On–Line Analysis of Local Values of the Heat Transfer Coefficient During a Pressurized Thermal Shock

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INTRODUCTION

The paper tackles the problem of determination of local, non-stationary values of the heat transfer coefficient (h) in the cooling phase of the pressurised thermal shock (PTS) events and, in particular, in the cooling phase of the large scale PTS experiments. The NKS-series of PTS experiments at MPA Stuttgart – Fig.1 (Kussmaul and Sauter, 1985), as well as the JRC Ispra, Italy, PTS experiments (Jovanovic, Volta, Lucia, 1988), have been used in development, testing and application of the methodology presented in this paper.

A PTS is usually defined as event or transient in the pressurized water reactors (PWRs), causing severe overcooling (thermal shock) concurrent with, or followed by significant pressure in the reactor pressure vessel. But, PTS is a structural safety and reliability issue in many other power and process plants, too. In both cases, integrity of the components exposed to single or cyclic PTS loads, is highly dependent on the behaviour of existing or assumed cracks in the component (vessel) walls, and therefore, the crack behaviour analysis represents the principal part of the integrity analysis.

h-ANALYSIS AS A PART OF THE PTS-ANALYSIS

PTS loads usually have three major components to be analyzed, namely:
- pressure in the primary loop (vs. time),
- temperature of the coolant (T_f in time and space coordinates), and
- h on the exposed surface(s).

The first two components can be usually measured without particular problems, but the third one – h , remains an open issue, both in plant analyses and in experiment analyses (Jovanovic, Sauter, Lucia, 1988). In some cases, simple geometry and simple boundary conditions may allow to determine the mean value (in time and in space) of h , e.g. by making an overall energy balance or by applying some of the correlations, but, in majority of the cases, precision and reliability of results obtained in this way are unsufficient. Furthermore, a complete analysis has also to take into account significant fluctuations of the local coolant temperature, and their cummulative effects, during one single PTS event (the fluctuations appear both in the experiments and in real plants).

Knowing h is essential for the structural safety analysis of the component exposed to PTS, because h determines the gradients in the temperature field (∇T) in the vessel or the test piece wall and consequently, the thermal stress and strain tensors (σ_{th} and ε_{th}, respectively), necessary to calculate the fracture mechanics parameters, like the J integral or the stress intensity factor K. In other words:

$$\nabla T \approx \nabla T(h) \qquad \text{and} \qquad \sigma_{th} = \sigma_{th}(E, \Delta a, \lambda, \nabla T(h)) \tag{1}$$

and

$$K = K(\sigma_{mech}, \sigma_{th}(h), \sqrt{a}) \tag{2}$$

$$J_k = J_k(\sigma_{mech}, \sigma_{th}(h), \varepsilon_{mech}, \varepsilon_{th}(h)) \tag{3}$$

The two fracture mechanics parameters are used then, either in the failure criteria:

$$K_I \leq K_{Ic} \qquad \text{or} \qquad J \leq J_{Ic} \tag{4}$$

or in the fatigue crack growth criterion (remaining life estimation)

$$a = \int_0^N \frac{da}{dN} \leq a_{allowed} \leq a_c \tag{5}$$

where a is the crack width and N is the number of fatigue cycles, while E, α and λ are material properties (here: Young's module, linear expansion and conductivity). First approximation for the mean value of h in the PTS analysis can be made using some of the basic correlations of convection heat transfer, e.g. the Nusselt's or the Jacobs's one (Holman, 1976), depending on the flow conditions (Fig.2). Also, it can be opportune to use some of the more appropriate, derived correlations, as for instance the one of Levy and Haelzer (1982), applicable in the PTS conditions during the emergency core cooling.

