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Numerical-experimental analyses by Hot-Wire method of an alumina cylinder for future studies on thermal conductivity of the fusion breeder materials

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Abstract.

The determination of the thermal conductivity of breeder materials is one of the main goal in order to find the best candidate material for the fusion reactor technology.

Experimental tests have been and will be carried out with a dedicated experimental devices, built at the Department of Civil and Industrial Engineering of the University of Pisa. The methodological approach used in doing that is characterized by two main phases strictly interrelated each other: the first one focused on the experimental evaluation of thermal conductivity of a ceramic material, by means of hot wire method, to be subsequently used in the second phase, based on the test rig method, to determine the thermal conductivity of pebble bed material. To the purpose, two different experimental devices have been designed and built. This paper deals with the first phase of the methodology.

In this framework, the equipment set up and built to perform Hot wire tests, the ceramic material (a cylinder of alumina), the experimental procedure and the measured results obtained varying the temperature, are presented and discussed. The experimental campaign has been lead from 50°C up to 400°C.

The thermal conductivity of the ceramic material at different bulk temperatures has been obtained in stationary conditions (detected on the basis of the temperature values measured during the experiment). Numerical analyses have been also performed by means of FEM code Ansys©. The numerical results were in quite good agreement with the experimental one, confirming also the reliability of code in reproducing heat transfer phenomena.

1. Introduction

The knowledge of the effective thermal conductivity of pebble beds, to be used as breeder material in fusion reactor, is of meaningful important to extract thermal power, as it is widely known in the scientific literature [1]-[7]. Breeding blanket material, in form of sintered block and pebble bed (among the candidate ceramics they are lithium orthosilicate, lithium titanate, etc.), is considered one of the most promising fusion blankets and worldwide efforts have been devoted to its R&D.

Pebble beds are used in many applications, such as nuclear reactor fuel rods, thermal insulation, heat exchangers, chemical catalysts, automotive catalytic converters, and recently, fusion blankets. Ceramic materials have some problems, such as uncertainty of thermal conductance at



breeder/structure interface, cracking due to high thermal stresses, creep, swelling etc., therefore an accurate prediction of the thermal conductance at its interface is required.

The pebble beds in fusion blanket offers several advantages, primarily due to the bed characteristics (e.g. size and shape of pebbles, pressure of cover gas, and bed packing) to be tailored to obtain the required thermal characteristics or to be adjusted to match the effective thermal conductivity [8][9]. Accordingly the effective thermal conductivity and the interface thermal conductance of the ceramic pebble beds are key thermal properties to be well measured and characterized: several parameters may influence them as the thermal conductivity of pebbles and filling gas, gas pressure, bed porosity, and pebbles' deformation. In literature it is also possible to find a lot of application of hot wire method for determining the thermal conductivity of solid materials.

Specifically, in respect to [10] and [11], where a thin wire, embedded in the pebble bed, a heated up and the wire surface temperature is measured as a function of time, this study uses a heating rod operated in steady-state condition aiming also at minimizing the accuracy of results that e.g. for deformed ceramic breeder and beryllium pebble beds is questionable [12].

In this framework an extensive experimental activity aiming at the evaluation of thermo-mechanical characterization of pebble beds, as a function of the average bed temperature in the range of 50÷500°C by adopting test ring method and hot wire technique, as described in [8] and [13], has been done and is still ongoing at the Department of Civil and Industrial Engineering (DICI) of the University of Pisa. The methodology used in doing that is based on:

- 1) the experimental evaluation of thermal conductivity of a ceramic material, by means of the hot wire method;
- 2) the adoption of test rig method to determine the thermal conductivity of pebble beds.

The effective thermal conductivity of the ceramic pebbles, namely λ_{PB} , is hence measured as function of a known conductivity of an alumina disc (λ_A) (used as reference value) and temperature differences across the alumina disc [13] and the bed, respectively ΔT_A and ΔT_{PB} .

This paper deals with point 1) of the above methodology.

In what follows, it will be presented and discussed:

- the experimental device used to determine the thermal conductivity of the alumina by Hot-Wire method;
- the experimental procedure;
- the results (experimental value of λ_A) obtained varying the furnace temperature from 20° to 500°C;
- the numerical results, obtained by means of FEM code Ansys©, and their comparison with the experimental ones.

