MODERN PRACTICES FOR MEASUREMENT OF GAS PATH PRESSURES AND TEMPERATURES FOR PERFORMANCE ASSESSMENT OF AN AXIAL TURBINE

Daniel OLARU, Valeriu VILAG, Gheorghe MEGHERELU

Romanian Research & Development Institute for Gas Turbines, Bucharest, Romania
(daniel.olaru@comoti.ro, valeriu.vilag@comoti.ro, gheorghe.megherelu@comoti.ro)

DOI: 10.19062/1842-9238.2017.15.1.10

Abstract: *Instrumentation of gas turbines is a wide ranging subject, covering aspects from the minimum required for safe operation to the comprehensive instrumentation of one or more components on a test rig or development engine. This paper refers to the instrumentation required during the development phase of an axial turbine, highlighting the custom designs of total pressure and total temperature rakes and also the numerical results obtained after their virtual testing in CFD environment. The study reveals the factors that influence the designs of pressure and temperature rakes and deals with the technological aspects of manufacturing this type of probes.*

Keywords: *axial turbine, custom design, total pressure rake, total temperature rake.*

1. INTRODUCTION

Worldwide a large number of research organizations have developed their own design practices for the application and evaluation of instrumentation.

In the context of a multitude of geometric and aerodynamic conditions offered by the gas turbine, such as space limitations, static and dynamic stress requirements, operating temperatures and pressure ranges, the total pressures and temperatures as well as static pressures need to be measured with great accuracy.

A probe design will always represent a compromise between dimensional limits resulted from the available space, strength criteria and the adequate aerodynamic probe characteristics to meet the required measurement accuracy.

2. DATABASE AND METHODS

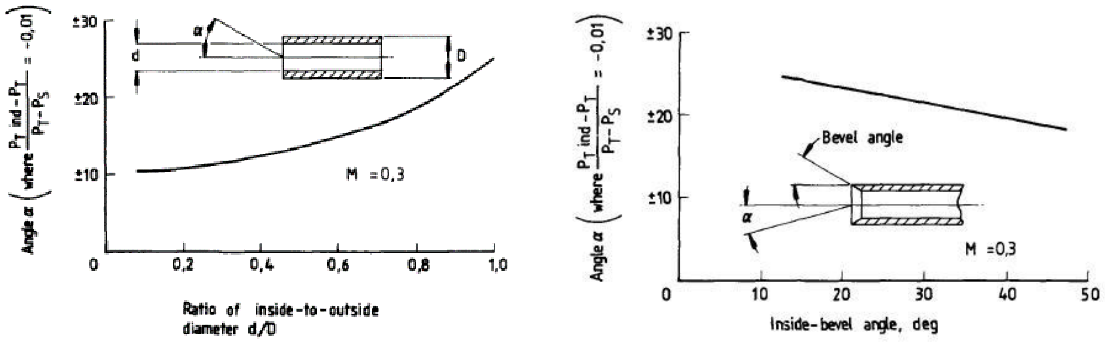
The database used for this study was [1]. The report summarizes various test results conducted on different types of probes and probe geometries over time, leading to a series of guidelines on the application of measurement systems.

2.1 Total pressure rake design. The key factors that influence and ultimately decide the design of a pressure probe are:

- flow direction variation during operating conditions;
- pressure gradients;
- interaction between sensor, sensor support, adjacent sensor, duct wall and upstream or downstream blade rows;
- effect of probe installation on the flow field.

Generally, total pressure can be measured by placing the open end of a tube into the flow field facing the oncoming flow. However, flow direction varies significantly due to the operating ranges of the gas turbines and consequently the probe must be designed in order to meet these requirements, as provided by [1] in “**FIG. 1**.”.

Flow direction insensitivity is achieved through a smaller ratio between the inside to outside diameter (thin wall tubes) as indicated in “**FIG. 1**.” (a). “**FIG. 1**.” (b) indicates an increase in flow direction insensitivity by beveling the inlet of the tube.



