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A device for measuring the heat flux on the cylinder outer surface in a cross-flow.

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Abstract

The paper presents heat transfer measurements results concerning a cylindrical element. The cylindrical rod that is the object of interest that is surrounded by a mixing region of hot and cold flows and, as a consequence, is subjected to thermal device for determining heat flux on the outer surface of fluctuations. The paper describes an experimental he rod, the method is based on the solution of the inverse heat conduction problem (IHCP). A heat flux measuring instrument is described together with its construction and tests performed at a special design stand.

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Keywords: heat flux, inverse method, measurements, temperature fluctuations, heat flux measurements

1. Introduction

The paper presents an instrument for measuring heat flux on the outer surface of cylindrical element. The work is a follow up of works that were performed to analyze and determine heat transfer phenomena occurring to a control rod of nuclear power plant [1-4,7]. The designed measuring instrument is able to measure heat flux and heat transfer coefficient on the outer surface of cylindrical element. The element could be immersed in fluid and subjected to rapid thermal fluctuations resulting from a jet impingement.

The determination of the unknown surface heat flux does not require any knowledge of temperature field in fluid and can base on measurements of the temperatures in some discrete points beneath the surface. These temperatures can be used to solve the inverse heat conduction problem (IHCP) [5, 6]. The IHCP can be defined as the estimation

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of the boundary conditions (here heat flux and temperature on the surface) from transient temperature histories at one or more interior locations. In order to test the IHCP-method a numerical test was performed [4]. In the test the transient temperatures calculated by CFD at some interior locations inside the stem were used as input data in IHCP-analysis [4] and surface heat fluxes and temperatures were calculated. The heat fluxes were then compared with respective calculated directly by CFD. The comparison shows good agreement between CFD and IHCP calculated surface heat fluxes and temperatures [7]. Based on these experiences the heat flux measuring instrument (MI) was designed, manufactured, armed with thermocouples and tested

2. Measuring instrument

Measuring instrument (MI) measures solid temperature at some discrete points, then by utilization the algorithm, which is described in [5, 6 and 7], heat flux and temperature are determined on the outer surface of the MI. The algorithm is incorporated in the software, and the software together with MI composes a unit. The construction is based on a metal pad (stainless steel) which covers a 94^o cylindrical sector. Figure 1 presents the geometry and dimensions of the pad. The pad represents ¼ of the full cylinder. The 94^o sector is equipped with 14 thermocouples equally spaced every 15^o on two radii R1 = 60.50 mm and R2 = 69.50 mm. Thermocouples are installed 0.50 mm from the inner and outer surface. As it is depicted in Fig. 2, thermocouples 1-7 are placed at the distance of 0.5 mm from the outer pad surface and thermocouples 8-14 at the distance of 0.5 mm from the inner pad surface. There are two measuring levels located 50.00 mm from the bottom and top of the MI. They are marked by thick red lines in

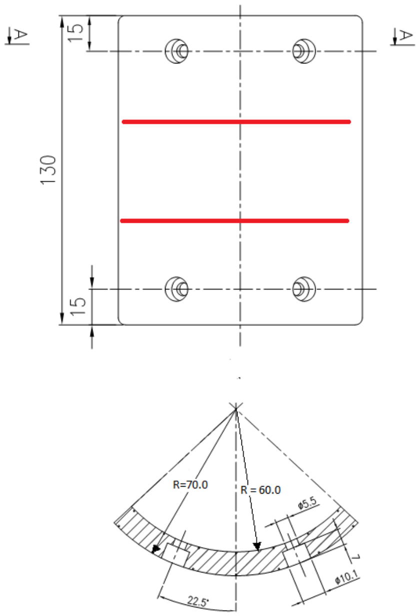

Fig. 1. The measuring pad: scheme and dimensions, the red lines show measuring level

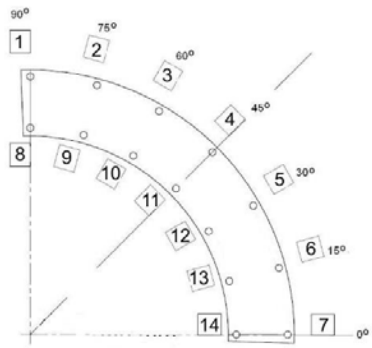

Fig. 2. Location of thermocouples in MI

The MI design includes openings (holes) where thermocouples are installed. The design requires special machining, which is a result of two factors. The first is the thermocouple diameter, which is 0.50 mm; the other is the great influence of thermocouple location on the determination of heat flux. Small displacements in the thermocouple's location can cause great errors in the heat flux value. The machining accuracy was 0.05 mm and 0.1o angle degree.

