SPATIALLY-RESOLVED MEASUREMENT OF GAS PHASE TEMPERATURE AND VELOCITY IN THE SUBCHANNELS OF A FUEL ELEMENT DURING DRY-OUT

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ABSTRACT

After the Fukushima accident the spent fuel pool has got a stronger focus in nuclear safety research. The objective of the German national joint project SINABEL (**SI**cherheit **NA**sslager **B**renn**E**lement-**L**agerbecken) is the experimental investigation and modelling of the thermal hydraulics of fuel elements in the pool dry-out phase. Key parameters for validation of the models are the steam temperatures and velocities in the subchannels. Due to the complex geometry and the thermal insulation of the test facility there is a strong limitation in the optical and mechanical accessibility for measurements. As a result there is a need for novel measurement techniques to provide spatially resolved gas phase temperatures and velocities.

Our approach is a modified wire-mesh sensor that is usually used for phase discrimination in two-phase flows via the measurement of conductivity or capacity in the crossing points of the wires. In the new sensor concept we integrate special miniaturized converters, which are resistance thermometers for the temperature and velocity measurement. The advantage of this technique is the possibility to overheat the sensor by increasing the current through the sensor. By controlling the sensor temperature the use of the thermal anemometry principle becomes possible.

KEYWORDS
Wire mesh sensor, Velocity grid sensor, Thermal Anemometry, Temperature grid sensor

1. INTRODUCTION

Since the Fukushima accident the focus in nuclear safety research has been considerably extended to the spent fuel pool. As interim storage for spent fuel as well as storage for fuel elements during revision periods in the reactor pressure vessels there is a potential risk with spent fuel pools if cooling fails for any reason, such as during a longer station black-out. In the worst case of a full long-term loss of cooling first the water temperature in the pool would increase up to the boiling point. From then on the water would evaporate resulting in a decrease of the water level and heating up of the fuel elements. The worst case scenario is the loss of fuel rod integrity and the danger of hydrogen explosions.

In the joint project SINABEL (**SI**cherheit **NA**sslager **B**renn**E**lement-**L**agerbecken) the thermal hydraulics of a fuel element is investigated in a corresponding mock-up. Simulated scenarios are loss of cooling and coolant respectively. The objectives are an improved CFD modelling and accompanying experimental investigations for CFD model development and code validation. The interface between experiment and simulation is the heat and mass transport during fuel element dry-out. Key parameters for validation are therefore the steam temperature and velocities in the subchannels. Due to the fact that there is no suitable measurement device for determination of the steam velocities in the subchannels commercially available, a part of the joint project is the development of a special measurement technology. The boundary conditions and the approach are described in this work.

2. OBJECTIVE AND APPROACH

2.1. Description of the Test Facility and the Measuring Task

For the experimental investigation of the thermal hydraulics during fuel element dry-out the determination of specific parameters is necessary. Therefore an experimental setup is built up by the Technische Universität Dresden within SINABEL. It consists of a replica of a full fuel element with original dimensions. These are 10 fuel rods in square, diameter D = 10 mm, pitch-to-diameter ratio of P/D =1.24 and a centric 2x2 water channel (figure 1). In the test facility the fuel rods are electrically heated with a characteristic power profile. To simulate different decay heat power levels the applied electrical power can be varied. Typically the fuel element is embedded in a storage rack and is surrounded by other fuel elements. The electrically heated rods are cooled by water or steam. Below the water level the generated heat is transferred to the water. The result is heating up of the water up to boiling temperature and evaporation. Above the water level the produced steam rises in the subchannels. During this the steam is heated up by convective heat transfer due to the temperature difference between the overheated rods and the steam. The heat flux is directed in the axial direction and is nearly zero in the radial direction. To replicate these conditions the investigated fuel element is surrounded by single fuel rods. Furthermore to reduce radial heat transfer the test facility is insulated and constructed without flanges in the axial direction. These design aspects exclude the accessibility to the subchannels from the surrounding surface of the mock-up. The only possibility is the access from the top side.

One topic of the program is the development of a measurement system for the determination of steam temperature and velocity in the subchannels above the water level. Besides this objective the test facility is also instrumented with a large amount of thermocouples which are distributed in axial and radial arrangement in the fuel element. Thereby the surface temperature of the fuel rods and steam temperature is measured. The measuring points of the presented measurement system are in a plane perpendicular to the axial direction of the subchannels. The grade of spatial resolution depends on the applied method. The axial position of the flow sensors should be in the area of a fully developed flow above the water level. As a consequence of this it is not necessary to position the flow sensor in the whole depth of the fuel element but rather in the upper section. For reasons of assumed symmetry of the flow over the cross-section it is sufficient to measure the flow parameters in only one quadrant. Figure 1 shows the fuel element during dry-out and the possible measuring range above the water level. The indicated measuring points are centered in the subchannels.