(a) (b)

FIG. 1. Variation of angle α with ratio of inside to outside diameter (a) and variation of angle α variation with inside bevel angle (b) [1]

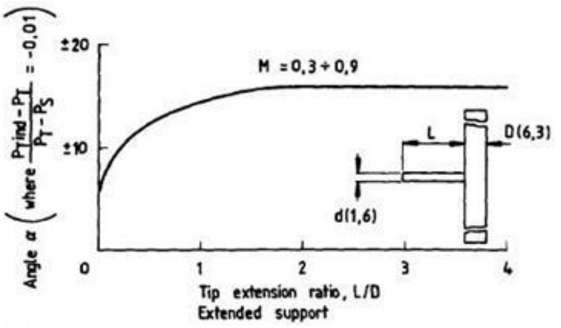
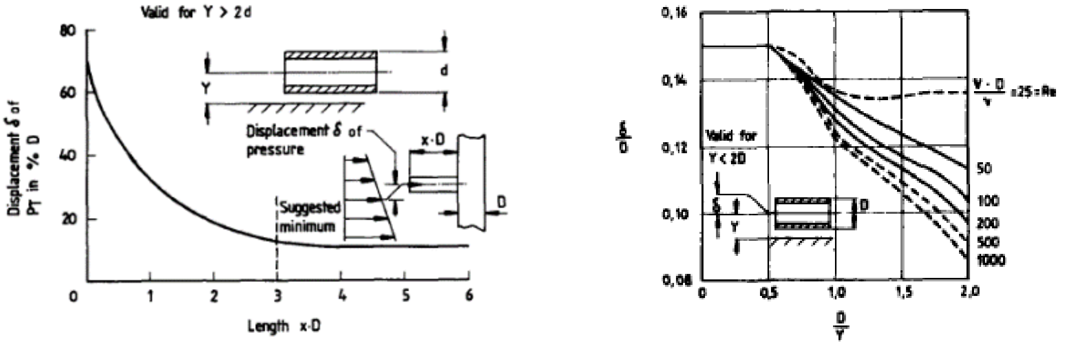


FIG. 2. Variation of angle α with tip extension ratio L/D [1]

The information given above is based on the assumption that the measurement is not affected by the sensor support. Practice however, illustrates that for ratios L/D<3 (L – tube length, D – tube diameter) this effect cannot be neglected, as stem interference will change the flow direction sensitivity of the probe, as shown in “**FIG. 2**.”



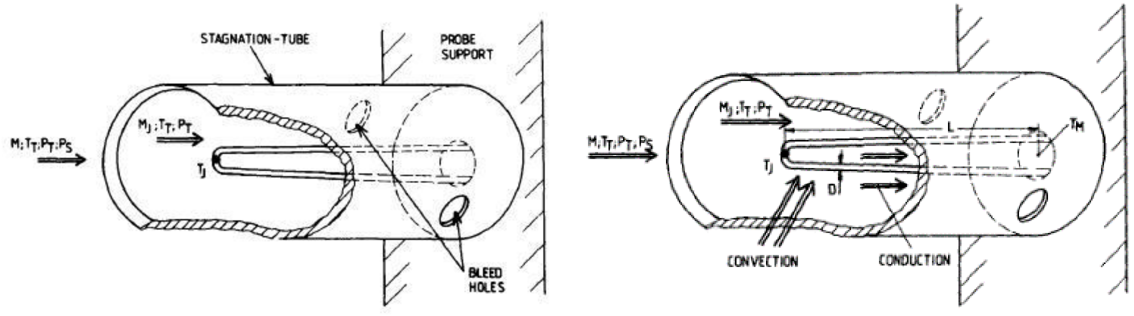
(a) (b)

FIG. 3. The effect of the probe length in a pressure gradient field (a) the effect of shear flow and wall in boundary layer (b)

A pressure probe consisting of a sensing element mounted on a support will deflect the flow so that the indicated pressure is not representative of the actual pressure at the center line of the tube. The stream lines of the flow field become displaced by the presence of the probe. This displacement is a function of the ratio of the length of the sensing element to the diameter of the support [1]. In practice, a ratio d/D>3 (d – length of sensing element, D – support diameter) is indicated to reduce this displacement by up to 10% of the support diameter, as shown in "**FIG. 3**." (a). In a similar way, for distances y<2D (D – stagnation tube diameter) the measured pressure is lower than the pressure at the center line of the sensor, as shown in "**FIG. 3**." (b).