The MI is shown in Figure 3&4.

Fig. 3. Details of MI with openings (holes): a) outer surface view b) inner surface view

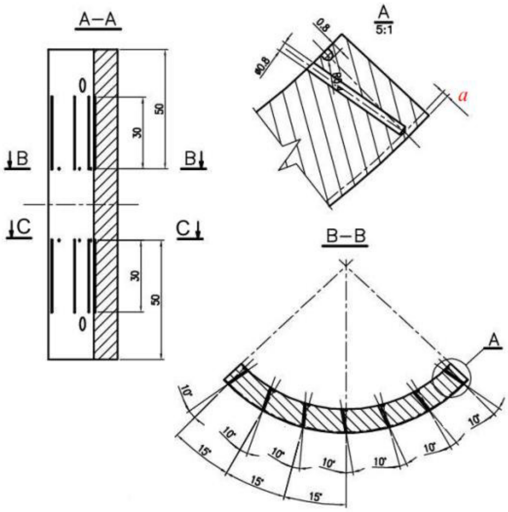

Fig. 4. The distance *a*

Thermocouples were placed in machined rows and fixed with metal mass glue. Various type of glue was tested. The test was performed in the following manner: a metal wire of Ø 0.8 mm was stuck to a metal pad and the glued elements were immersed in boiling water for 1 h. Then the glued elements were kept in a container with water for 48 h. After the test the Technicoll Super Metal 1(E-433) glue was chosen for further applications. The E-433 has the thermal resistance up to 120^{o}C and is water proof. Thermocouples are distributed on the radius R = 69.50 mm in opening. Holes are drilled starting from the inner side of the pad in a radial direction. The opening diameter equals 0.8 mm. To avoid collisions between thermocouples, openings were drilled with an angular displacement equal to 10^{o}. This situation is illustrated in Fig. 4. Thermocouples, which are installed in such machined openings, reach the location close to the outer surface (0.50 mm beneath the outer surface).

3. Verification of thermocouples location

As mentioned earlier deviation between actual and expected position of thermocouples beneath the outer surface significantly affect the measurement errors. In the case of rows, the location of thermocouples was very easy to observe due to their construction. Thermocouples were placed exactly in machined rows and covered by metal-mass glue. It could be assumed that the displacement of thermocouple location corresponds to the machining accuracy of rows. In the case of openings, the situation is not so clear; the openings bottoms with installed thermocouple were not accessible for a simple examination. Therefore the location of thermocouples in openings was verified using computer tomography. The aim of the investigation was to determine the distance a between openings bottoms and the outer surface Fig. 4. The illustration of the computer tomography measurement process is shown in Fig. 5. The distance a, which should be equal to 0.50 mm, was determined for each opening. The conclusion is that 0.50 mm is preserved for most openings. The measurement accuracy follows from the pixel size which is equal to 157.86 μm. The measured values were introduced in to the algorithm for calculating surface heat flux and temperatures in order to improve the accuracy of determination of surface heat flux and temperature.

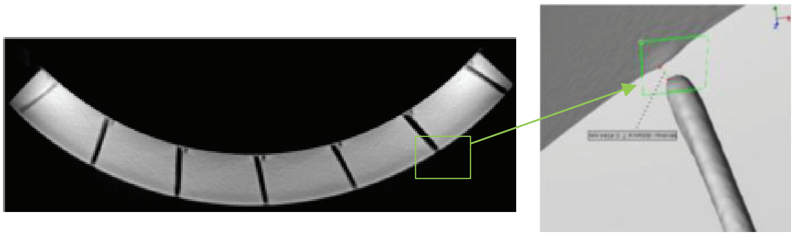

Fig. 5. Computer tomography, of MI, zoomed area of opening.

