Gradient Heat Flux Measurement for Reflux Condensation Phenomena Investigation

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INTRODUCTION

The PRECISE test facility (*Precise REflux Condensation Investigation Setup*) is constructed at Paul Scherrer Institute (PSI), Switzerland, in order to provide high quality and resolution data for reflux condensation, phenomenon which occurs inside steam generator tubes of a pressurized water reactor (PWR) during design basis or severe accident and maintenance conditions. This phenomenon is capable of removing residual decay heat from the reactor coolant system which suppresses or, at least, delays the core uncovery in a hypothetical loss of coolant accident.

Good understanding of the phenomena is crucial to assess the heat removal capabilities under a broad range of thermal-hydraulic conditions, specifically in the presence of non-condensable gases. The PRECISE facility uses novel sensors to study the phenomenon under well controlled conditions and perform high resolution measurements of the thermal-hydraulic parameters and their influence on the heat removal capabilities in a single steam generator tube.

In order to achieve this goal, accurate and high-frequency measurements of the heat flux through a tube wall are necessary. Having such data will enable studying not only integral heat transfer behavior but also instantaneous variations, including influence of the liquid film forming on the inner wall. Easily available, off-the-shelf sensors do not meet the requirements in term of size, working temperature range or measurement frequency.

In this work, we assess the applicability of the newly developed Gradient Heat Flux Sensor by Mityakov et al. [1] to measure heat flux through tube wall reflecting geometry of PWR steam generators tube but also the broader possibility to use the sensor for general heat flux measurement applications. We describe the technical preparations of the sensor, the calibration process and present first recorded signals.

The financial support of this project by the swissnuclear organization is gratefully acknowledged.

PRECISE FACILITY

Reflux condensation experiments will be conducted in a vertical tube of 20 mm inner diameter and 5 mm wall thickness, which corresponds very well to tubes used in PWR steam generators. The tube will be closed at the top to reduce uncertainties in the mass balance and to simplify the test rig. Steam will be supplied from a tank with a heating rod, located below and the tube will be surrounded with coolant water, flowing through a concentric cooling jacket. In this arrangement, the incoming volume flow of vapor will be equal to the flow of returning condensate under steady state conditions. This makes it possible to calculate the integral the fluxes from vapor and water from the heating power alone.

GRADIENT HEAT FLUX SENSOR

$$E = S_0 * A * q \qquad (1)$$

The Gradient Heat Flux Sensor (GHFS) is an artificial anisotropic thermo-element. Due to the anisotropy, temperature gradients appear in two directions: along and perpendicular to the applied heat flux. The transverse Seebeck effect generates thermo power with vector E proportional to the transverse temperature gradient, sensor area A, and is normal to an applied heat flux q, see Figure 1 and Equation (1). S_0 stands for the sensitivity of a GHFS and its value depends on the sensor used. The polarity of the signal can be related to the direction of the heat flux through the sensor.

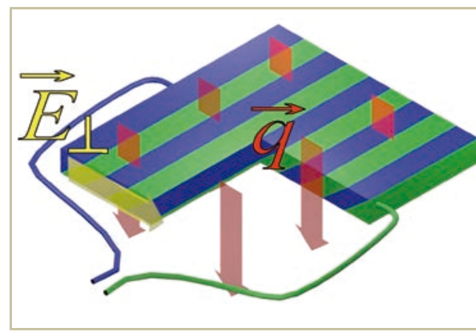

Figure 1. GHFS principle of operation.

The GHFS in operation in the PRECISE facility is made of sintered, alternating layers of stainless-steel and nickel foil of 0.1 mm thickness. According to [1], the properties can be summarized as follows:

- Working temperature up to 1300 K
- Sensitivity 0.4 mV/W
- Thickness of the sensor can be made very small without losing sensitivity
- Response time estimated in the order of 10^{-9} seconds

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The GHFS, due to its achievable compact size (0.2 mm thickness, 5x5 mm area) yield only small perturbation to the measured heat flux.

SETUP

To test the sensor and acquire experience for application to condensation heat flux measurements two setups are established. Firstly, resistive heating with a precise power source is used to estimate the sensitivity and confirm the relation between heat flux and sensor output.

In the second setup, the GHFS is attached to the inside wall of a 20 mm inner diameter vertical tube and steam at atmospheric pressure is supplied through the tube, with the outside being cooled by water in natural convection regime, and sensor output signal is observed during steam condensation. The sensors dimensions are on average 4 by 4 mm with 0.2 mm thickness.

The measurement system developed is capable to sample the GHFS signal with a sampling rate of 50 kHz.

For the nickel-steel sensors used, the initially measured sensitivity ranges from 0.2 to 0.8 mV/W. Due to disturbances to the heat flux path introduced in the process of attaching the sensor to the pipe wall, each unit has to be calibrated in situ, to account for those variations.

INITIAL RESULTS

The signal amplitude was found to be nearly linearly dependent on the supplied heat flux, Figure 2.