2.2 Temperature probe design. Thermocouples represent the most common gas temperature sensors used in gas turbines development. Their advantages over other sensors are their small size, ease of manufacture, adaptability to high temperature application and costs.

The scope of a temperature probe design is to produce an environment which will allow the thermocouple to measure the gas temperature with the required accuracy, as indicated in "**FIG. 4**.".



(a) (b)

FIG. 4. Typical total temperature sensor [1]

The key factors that shape the design of a temperature probe are:

- velocity error (Y_V);
- conduction error (Y_K);
- radiation error (Y_R);
- catalytic error (Y_C).

Due to the fact that in the probe the gas is not brought to rest adiabatically, the indicated temperature at the junction (T_J) is below the total temperature of the gas (T_T). Thus, the velocity error can be expressed as:

$$Y_V = T_T - T_J = (1-r) * \frac{\frac{\gamma-1}{2}M_J^2}{1+\frac{\gamma-1}{2}M_J^2} * T_T \tag{1}$$

$$r = \frac{T_J - T_S}{T_T - T_S} \tag{2}$$

Equation (2) defines the recovery factor of a thermocouple, a ratio of the total thermal energy available from the adiabatic deceleration of the gas stream at the junction. The literature [1] recommends that r can be varied between the following limits (bare thermocouple wires):

wires normal to flow r = 0.68 ± 0.07

wires parallel to flow r = 0.86 ± 0.09

As we can observe in the equation (1) by decreasing the Mach number at the thermocouple junction M_J by means of a stagnation tube, the velocity error can be minimized. The expression summarizes various test results presented in the literature [2]. M_J represents a function of the free stream Mach number (M_F), the entry to exit (bleed holes) ratio A_E/A_B of the stagnation tube and the gas density and its expression is:

$$M_J = \frac{M_F}{\left(\frac{A_E}{A_B}\right)}\left(1 + \frac{\gamma - 1}{2} * M_F^2\right)^{1/\gamma - 1} \tag{3}$$

, where γ - ratio of specific heats

Under the assumption that the thermal energy transferred from the fluid to the junction wires by means of forced convection is equal to the thermal energy transfer by means of conduction along the thermocouple wires and the junction is generally treated as one dimensional fin, as shown in “**FIG. 4**.”(b) an expression for the conduction error (Y_K) is obtained:

$$Y_K = T_T - T_J = \frac{T_T - T_M}{\cosh L\left[\frac{4h_e}{D * k_s}\right]^{1/2}} \tag{4}$$

, where T_M - mount temperature (temperature at the thermocouple base) determined by the action of the external environment on the support and the stagnation tube; L - wire length; D - wire diameter; h_e - convective heat transfer coefficient; k_s - thermal conductivity coefficient of the thermocouple wire.

Increasing L/D ratio up to the limit of mechanical stability and space available represents the most effective way of reducing the conduction error. Another way of reducing the conduction error is by selecting thermocouple wires with a very small coefficient of thermal conductivity. In our case, type K thermocouple wires with a thermal conductivity coefficient of 17 W/m/^{o}C.