4. Research stand for tests of measuring instrument

A stand was built for testing experimental technique as measuring. The scheme of the research stand is presented in Fig. 6. The MI (j) is installed in a specially manufactured measuring section (MS) (a) and placed in a tube (b) with a diameter equal to 250 mm. MI and MS are affected by the surrounding air. Air flow is forced by the axial flow fans (c) and (h). From below the air flows through the inlet (d) and flow straightener (e). A parabolic bluff body (f) is installed upstream to the MS in order to preclude wake and vortex creation. At the vertical inlet, a heater (g) is installed to heat incoming air. A step change of air temperature around the MS is achieved by using heaters (g) or (i) or changing the volume flow of the air. The maximum air volume flow rate from below is 300 m3/h at ambient

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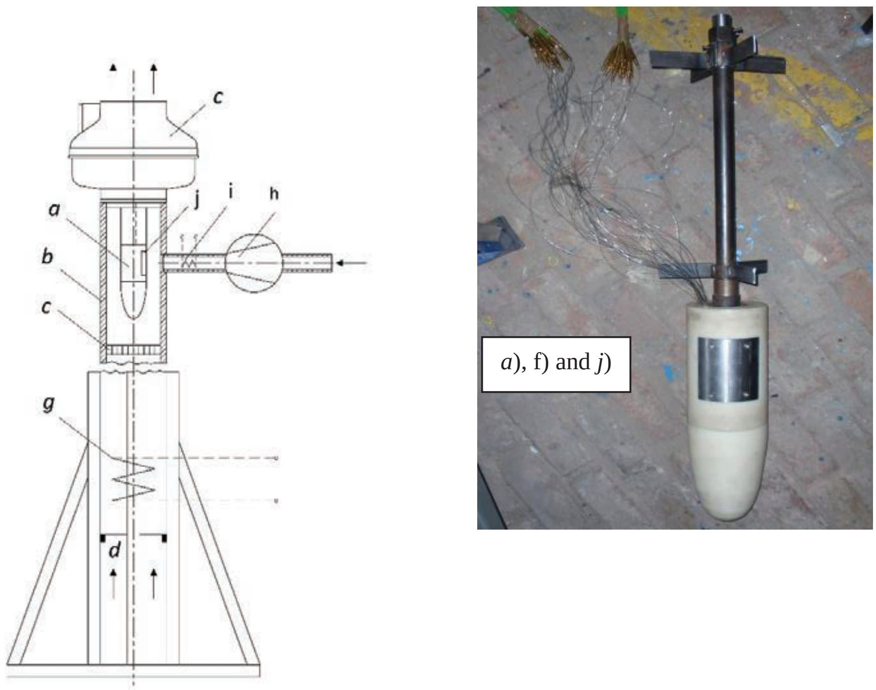
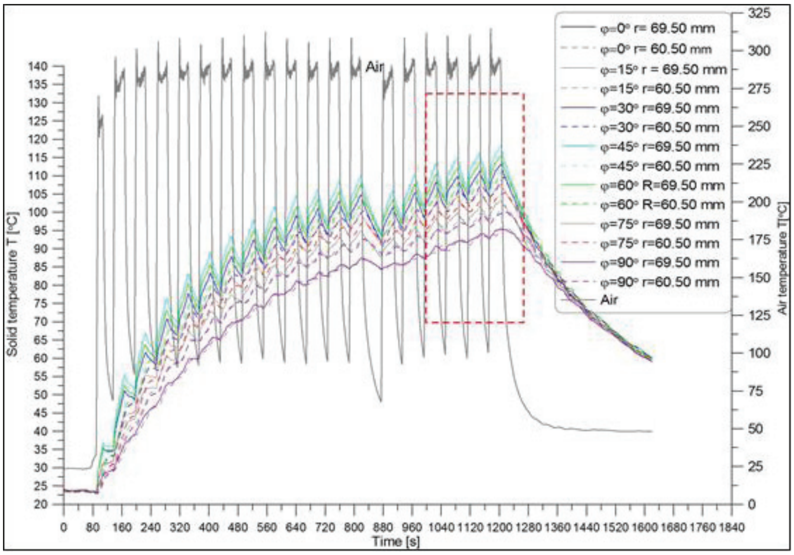