2. Hot Wire Method (HWM): description of experimental device

The experimental equipment, consists of the following main parts: the furnace; the cylinder of alumina, which was composed of three cylinders in series as shown in Figure 2; the thermal resistance; the Fan-Inverter system and the Data Acquisition System (DAS).



Figure 1- Alumina sample used in 'hot wire test' for determining the thermal conductivity

The alumina specimen, namely Alubit 90 (of same material of that used in "hot plate method with guardian rings" tests), is 35 mm in diameter and 280 mm length. The cylinder of alumina has three

holes (Figure 2) of which one central through, to accommodate the electrical resistance, and the other two radials with the bottom end, to insert the thermocouples. These latter are positioned respectively at 7.75 and 21.2 mm from the centre of the specimen.

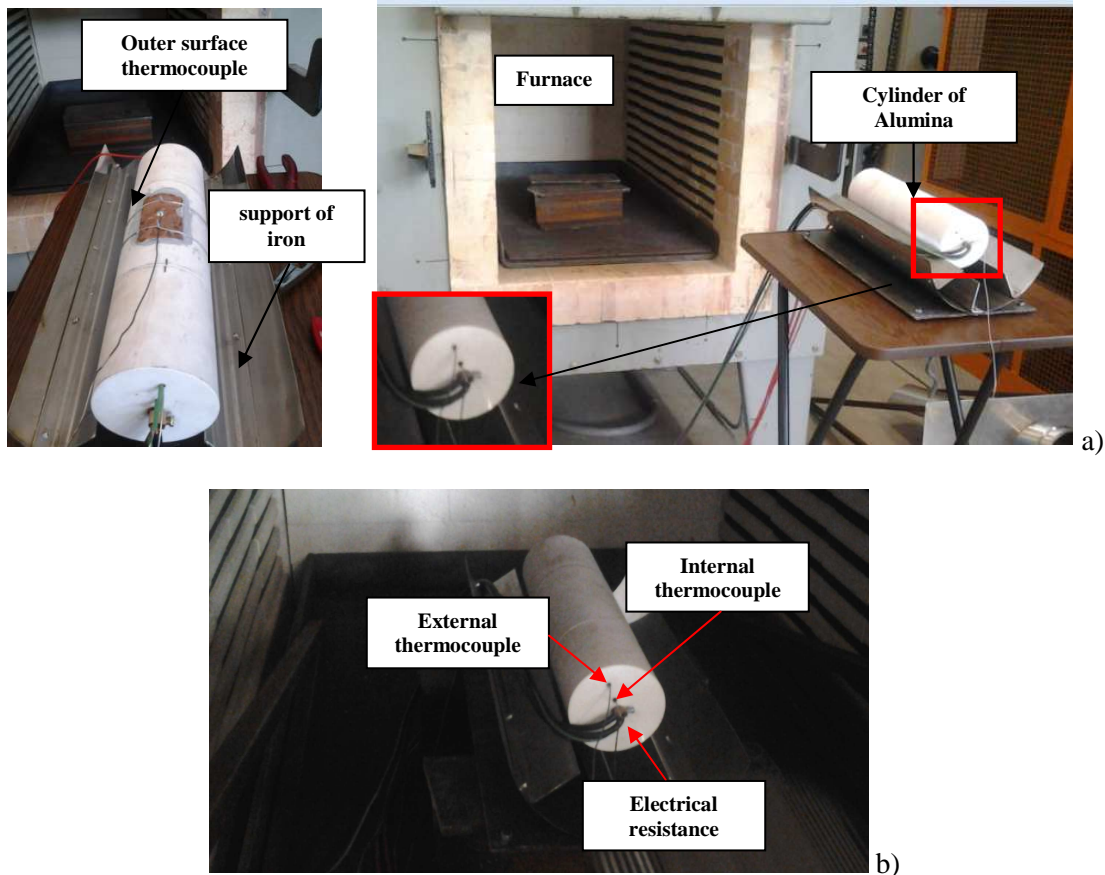


Figure 2 a, b - Experimental equipment

The two thermocouples, type K, have been equipped with a final cap in aluminium in order to ensure the adherence to the walls of the holes.

