bias error of "Y" in turn is proportional to the partial gradient of "Y" to "X_i" and thus:

$$B_{Yi} = \frac{\partial Y}{\partial X_i} B_i \qquad (4)$$

When several independent variables are involved then:

$$B_Y = \left(\sum_{i=1}^{N} \left(\frac{\partial Y}{\partial X_i} B_{X_i} \right)^2 \right)^{1/2} \qquad (5)$$

The precision error of any individual independent variable, X_i, is determined as the standard deviation of the mean of a set of N observations.

$$P_{Yi} = \left(\frac{\sum_{i=1}^{M} \left(X_i - \overline{X_i}\right)^2}{M(M-1)} \right)^{1/2} \qquad (6)$$

where "M" is the number of readings of each "X" for a given time. Like the bias error, the overall precision error of "Y" can be determined as:

$$P_Y = \left(\sum_{i=1}^{N} \left(\frac{\partial Y}{\partial X_i} P_{X_i} \right)^2 \right)^{1/2} \qquad (7)$$

For the determination of uncertainty, the following information must be available:

- The bias error, B_{Yi}, which basically arises from the systematic experimental errors.
- The mean value of a set of "*M*" observations of the measurement. According to the guidelines of the ASME Journal of Heat Transfer Editorial Board for estimating uncertainty, a sufficient number of samples (>30) should be taken over a sufficient sampling period.

For a typical fouling experiment, the results are normally presented either as the fouling resistance and/or the heat transfer coefficient. These two values are calculated as:

$$R_f = \frac{T_s - T_{s0}}{\dot{q}} \qquad (8)$$

$$a = \frac{\dot{q}}{T_s - T_b} \qquad (9)$$

Fig. 3 presents a flowchart for the determination of uncertainty of fouling resistances.

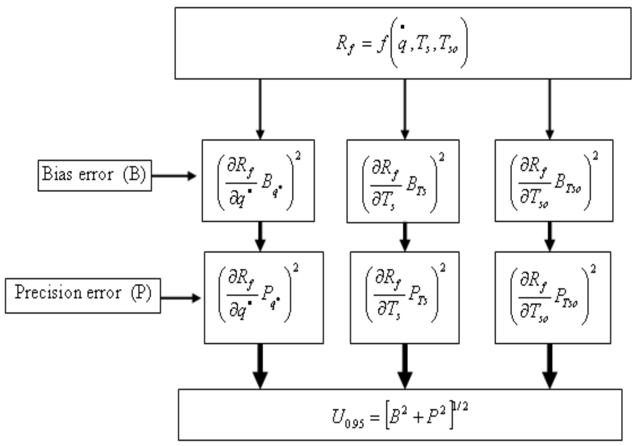

Fig. 3 Flowchart of uncertainty calculation for a fouling run.

In what follows, two distinctive but interrelated case studies of fouling during convective and pool boiling heat transfer will be presented. The uncertainty of both heat transfer coefficient and fouling resistance changes over time due to a complex series of events at micro- and macro-scales. Accordingly, the uncertainty is calculated at the early and final stages of fouling runs, possibly when the fouling resistance reaches a constant or asymptotic value.

3. CASE STUDY I: CONVECTIVE HEAT TRANSFER

The convective heat transfer fouling experiments are performed in a closed loop set-up consisting of two vertical rectangular ducts in which the test specimens are mounted. During a selected experiment the heat flux transferred from the surface is continuously recorded, and regulated by means of an automatic PID controller. The bias error arises from the systematic errors of i) approximately ± 0.2°C in temperature measurement and ii) about ± 4.8% for the determination of the heat flux as a result of systematic errors in the measurement of electrical current and voltage. Fig. 4 shows a typical fouling run with 80 kW/m^2 heat flux, 40°C bulk temperature, and 3.75 g/L $CaSO_4$ concentration (Al-Janabi, 2009). The results are presented in terms of fouling resistance and heat transfer coefficient. The calculated uncertainties are plotted in Fig. 5. It is obvious that the largest uncertainty of fouling resistance occurs at the start of all experiments when the temperature difference between heat transfer surface at time zero and at the actual time is small, while for the heat transfer coefficient, only a marginal difference in uncertainty values of around 4-5 % has been observed at the initial and final stages. This is somewhat expected since the characteristic temperature difference (T_s – T_b) is large in both cases.

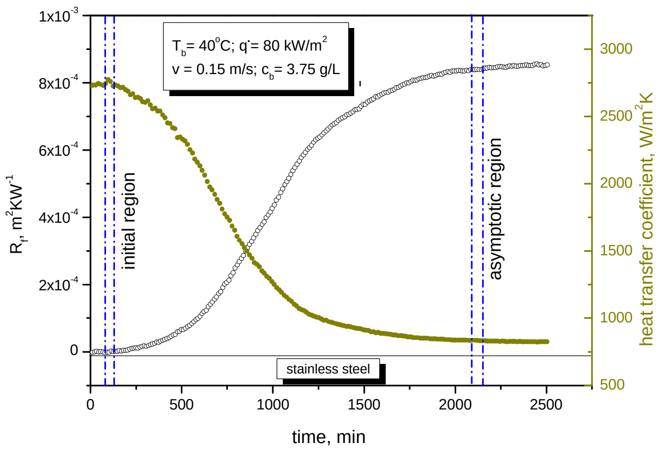

Fig. 4 Fouling resistance and heat transfer coefficient for a typical fouling run (Al-Janabi, 2009).