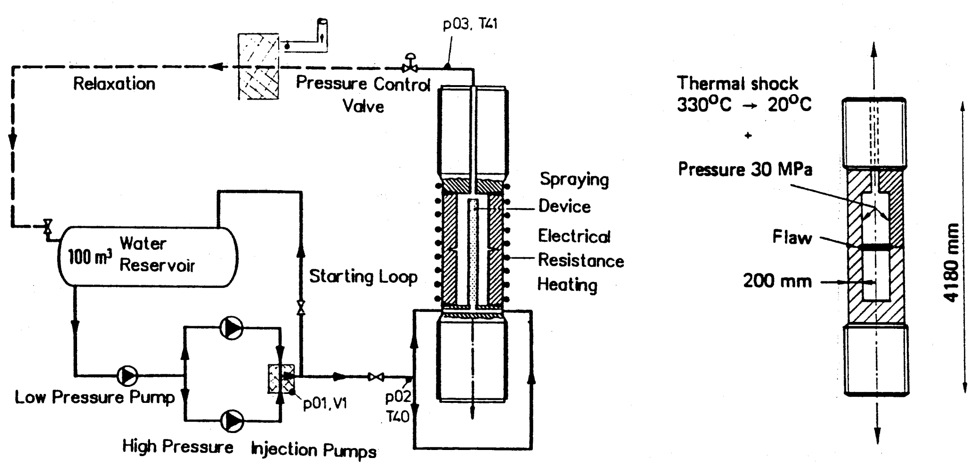
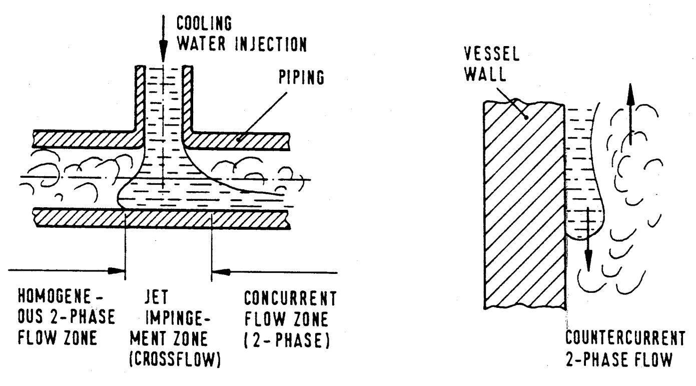


Fig.1 - NKS tests of MPA Stuttgart: layout (left) and the testpiece (right)

Fig.2 - Different heat transfer conditions in PTS



DIFFICULTIES IN THE HEAT TRANSFER COEFFICIENT ANALYSIS

Physical nature of the transient phenomena occuring during a PTS event is the main source of difficulties in the h analysis. In the majority of cases, a PTS event involves injection of the cooling water. The water jet impingement on the vessel wall and its mixing with the fluid in the vessel, create zones with substantially different heat transfer mechanisms (Fig.2). Although the correlations corresponding to these conditions (e.g. for the cross-flow or for the undeveloped turbulent flow) can be found in the literature, the uncertainties coming out from (e.g.): measurement techniques and procedures, and/or subjective (human) judgement, involved, appear regularly. The questions like how appropriate the chosen correlation for given conditions is, or what is our knowledge about the interdependencies among the quantities appearing in the correlation, about their local and global values (many of them, like the equivalent density, are virtually unmeasurable in real conditions), can be given as examples. Influence of these uncertainties can be large, causing sometimes prediction errors of more than 100%. In the MPA experiments, the nominal value of $h \approx 4000 W/m^2K$, showed peaks of over $11000 W/m^2K$, while in the JRC ones, calculations based on the nominal values significantly overestimated the actual flow subdivision and underestimated the equivalent density.

These uncertainties are typical for most of the experiments/analyses, and they stay in contrast to the complexity of the complementary numerical analysis (e.g. finite element based stress analysis, fracture mechanics analysis, etc.). As an illustration, some statements from some of the PTS related papers presented at the 9th SMiRT Conference (1987) can be quoted, e.g. *"... heat transfer coefficient is* 1500 *to* 3000 W/m^2K *...", or "...a constant heat transfer coefficient of* 10000 W/m^2K*... ... combined with an FE model with* 28040 *degrees of freedom", or "... the correlation unpredicts the experimental values substantially."*. In principle there are two possibilities to tackle the problem: to treat the uncertainties by some of the suitable (e.g. probabilistic or possibilistic) methods, or to refine the analytical and measurement methods. Both ways have been examined and applied at MPA. The first one is described in the work of Jovanovic, Servida and Sauter (1988), while the second one is presented hereafter.

METHOD FOR THE ON-LINE ANALYSIS DEVELOPED AT M P A

The method allows a real-time determination of h, at each time step in which the temperatures are measured (e.g. each 0.2 s in the MPA NKS PTS tests). The method is based on the orthogonal polynomial regression analysis of the measured temperature profile(s) across the wall thickness. The numerical analysis is performed using subroutines from the IMSL (1982) mathematical library. Once decoded back to the original physical variables, the gradients are analytically derived from the regression curves, and, from boundary conditions of the third kind, values of h are obtained (Fig.3). However, uncertainties regarding the position or the measurement precision of the thermocouples, are reflected on the h values. A pre-scrutiny of measurement results can, therefore, be useful. The flowchart of the code is given in Fig.4.