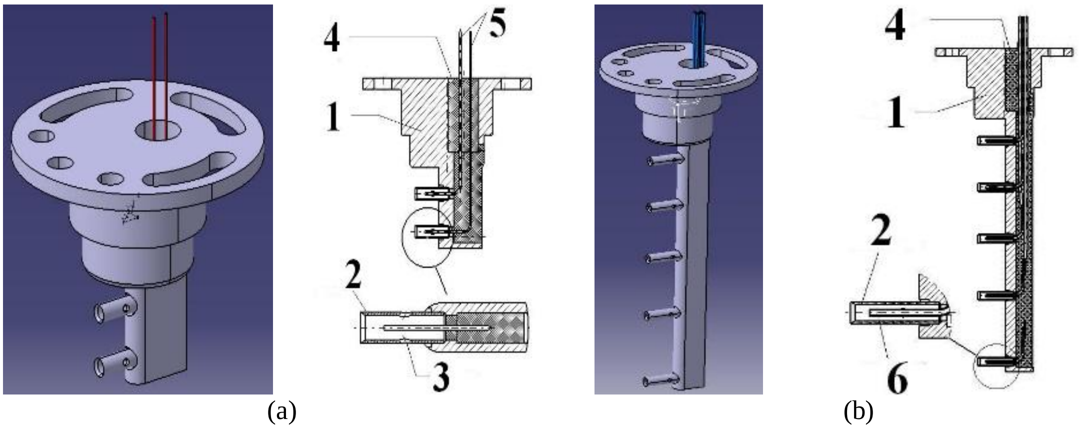
Care must be taken when the thermocouple wires are mounted in the rake body to prevent conduction error. The wires are isolated from the rake body and from each other as well by an insulator composite, as shown in “**FIG. 5**.”, containing ceramic fibers. The composite also can fix the wires in the desired position.

3. NUMERICAL SIMULATIONS

In order to obtain, in a direct manner, the total pressures and temperatures in two measurement sections of an axial turbine (inlet section and outlet section), rake probes are needed. The custom design of the rakes results from the uniqueness of each application and its own requirements.

The total pressure rakes as well as the total temperature rakes feature two measurement locations for the inlet section of the turbine and five measurement locations for the outlet section resulted from the available space, as presented in “**FIG. 5**.”. Their positions on the probe bodies were determined by the constant mass flow sections.

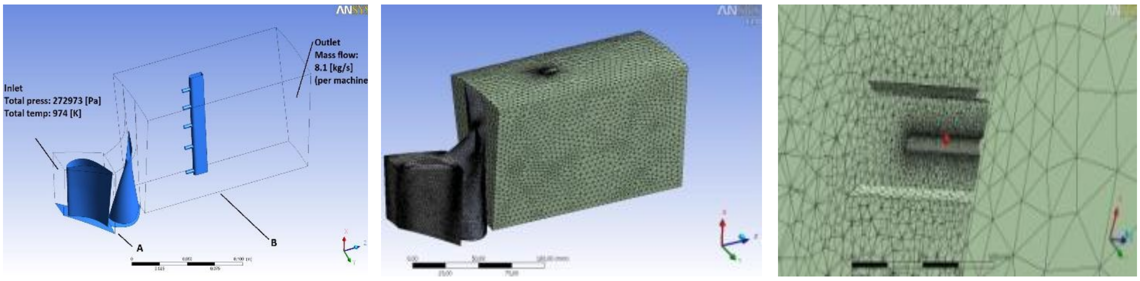
In order to verify the rakes aerodynamic characteristics and simulate the conditions that they will encounter in an experimental axial turbine testing, a CFD analysis has been performed using ANSYS 13.0 CFD software.



(a) (b)

FIG. 5. Total temperature rake inlet section (a) and total pressure rake outlet section (b) (1 – rake body, 2 – stagnation tube, 3 – bleed holes, 4 – insulator composite, 5 – thermocouple wires, 6 – pressure duct)

The geometry subjected to CFD analysis consists in: the third stage of the axial turbine reduced, due to its complexity, to a single stator-rotor passage, featuring frozen rotor type interfaces (A); an outlet duct section featuring instrumentation (a total temperature rake) (B), as shown in “**FIG. 6**”(a).



(a) (b) (c)

FIG. 6. Analyzed geometry (a), entire domain mesh (b) and a detail of the total temperature sensor mesh for the inlet section (c)

Periodic boundaries are used to allow only a small section of the full geometry to be modeled. The mesh used is unstructured, consisting in tetrahedrons, numbering 2403576 elements, as presented in “**FIG. 6**”(b).

“**FIG. 6**”(c) indicates the mesh around the stagnation tube and sensor.