The expected properties of the steam can be derived from previous studies [1, 2]. The maximal steam temperature that was measured in the experiments is $\vartheta = 470\ °\mathrm{C}$, but is limited by undesired radial heat transfer losses. The developed measurement system will be designed for steam temperatures up to $\vartheta = 500\ °\mathrm{C}$. From the evaporation rate and the temperature the steam velocity range can be calculated. This calculation gives an expected velocity between $v_{\min} = 0.01\ \mathrm{m/s}$ and $v_{\max} = 0.15\ \mathrm{m/s}$. The flow conditions are expected to be laminar in the subchannels.

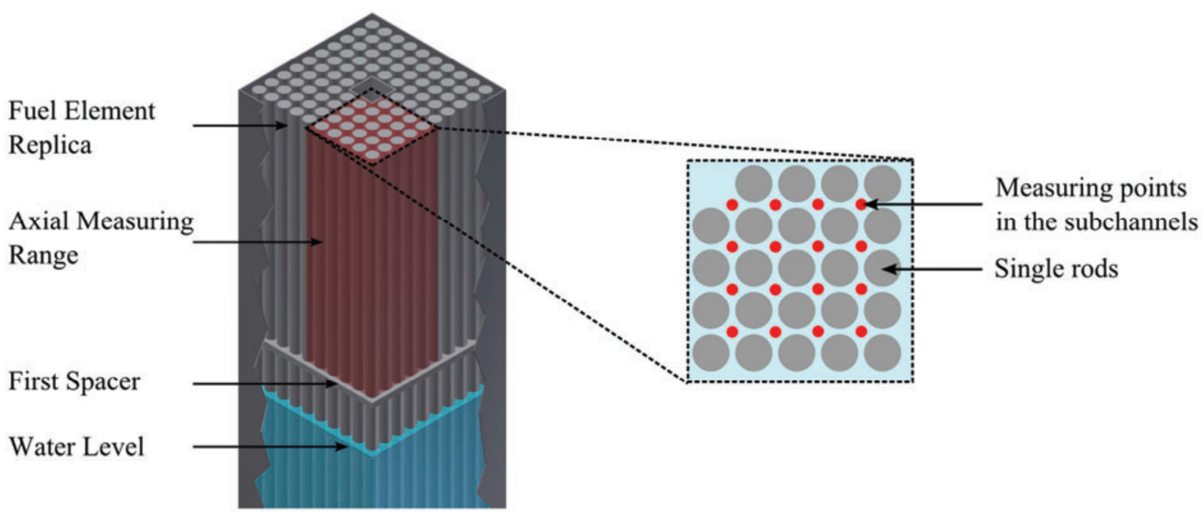

Figure 1. Fuel element replica with measurement range (left) and measuring points (right).

Due to the given design the accessibility for most sensor arrangements is restricted. Thus, cables and fixing units for installations have to be introduced from the top side of the test facility. Another aggravating fact is the geometry of the fuel element. The gap between the individual fuel rods is d = 2.4 mm. Therefore installations of the measurement system have to be miniaturized to reduce their invasiveness.

2.2. Selection of the Suitable Methods

For flow measurement several methods are known. The applicability of most of these is restricted by the design limitations mentioned above. The main criteria for the selection are the realization of spatial resolution and the technical boundary conditions of the individual method. The compatibility for the measurement of temperature and velocity in one system is preferred.

The advantages of optical methods, e.g. PIV or LDA, are non-invasiveness and good temporal and spatial resolution. However their suitability for the present application case is strongly limited by the problematic optical access. Furthermore tracer particle injection in the smoothly rising steam flow close to the decreasing water level seems to be very difficult. The Schlieren technique, another option, requires temperature gradients in the fluid that can be excluded in the experiment [1].

Pressure based measurement methods like Pitot tube, vane anemometer or vorticity sensors are unsuitable because of the minor pressure effects created at the very low steam velocities. Also, the sensing elements would be too intrusive.

For the investigation of turbulence in gas flow between rod bundles a frequently applied method is hot wire or hot film anemometry (HFA). Thermal anemometry enables the possibility of combined measurement of temperature and velocity by varying the electrical supply [3]. The dimension of the sensor elements, that is typically a platinum or tungsten wire with a diameter of d = 5 µm, reduces the invasiveness to a minimum and provides necessary sampling rates for resolving small scale turbulences.