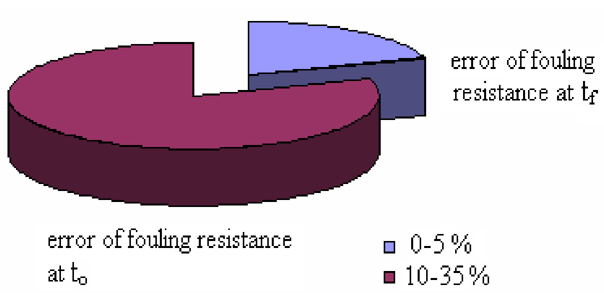

Fig. 5 Uncertainty of fouling resistance for a fouling test

4. CASE STUDY II: POOL BOILING

These fouling experiments are performed in a pool boiling test rig which consists of a cylindrical stainless steel vessel where the test tube is mounted horizontally. The fouling experiments were carried out under saturated boiling conditions of $CaSO_4$ solution. A constant and stable power to the heater is transmitted by means of power stabilizer to minimize the power fluctuations. However, a bias error of approximately ±2% in the calculated heat flux is due to errors in the measurements of electrical current and voltage. The systematic errors of both the bulk and surface temperature measurements are approximately ±4°K. Fig. 6 shows the variations of heat transfer coefficient and fouling resistance during a typical pool boiling fouling run with 1.6 g/L $CaSO_4$ concentration and 200 kW/m^2 heat flux (Esawy et al., 2009). As for the previous case study, the uncertainty is calculated for both heat transfer coefficient and fouling resistance at the beginning and the end of the experiment. Calculated uncertainty values at two times are presented in Table 1. The uncertainty for heat transfer coefficient changed from 7 % to 2.7 % while for fouling resistance it changes from 25.4 % to 4.5 % at the beginning and the end of the run respectively. Referring to Eqs. (8) and (9), it is obvious that the largest experimental uncertainty for both, heat transfer coefficient and fouling resistance, occurs for the smallest characteristic temperature difference, i.e. at the start of the experiment.

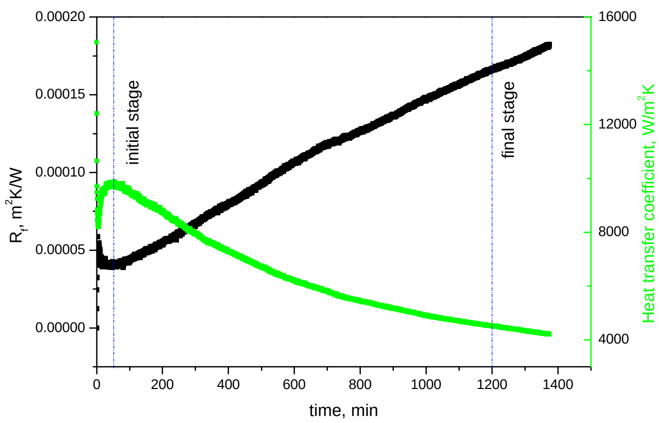

Fig. 6 Fouling resistance and heat transfer coefficient versus time for a typical pool boiling fouling experiment with 1.6 g/L $CaSO_4$ concentration and 200 kW/m^2 heat flux

Table 1 Calculated uncertainty values

	Bias error (B_i)		Precision error (P_i)		Uncertainty (U_i)	
Heat flux (q˙)	± 2 %	± 2 %	318.7	313.2		
Surface temperature(T_s)	± 0.4°K	± 0.4°K	0.808	0.232		
Bulk temperature(T_b)	± 0.4°K	± 0.4°K	0.116	0.105		
Heat transfer coefficient(α)	502.15	150.8	625.11	26.25	7%	2.7%
Fouling resistance(R_f)	2.89E-6	3.2E-6	4.1E-6	7.49E-7	25.4%	4.5%

5. CONCLUSIONS

Fouling experimentation is complex and the exclusive report of systematic error will not represent the actual overall error. Instead, it is imperative to calculate the experiment uncertainty which involves both the bias and precision errors. Two case studies for convective and pool boiling fouling experiments are reported. The results show that the uncertainly is not constant and can vary up to a factor of 4 over the course of fouling runs exemplified in this work. The largest uncertainty occurs at the start of fouling runs where the deposits are still loose and hence the fluctuation is high.

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Nomenclature

B	bias limit
c	concentration, g/L
M	number of observations
N	number of independent variables
$\dot{q}$	heat flux, W/m^2
R_f	fouling resistance, $m^2\ K\ W^{-1}$
T	temperature, ^oC
P	precision limit
U	uncertainty
v	velocity, m/s
$\overline{X}$	mean value of a set of N observations

Greek symbols

a	heat transfer coefficient, $W/m^2\ K$

Subscripts

b	bulk
s	surface
o	initial state
f	final state

Abbreviations

PID	Process Identification Number

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