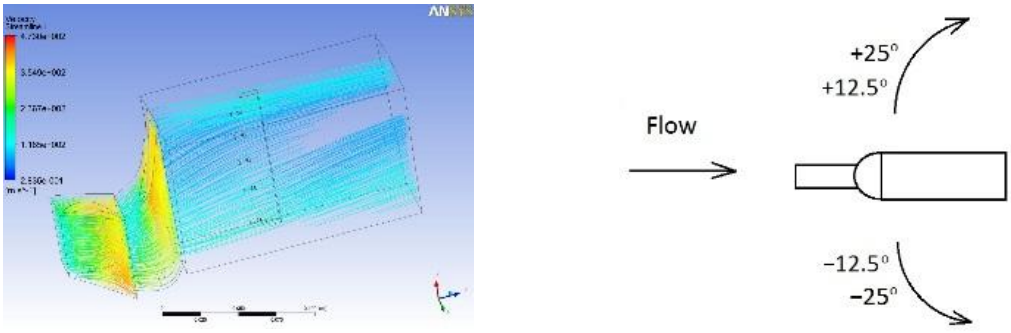
The boundary conditions are extracted from the thermodynamic cycle proposed for the gas turbine to work with this axial turbine (similitude conditions): total pressure at inlet: 272973 [Pa]; total temperature at inlet: 973 [K]; mass flow (at outlet) per machine: 8.1 kg/s.

The rotational speed of the rotor is set to 22000 rpm, the working fluid is air ideal gas and the model used for the simulation case is Shear Stress Transport.

The simulation results are presented in the following section.

4. RESULTS

Due to the fact that the flow direction at the outlet of the stage 3 rotor varies significantly, as we can observe in “**FIG. 7**”(a), numerical simulations with the rake positioned at various yaw angles were performed, as shown in “**FIG. 7**”(b), and the results obtained at the junctions were compared with the reference hub to shroud line located in front of the stagnation tubes in order to analyze their accuracy in the context of flow direction instability conditions.



(a) (b)

FIG. 7. Velocity streamlines and rake position in the flow

In “**FIG. 8**” velocity vectors are plotted in each junction horizontal plane in order to visualize the difference in flow direction. Although the flow direction varies significantly, it can be observed the fact that no vortices are present around the junctions (also in all other rake positions), thus excluding one potential factor that could affect the measurement at the junction.

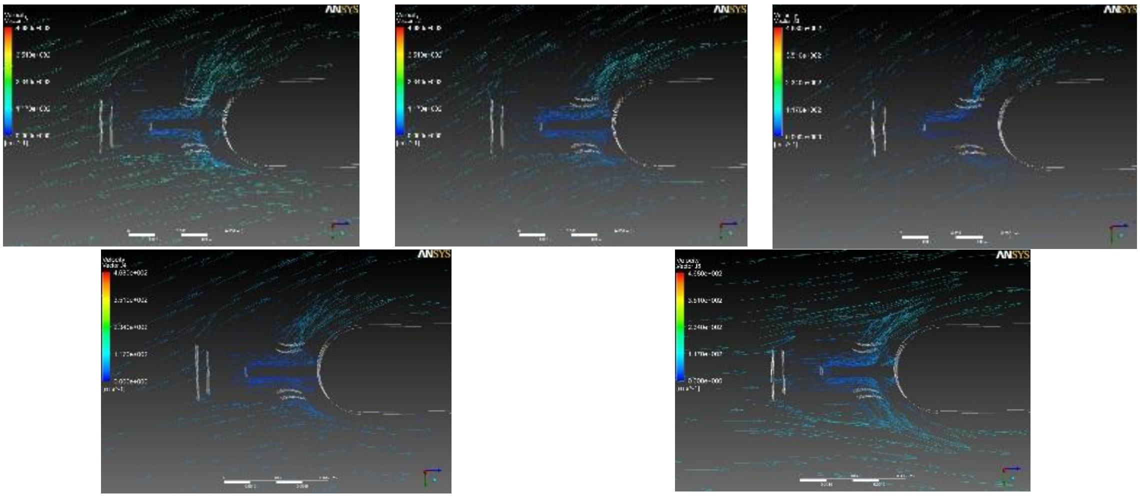


FIG. 8. Velocity vectors for each junction horizontal plane (rake position: 0 degrees)

“**FIG. 9**” presents a comparison between the total temperature measurements at each junction for different positions of the rake in the flow.