There are other numerous possibilities for flow measurement that are not presented here. They have properties which disable them, e.g. radiotracer methods with a complex safety concept for the test facility. The preferred flow measurement method is a technique based on the thermal anemometry principle [4].

2.3. Device for Realization of Spatial Resolving Measurements

Usually single hot film or hot wire anemometer sensors are mounted in supports which fix the sensors at the point of interest. Depending on their dimensions they are more or less intrusive. For inserting them in the axial direction of the fuel element subchannels extended supports are necessary. Measuring simultaneously in every subchannel as shown in figure 1 both the sensor and the supports has to be introduced from the top. A substantial part of the flow area will be blocked. The influence of this constriction on the flow was not investigated until now.

The approach to avoid this massive intrusion is the application of a smart single sensor carrier system. A technique for the determination of spatially-resolved information in a cross-section is the grid sensor. It consists of two planes of parallel wires. Both planes are staggered parallel with a specific distance and are angled 90° to each other. The result is a grid or a matrix of wire crossing points respectively. An application is the wire mesh sensor [5], that is shown in figure 2. It is originally used for phase discrimination in two-phase flows by measuring the conductance or capacitance of the fluid at the crossing points of the wires. Besides high spatially resolved measurement, advantages are minimal-intrusiveness and reduced wiring effort compared to single-sensor applications.

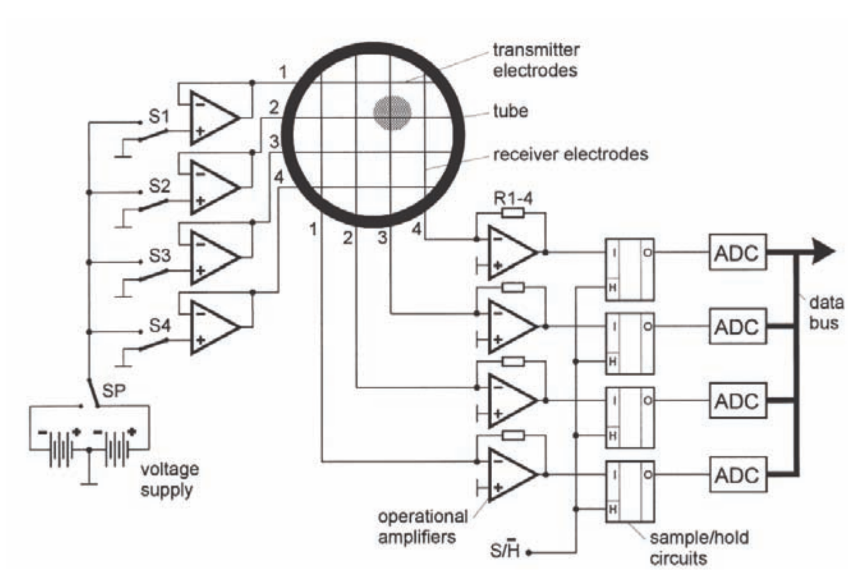

Figure 2. Scheme of conductance wire mesh sensor [5].

The grid sensor technique is the base for the presented measurement system. Instead of measuring electrical fluid properties at the crossing points the gas velocity and temperature are the parameters of interest. This will be carried out by integrating special converters at the crossing points. The grid sensor fulfills the function as mechanical probe holder as well as electric supply.

2.3. Technical Approach

The fundamental principle of thermal anemometry is to determine the convective heat transfer coefficient of an overheated sensor in the flow [4, 6]. The general heat balance for a sensor element is

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = P - \dot{Q}_\mathrm{c} - \dot{Q}_\mathrm{l} - \dot{Q}_\mathrm{r} \tag{1}$$

with Q being the heat, P the electrical heating power, $\dot{Q}_\mathrm{c}$ the convective heat transfer rate, $\dot{Q}_\mathrm{l}$ the conduction heat transfer over the supports and $\dot{Q}_\mathrm{r}$ the radiative heat transfer. The last two terms $\dot{Q}_\mathrm{l}$ and $\dot{Q}_\mathrm{r}$ are ideally negligible.