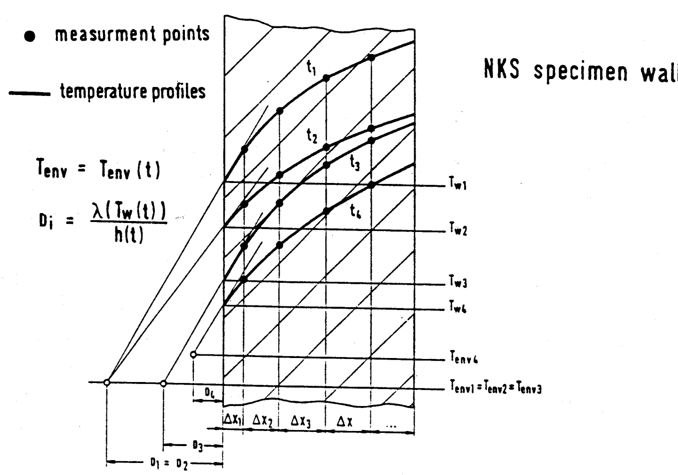


Fig.3 - Analysis of h, based on the temperature measurements in the test-piece wall

The method has been implemented in the frames of an ABAQUS (1988) preprocessor developed at MPA for the JRC Ispra (Jovanovic and Lucia, 1988), called FRAP. It can be used in two main ways. In the first case, the input data are given as a file (for **each** measurement location, i.e set of of the through-the-wall series of thermocouples, directly from the data acquisition device, in the form of the matrix time vs. measurement points along the component wall thickness. FRAP output in this case is the function $h = h(t)$. In the second case only one line of the above given matrix is expected as input, given interactively.

Form the matrix time vs. measurement points
in the vessel cross-section in which the local value
of the heat transfer coefficient is searched

$\Downarrow$

Read data for the nearest mesurement point
for the fluid temperature measurements

$\Downarrow$

Check for possible measurement errors

$\Downarrow$

Read the initial temperature profile

$\Downarrow$

$\Rightarrow$ Find the regression curve (analytically)
$\Uparrow$ for the time step

$\Downarrow$

Derive gradients

Next time step t_{i+1}

$\Downarrow$

Calculate $h(t_i)$

$\Downarrow$

Update the matrix $[h(t_i); t_i]$

$\Downarrow$

$\Leftarrow$ *no* $\Leftarrow$ The Pre-established time elapsed ?

$\|$

yes

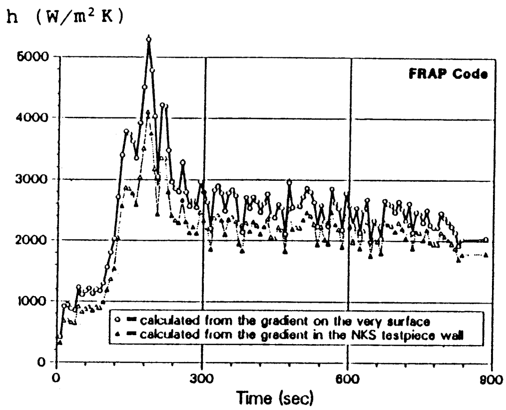
$\Downarrow$

Plot results

Fig.4 - The simplified flowchart of the computer code for the h-analysis (FRAP subroutine)

APPLICATION IN THE P T S EXPERIMENTS

Further use of results obtained by this method (in the heat conduction analysis, in the stress analysis and in the fracture mechanics analysis), confirmed their validity. The method is thoroughly tested in the MPA NKS experiments and in some of the JRC Ispra experiments. The results for the MPA test NKS4 (Fig.5) show FRAP results when the input data are coming directly from the data acquisition ("on-line"). Further heat conduction analysis, using h from Fig.5, shows an excellent agreement with measured data (Fig.6). Application of FRAP for the NKS5 shows how the h-analysis is performed when the input is given "manually" (Fig.7), in chosen moments during a PTS event. In order to enable practical use of the method, a special measurement micro-thermocouple thimbles have been designed and applied (Jovanovic, Lucia, 1988). They allow to measure the wall temperatures virtually along a single line across the component wall thickness.