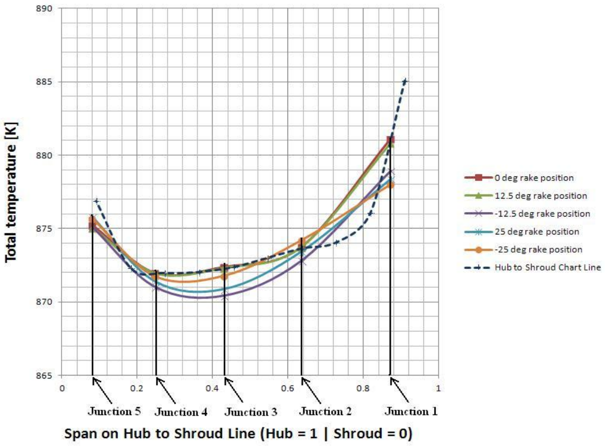


FIG. 9. Total temperature measurements

These results are then confronted with the reference hub to shroud line located in front of the stagnation tubes leading to a maximum difference in reading between the highest and lowest total temperature of 1.21%. The highest total temperature is registered at junction 1 (rake position: 0 degrees) and has a value of 870.41 K while the lowest total temperature is registered at junction 3 (rake position: -25 degrees) and has a value of 870.41 K.

In a similar way, "**FIG. 10**" presents a comparison between the total pressure measurements at each junction for different positions of the rake in the flow.

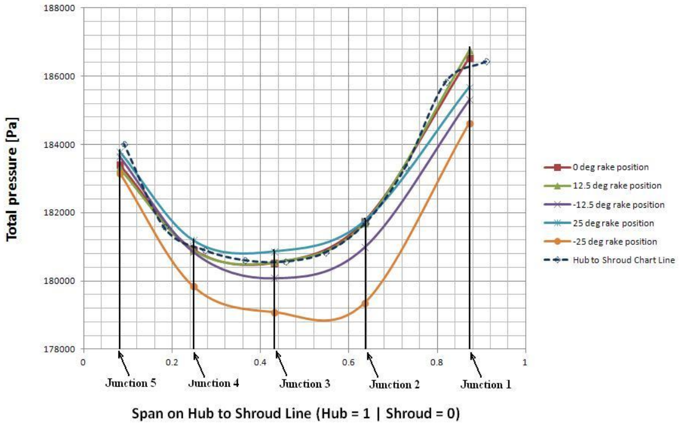
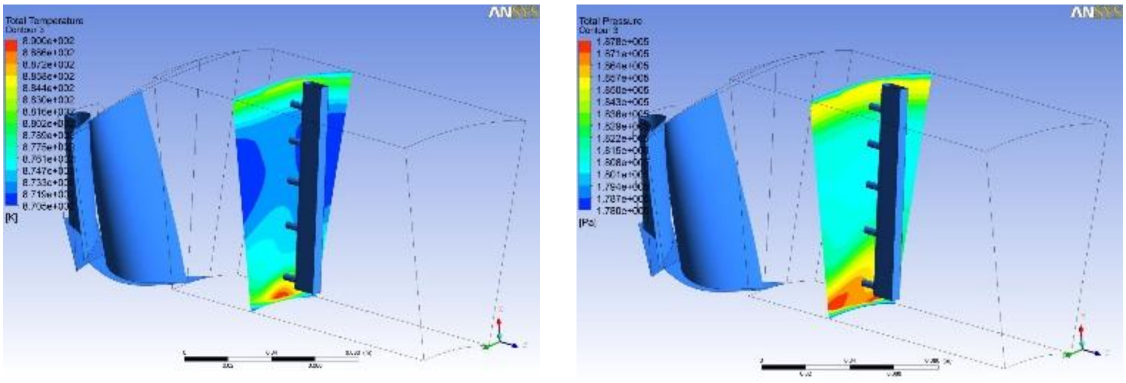