The sensor is heated by the electrical current I and has the temperature ϑ_s with its relating temperature depending resistance R. The convective heat transfer is characterized by the sensor surface area A, the temperature difference $\vartheta_s - \vartheta_\mathrm{f}$ between the sensor and the fluid and the convective heat transfer coefficient α, that is a function of the flow velocity v. This gives

$$0 = I^2 R - \alpha A(\vartheta_\mathrm{s} - \vartheta_\mathrm{f}). \tag{2}$$

One basic requirement for the sensor is a material that has an increased electrical resistance compared to e.g. copper and a high thermal coefficient of resistance. Usually this is platinum, tungsten or nickel. Taking into account that the expected flow is laminar, the frequency response of the sensor is in the range of a few Hertz to resolve non-turbulent velocity changes. Since there is no requirement to resolve turbulences, the necessity to use fine wires for the sensor is not given. Instead of thin wires plane ceramic substrates with a platinum film applied in thin or thick film technology are preferred. This is similar to resistance thermometers. Applying a current I_ϑ as low as to exclude self-heating of the sensor the fluid temperature distribution can be measured. Such a device was already presented by Schäfer [7]. Increasing the current to an upper level I_{velo} the sensor overheats. Depending on the operation mode the sensor temperature is controlled or just measured and assigned to a flow velocity on the base of calibration data [8]. For measuring within one sensor the applied current is switched between the two levels. The result is a sequential measurement of temperature and velocity.

Figure 3 shows two design drafts for the technical realization. In both variants the sensor carrier consists of aluminium oxide or glass ceramic. For minimal flow invasiveness the support wires can be levitating (figure 3a). A major disadvantage of this variant is a low robustness, especially for the mounting process. To prevent this problem in the second variant the support wires are embedded in thin ceramic sheets to protect them (figure 3b). The additional influence of the sheets and the sensors on the flow has to be investigated separately but is expected to be small. The sensor elements are implemented in the crossing points of the supporting wires. To protect all parts against corrosion and short-circuit currents a suitable coating material will be applied on the surface.

An important fact for the measurement of changes of the velocity in the laminar flow is the achievable sampling rate. For temperature measurement the influencing variables are the multiplexing frequency of the electronics and the thermal inertia of the sensors during temperature changes. In the case of flow measurement the anemometer operation mode becomes more important. Using the constant temperature mode (CTA) the influence of thermal inertia is minimal. But for others, like constant current,constant voltage and thermal transient anemometry [9], the dynamic time behavior of the sensor temperature is crucial. Compared with thin wires the thermal inertia of the sensor will be increased and reduces the sampling frequency to a few Hertz.

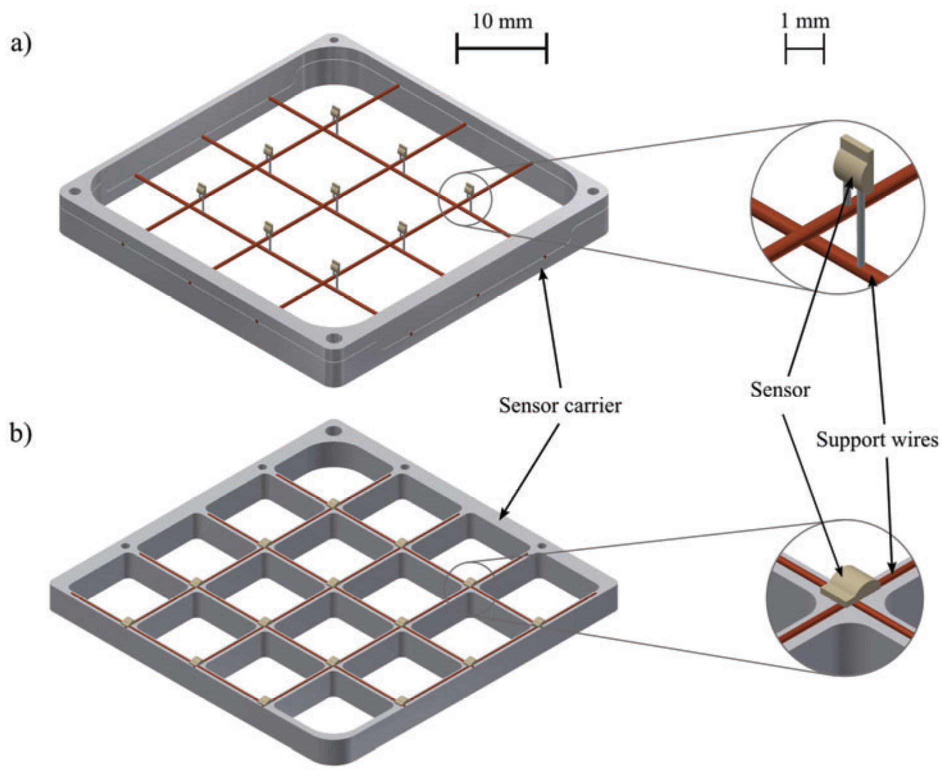

Figure 3. Design variants for the grid HFA sensor.