Linear relation between output signal and heat flux might not be valid when sensor operates under elevated temperatures. Tests with resistive heating will be replicated in broader range of temperatures (20 to 200 °C) which is the operating range of the PRECISE facility.

In addition it was found, that the signal quality suffers when there are large temperature gradients in the sensor plane, causing additional electromotive force and interfere with the signal. A solution to this problem was found by creating a double layered sensor, which mitigated the issue, but has to yet been optimized to completely diminish the influence of such temperature gradients.

Tests with steam proved the sensor is capable to record condensation heat flux. Using spectral analysis of the signal will enable us to investigate the behavior of the liquid forming/flowing over the sensor area, such as film thickness oscillations or droplet formation.

During these tests, an attempt was made to use a pair of chromel-alumel wires at each end of the sensor. The measured signal using chromel-chromel and alumel-alumel wires provided the heat flux signal, while measuring using mixed wire pairs resulted in a simultaneously recorded temperature signal, because type K thermocouples junctions were formed, Figure 3.

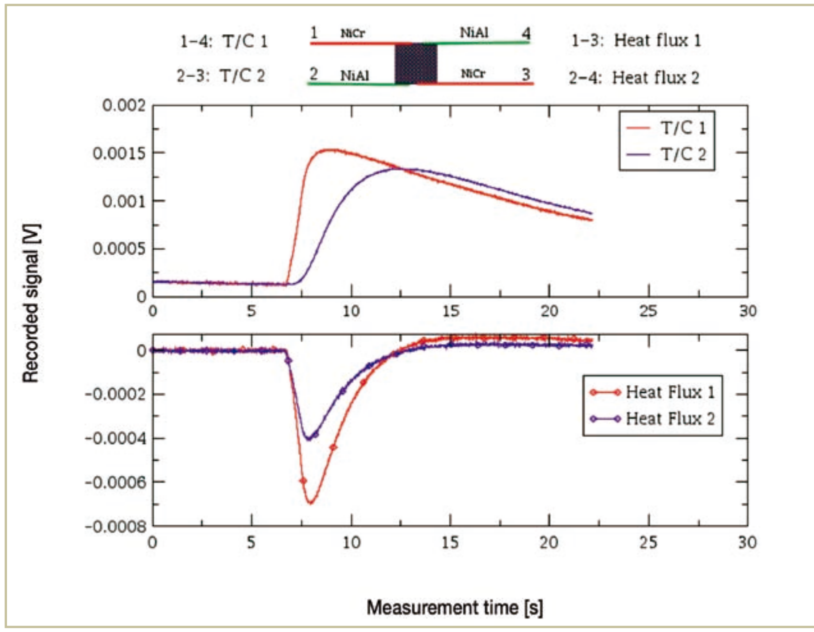

Figure 3. Two heat flux and two themocouple signals obtained from GHFS sensor after applying heat to one side. Measurement layout explained at the top.

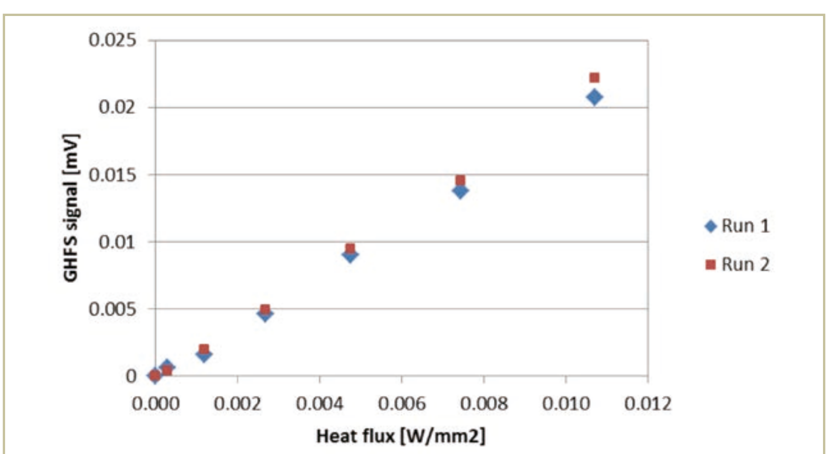

Figure 2. GHFS signal amplitude as a function of heat flux (temperature gradient through the sensor was varied from 0 to 20°C).

CONCLUSIONS AND OUTLOOK

Results from first experiences obtained so far with GHFS sensor show a promising picture to use this device in the PRECISE facility. Its form factor, operating temperature range and response time makes it unique and will help to provide new insights in heat flux phenomena in reflux condensation conditions.

Additional testing has been undertaken, to tackle remaining technical issues, i.e. eliminating influence of sensor plane temperature gradients, improving sensor mounting, signal amplification and filtering.

REFERENCES

[1] A. V. Mityakov, S. Z. Sapozhnikov, V. Y. Mityakov, A. a. Snarskii, M. I. Zhenirovsky, and J. J. Pyrhönen, “Gradient heat flux sensors for high temperature environments,” Sensors Actuators A Phys., vol. 176, pp. 1–9, Apr. 2012.