In addition, on the outer surface of the specimen it was glued a thin copper plate, on which was welded a thermocouple that has allowed to control/measure the surface temperature of the specimen.

It is also worthy to note that the cylinder is resting on a support of iron, in this way, the alumina will not be in direct contact with the surface of the furnace in which it will be placed. Additionally in order to properly determine the thermal conductivity of the alumina specimen, the power generated by the electrical resistance has been removed by forced convection (Figure 3).

To the purpose a fan, duly supported to guarantees the parallelism of the tube with the ground, has been connected to an inverter to obtain a more precise regulation: pipe connected to the fan conveys the air directly on the outer surface of the alumina.

During the tests, a data acquisition system (National Instruments-SCXI 1000) directly connected to the PC via Lab View© interface) allowed to control and measure the temperatures of:

- alumina (on the external surface and inside the specimen);
- furnace;
- ambient air.

The thermocouples were of course calibrated, before the execution of the tests: the calibration was carried out every 10°C from 30 to 450°C in order to cover the temperature range foreseen in the wire tests (50 ÷ 400°C).



Figure 3 - View of the Fan-Inverter system

2.1. Tests execution

After having placed the alumina specimen in the furnace and connected the acquisition system and the ventilation system, the furnace was closed and heated up to the fixed temperature.

The power generated by the thermal resistance has been removed by forced convection, in this way the two thermocouples reach the steady state condition: a difference of 4°C is observed from each other.

The thermal conductivity of the alumina specimen was therefore determined at stationary conditions: the temperature gradient arisen across the longitudinal direction of the specimen was measured by the internal and external thermocouples for at least 5 minutes. The thermal conductivity (λ_A) is therefore calculated accordingly to the following equation:

$$\lambda_A = \frac{\phi_0}{2 \pi \Delta T L} \ln\left(\frac{r_2}{r_1}\right) \quad (1)$$

Where Φ_0 is the power of the heat source; ΔT the temperature difference measured by the thermocouples between the inner and outer of the alumina; L is the length of the source which corresponds with the length of the cylinder of alumina; while r_1 and r_2 are the radial distances where internal and external thermocouples are positioned (see Figure 2).

2.2. Experimental results

The tests were carried out in the temperature range 50÷400°C, with increment of 50°C. The temperature behaviour measured, as an example, at 300°C, vs. time is represented in Figure 4: the red box indicates the stationary conditions, while, of course, in the first part (up to ~700 s) of the diagram the temperatures are different. Results in Figure 4 show that under an average temperature of 300°C, an average power of 217.1 W and a temperature difference between the internal and external thermocouple of 13°C, the thermal conductivity of alumina is equal to 9.41 W/m°C.

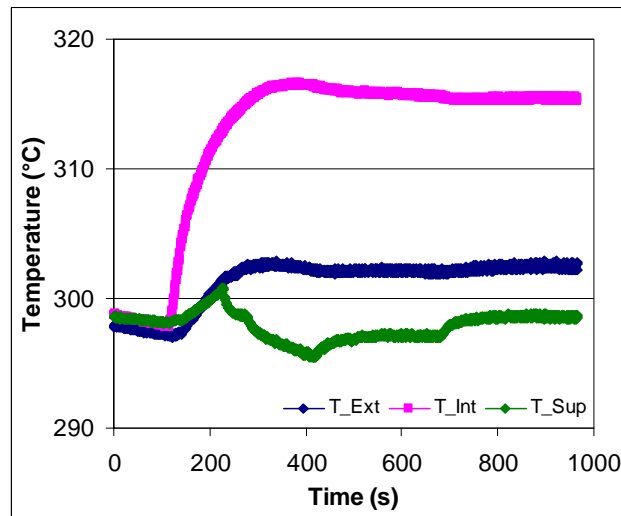


Figure 4 – Hot wire test results at 300°C: temperature measured across the alumina specimen

The wire tests were repeated several times; for each test campaign the calibration of thermocouples were also repeated. The thermal conductivity calculated on the basis of the hot wire tests are showed for different temperature in Figure 5. Analysing the λ_A behaviour, it is possible to observe that the conductivity decreases along with the increase of the test temperature; the calculated maximum deviation resulted about 1.3% (experimental data have been interpolated with a third-order polynomial curve). Finally taking into account the error related to acquisition system, the mean error of the measure resulted less than 3.5%.