3. PRELIMINARY RESULTS

Usually applied sensors in thermal anemometry are thin wires or films on substrates. Instead of this the use of resistance thermometer elements is intended. Preliminary tests were done in terms of applicability. For this purpose a PT100 sensor (figure 4a) was mounted centrally in a tube. The tube dimensions were $l = 0{,}75$ m length and $d = 0{,}018$ m diameter. A sponge was mounted at the entry of the tube to straighten the flow.

The airflow was adjusted by a mass flow controller. The overall flow velocity was varied in the range between $v_{\min} = 0.0065$ m/s and $v_{\max} = 0.1$ m/s. The corresponding Reynolds numbers are $Re_{\min} = 8$ and $Re_{\min} = 117$ respectively, that are representative for a laminar flow. The flow velocities at the sensor position in the tube can be calculated from the mass flow under the assumption of parabolic flow profile.

For measuring the sensor resistance both, the current I and the voltage drop U were measured. In the first step for temperature measurement the low current level $I_{\vartheta} = 1$ mA was applied. The flow temperature can be calculated from the measured resistance. In the second step the current was increased to overheat the sensor. To apply the constant temperature anemometry operation mode, the sensor resistance and temperature respectively was adjusted to an overheat of $\vartheta_s - \vartheta_f = 15$ K between the sensor and the fluid by varying the applied current.

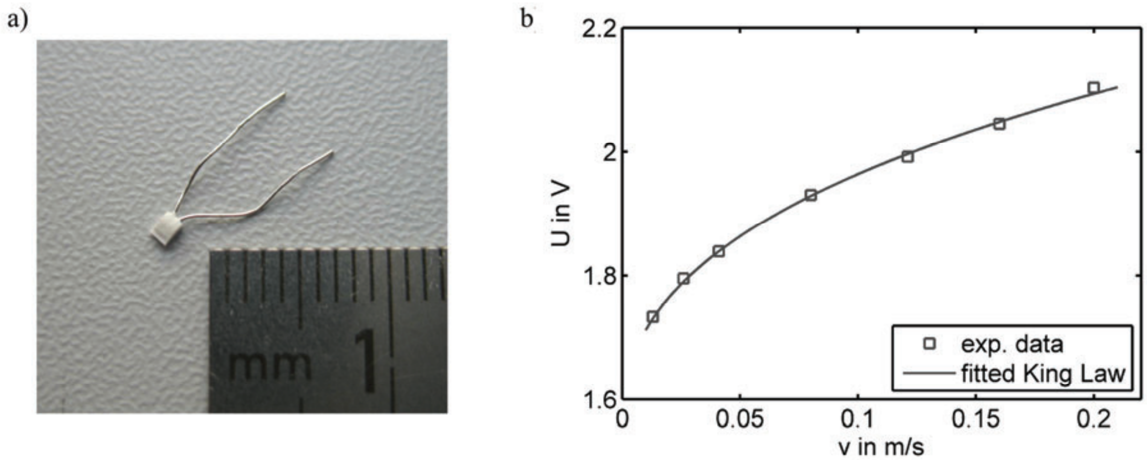

Figure 4. a) Miniature PT100 sensor and b) calibration curve for CTA mode.

The measured voltages are shown in figure 4b. As expected the voltage drop U increases with increasing fluid velocity v. The experimental data can be fitted using King`s law [10]

$$U^2 = A + Bv^n. \tag{3}$$

The determined constants for this curve are $A = 2.42$, $B = 4.05$ and $n = 0.45$. It can be concluded that resistance thermometers are applicable for temperature measurement as well as flow measurement. For use in overheated steam their mechanical resistivity must be examined.

4. CONCLUSIONS

In this paper an approach for the determination of gas phase temperature and velocity in the subchannels of a fuel element during coolant dry-out is presented. Caused by the complicated accessibility in the test facility the application of established flow measurement techniques is restricted. The presented solution bases on the application of the grid sensor technique. The integration of special converters at the crossing points of the grid sensor allows the measurement of temperature and gas velocity. Using platinum active sensor elements allows the sequential measurement of temperature and gas velocity applying the thermal anemometer principle.

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