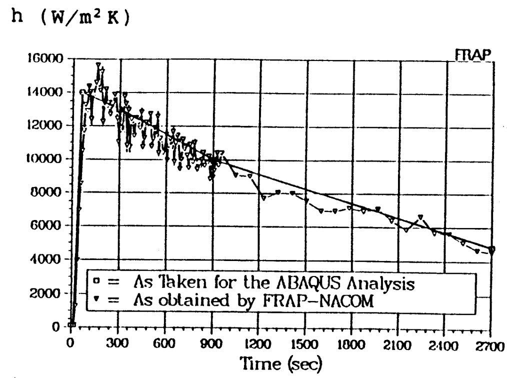
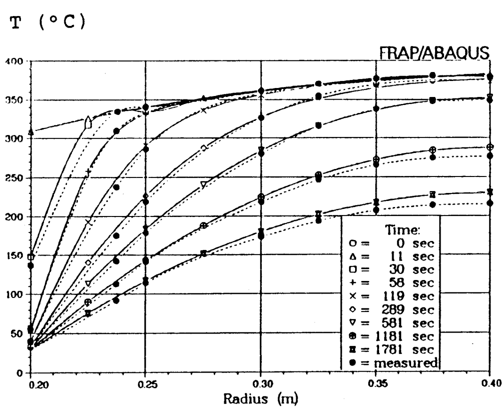


Fig.5 - FRAP applied to the MPA NKS4 experiment: NKS4-1 (left) and NKs4-2 (right); $\Delta t = 0.2 sec$



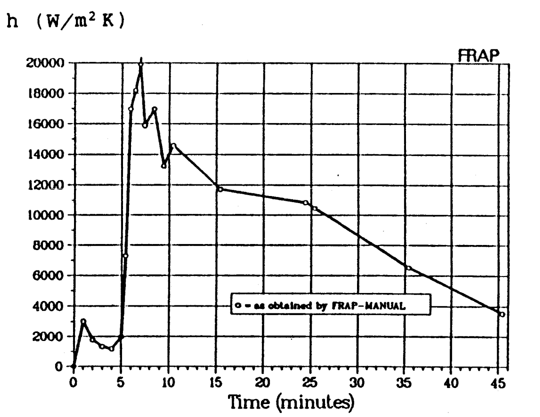


Fig.6 - Results of FRAP/ABAQUS heat analysis vs. measurements (NKS4-2)

Fig.7 - FRAP results for the NKS5 experiment

CONCLUSIONS

Apart from the verified applicability and practical usefulness, shown above, the method has an additional advantage in respect to the direct use of the measured temperatures in the finite element analysis (Fig.8). As discussed and shown in the work of Jovanovic and co-workers (1988), the overall error is smaller when h is accurately analysed and then given as boundary condition to the analysis (due to a better interpolation pattern), than when the measured temperatures are introduced directly. Both characteristics of the method give a possibility further to improve the structural analysis of components exposed to PTS loads.

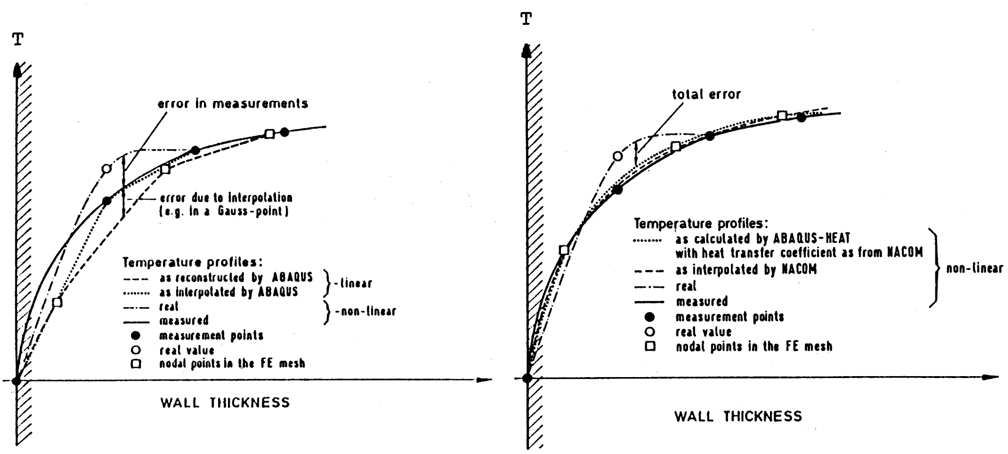


Fig.8 - Direct use of measured temperatures (left) and use of h calculated by FRAP (right) NACOM=subroutine in FRAP)

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