Fig. 6. Test stand for MI teting: a) MS, b) pipe, c) fan, d) mean air stream inlet, e) flow straightener, f) parabolic straightener, g) heater, h) fan, i) heater, j) MI , k) stub pipe, l) opening for measuring inlet air temperature

This air can also be heated by the heater (g) to the temperature 40^{o}C. With use of the components (h) and (i) it is possible to form a jet which hits the outer surface of the MI. The temperature range that is possible to obtain is from ambient temperature to 600°C, and the volume flow rate could be controlled in the range from 0,2 m^3/min to 0,6 m3/min. Three elements: MI with thermocouples, MS, and straightener are joined and mounted on a hanger. This assembly forms a complete element which is mounted inside the pipe (b). The assembly of these elements is shown in Fig. 6. The whole assembly is placed inside the pipe and wires are led out and plugged into data acquisition hardware. The total height of the test stand is 3.80 m. The test stand is equipped with additional equipment for measurements of air mass flow rates and temperatures. The temperature of air jet is monitored. All installed thermocouples are connected to the data acquisition system to store all data online.

5. Test results

The main steps in the test were as follows. First, the axial fan (c) (Fig. 6) was turned on and worked for 45 minutes to equalize MI temperature to an ambient temperature. Then the hot air blower (h) (Fig. 6) was turned on to heat up the MI. The maximal air temperature was set to 300°C at the mass flow rate of 0,5 m3/min. This heating lasted for about 30 s then the air temperature was set to 50°C and the cooling process started. The cooling lasted also for 30 s. The MI was heated and cooled alternately with a time step equal to 30 s until reaching the maximum allowed temperature of 120°C. Tests were performed with time steps varying between 30 seconds and 30 minutes. The temperatures measured with time step 30 seconds are shown in Fig. 7. Temperature histories presented in Fig. 7 were used as the inputs to the developed method based on the IHCP for determining the surface heat flux and temperature. The ashen line represents hot air temperature; dashed lines represent metal temperature captured by the thermocouple located 0.5 mm from the inner surface. The solid lines show metal temperature 0.5 mm from the outer surface. Calculation results for selected time periods, marked by a rectangle in Fig. 7, are presented in Fig. 8. Results are presented for two angular positions 60° and 45° which represent positions 3 and 4 according to Fig. 2.



appears before solid temperature drop, which is consistent with laws of physics.

Fig. 7. Measurement results: air temperature and solid temperature measured at radius 60.5 and 69.5 mm, for various angular coordinates

Heat flux positive values correspond to the heating process while negative values correspond to the cooling process and appropriate temperature drop. From performed calculations and measurements it can be observed that the MI work correctly. From performed measurements it can be observed that the cold stream of air deflects hot air blow, and as a consequence left or right side of the MI is heated more intensively.