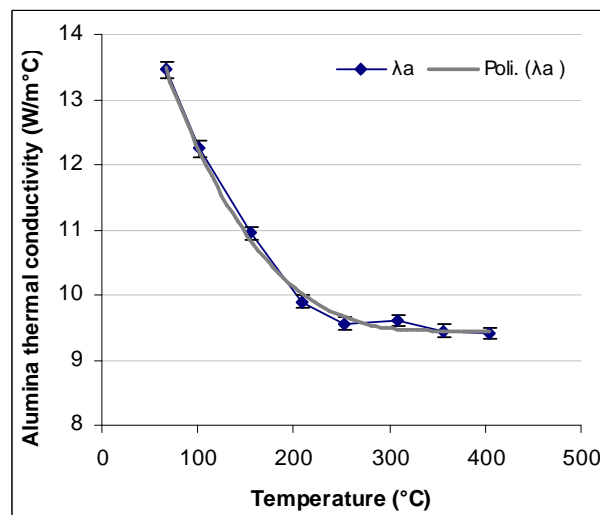


Figure 5 - Values of the thermal conductivity vs. temperature

Moreover the thermal conductivity values of the alumina, experimentally determined, were compared to the literature ones (Figure 6): a good agreement is observed at 400°C, while for temperatures above or below 400°C a relevant discrepancy appears. An explanation of that could be possibly relied on the different conditions based on which literature data has been determined (no accurate description of the procedure adopted); another relevant aspect to think about is however the lack of data available in literature.

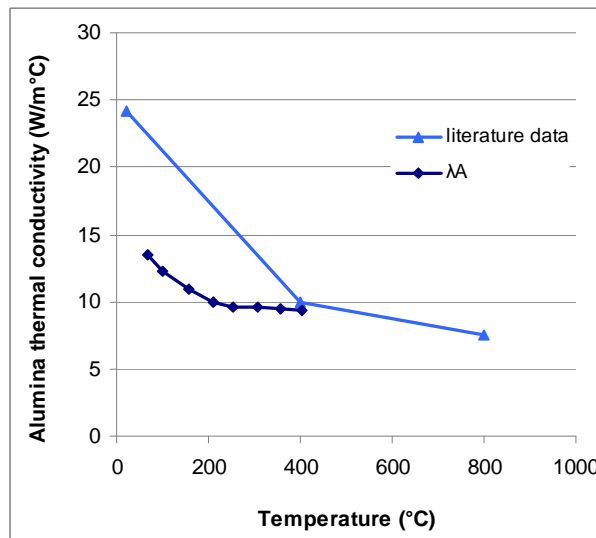


Figure 6 - Comparison between the literature and experimental values of the thermal conductivity of alumina

3. Numerical simulations

Numerical simulations (both steady state and transient) were also performed in order to validate the experimental hot wire tests and, in turn, the measurements of the thermal conductivity. In what follows, are briefly described the FEM simulations carried out along with the assumed initial and boundary conditions (Figure 7 a). The FEM model of the experimental device (1:1 scale) has been implemented by using four nodes axial-symmetric elements, as shown in Figure 7 b.

Input data entered to the code, characterizing the alumina, are:

- Thermal conductivity experimentally determined by tests (see previous Figure 5);
- Density = 3940 Kg/m³;
- Specific heat capacity = 0.8 J/KgK.