FIG. 10. Total pressure measurements

These results are then confronted with the reference hub to shroud line located in front of the stagnation tubes leading to a maximum difference in reading between the highest and lowest total pressure of 4.1%. The highest total temperature is registered at junction 1 (rake position: 12.5 degrees) and has a value of 186757 Pa while the lowest total temperature is registered at junction 3 (rake position: -25 degrees) and has a value of 179090 Pa.



(a) (b)

FIG. 11. Total temperature (a) and total pressure contours (b) in reference plane

To justify the difference in measurements at each junction, the total temperature contour is illustrated in the plane reference (located at 0.5 mm in front of the stagnation tubes), as shown in "**FIG. 10**" (a).

In order to identify the position of the rake that offers best readings to be used in the calculus of turbine performance, the total temperature area average and total pressure area average are calculated using the ANSYS 13.0 software and used as reference. In our case the values are 874.755 K and 182643 Pa.

The average total temperature per rake position is then calculated and the closest value to the reference mentioned above is 874.78 K (rake position: 12.5 degrees).

In a similar way, the average total pressure per rake position is then calculated and the closest value to the reference mentioned above is 182648.2 (rake position: 12.5 degrees).

CONCLUSIONS

Pressures and temperatures in gas turbines are measured with a variety of probes. This paper focuses on the total pressure and total temperature rakes designs, custom made for the instrumentation of an experimental three stage axial turbine developed at the Romanian Research & Development Institute for Gas Turbines, Bucharest.

The theoretical aspects are covered in the first part of the paper, highlighting the critical factors that determine a rake's design. The rakes' designs presented in this paper are in accordance with these theoretical aspects from the literature.

A CFD analysis is conducted in order to simulate the conditions that these types of probes will encounter in the turbine. Initially, the conditions for measurement are studied, illustrating the velocity vectors in each horizontal plane of the junctions. Even though the flow direction is different in each plane, the condition for measurement is not altered, as no vortices form around the sensors.

From the comparison analyses presented between the total temperature measurements at each junction for different positions of the rake in the flow a resulting 1.21% difference in readings is registered, while from the comparison analyses presented between the total pressure measurements at each junction for different positions of the rake in the flow a resulting 4.1% difference in readings is registered. This indicates the fact that more accurate thermocouples are needed to measure the total temperature in the respective flow field.

Also, the position of the rake that offers best readings to be used in the calculus of turbine performance is identified by comparing area average values for total temperature and total pressure (provided by the software) against the average values obtained at each rake position.

Further numerical studies will be performed at various working regimes of the turbine, recording the parameters and monitoring the reading obtained from the sensors. Their accuracy will be closely monitored to ensure adequate performance calculus that will be finally validated by the turbine experimentation.

REFERENCES

[1] AGARD Advisory Report No. 245, *Recommended Practices for Measurement of Gas Path Pressures and Temperatures for Performance Assessment of Aircraft Turbine Engines and Components*, Sept. 1990;

[2] Moffat J., *Gas Temperature Measurements. Applied Methods and Instruments*, Charles R.Herzfeld, gen. ed. 4 vols. New York: Reinhold Publishing Corp., Vol. 3, Part 2, A.l.Dahl. ed. (1962);

[3] Millan, F.A., *Experinments on Pitot Tubes in Shear Flow*, Great Britain ARC Rep Mem. 3028, (1957);

[4] AGARDOGRAPH No. 207, *Modern Methods of Testing Rotating Components of Turbomachines (Instrumentation),* April 1975;

[5] *Standard Recommended Practice for Preparation and Use of Freezing Point Reference Baths*, ASTM E. 563-76, American National Standard, Reapproved 1980;

[6] Couch, L.M., *Geometric Optimization of the Supersonic Stagnation Pressure Probe*, ISA ASI 7SL42 (251 1-2557), 1975.