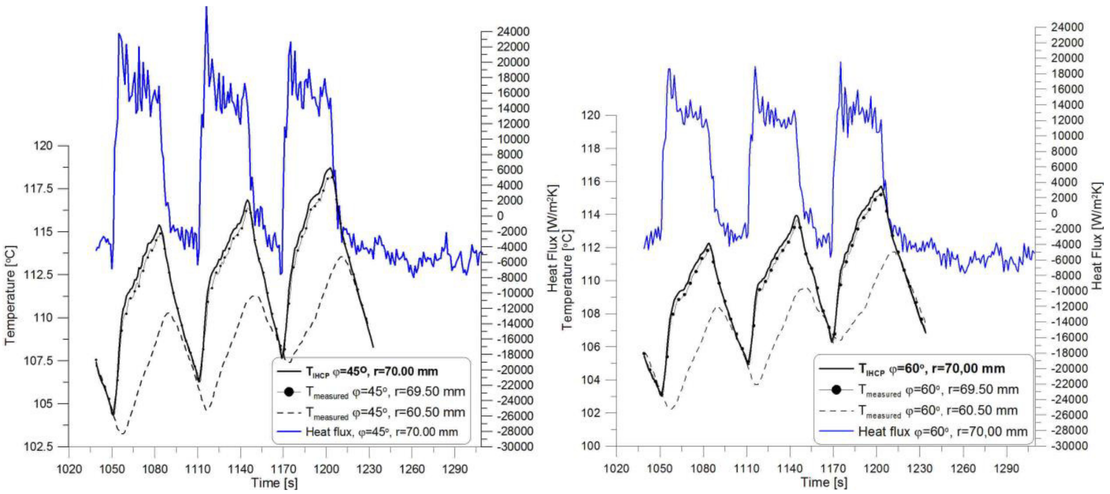


Fig. 8. Results of the inverse analysis-surface heat flux values for two angular positions: a) 45°; b) 60°.

Such a situation causes asymmetric temperature distribution in the MI and circumferential heat conduction from left to right side of MI or inversely depending on the situation. The IHCP algorithm takes into account temperature differences in circumferential direction. Thus, it makes possible to determine angular temperature and heat flux distribution at the MI surface.

6. Estimation of heat flux measuring error

To determine the heat flux measuring errors it was necessary to introduce the disturbance to the calculation model. This action allows influence of the random error to determination of heat flux value to be assessed. Random errors were generated from the range (-0.55 [K] to 0.55[K]).

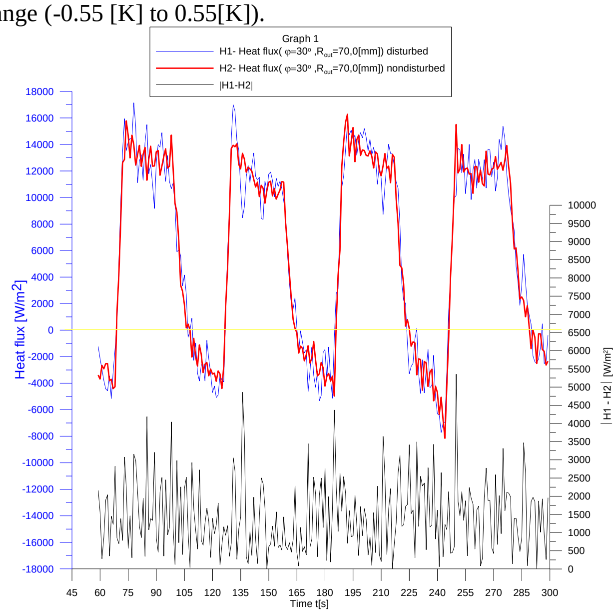


Fig. 9. The difference between determined heat flux H2 and heat flux disturbed by random errors H1

The range was found by assuming that the thermocouple initial location is displaced by 0.15 mm in the radial direction and by 1.5^{o} in the circumferential direction. Such a displacement was introduced in to the numerical model and maximum and minimum temperature difference was found. Generated errors have the normal distribution and 0 mean value. Random errors were added to the values of measured temperature on radiuses R = 60.5 mm and R = 69.5 mm. Fig. 9 presents the difference between determined heat flux and the heat flux disturbed by random errors. The average difference δ_{ave} between determined heat flux values |H2-H1| is equal to 1446 W/m2. Dividing δ_{ave} by maximum value of the heat flux H_{max} from analyzed time period one obtains percentage error equal to 8.8%. This value is representative for all created MIs.

7. Conclusion

Measuring items of two designs were constructed. Data acquisition system has been completed including the software for determination of surface heat flux and temperature. The functions of the system have been tested in the air test rig. The transient heat flux might be measured accurately using constructed MI and developed method. The method and instruments do not require any knowledge of the fluid temperature. In spite of the fact that large thermocouple displacement was assumed the estimated error of heat flux determination was calculated with the value equal to 8, 8%. The measuring system is now ready for performing measurements of transient heat transfer in gases as well as in water environment.

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