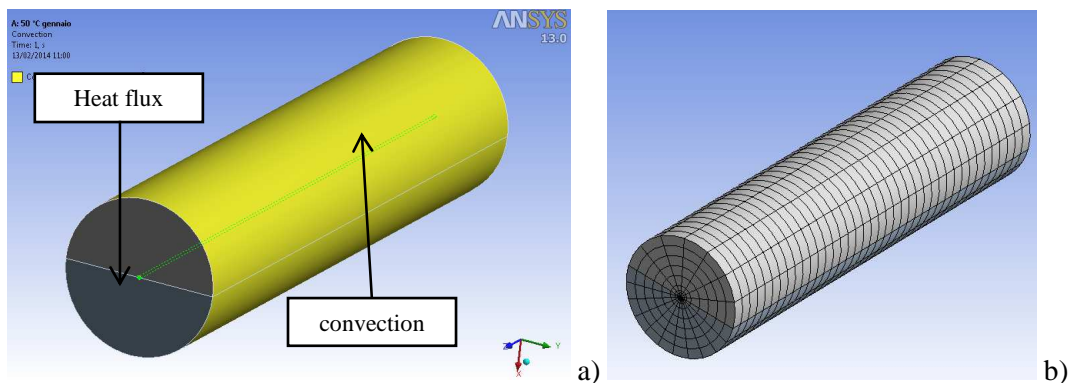


Figure 7 – 3D (a) and discretized (b) FEM model

3.1 Steady-state thermal analysis

The initial and boundary conditions reproduce the hot wire tests conditions, as follows:

- the initial temperature refers to the uniform temperature reached by the alumina specimen;
- the heat flow value, applied in the hole of lodging resistance, is the average value of power obtained from each test in the last five seconds divided by the surface of the hole;

- the convection on the outer surface of the specimen (Figure 7 a) is calculated by dividing the average power for the outer surface and temperature difference $-\Delta T$ - between that of the alumina wall and that of the cooling fluid (air conveyed by the fan on alumina).

Figure 8 show that the results obtained experimentally are very similar to the numerical ones; in the graph are represented the radial behaviour (a thermal path) of the thermal conductivity of the alumina.

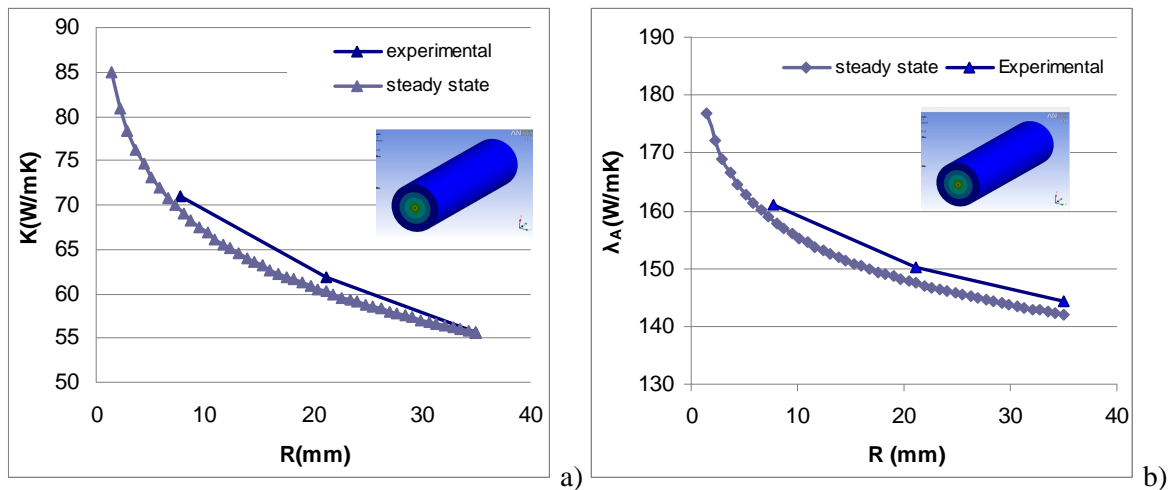


Figure 8 – Radial behaviour of the thermal conductivity of the alumina at 50°C (a) and 150°C (b)

3.2 Transient thermal analysis

The transient analyses have been carried out on the model of Figure 7 by implementing the same initial and boundary conditions, used for the steady state analysis, and the thermal steps summarized in Table 1, which represent the heating conditions (initial steady state, the ramp representing the ignition of the resistance, the final steady state) observed during the wire tests.

Table 1- Initial conditions of thermal transient simulation

Step	Time (s)	HTC (W/m ² °C)	Heat flux (W/m ²)	T _{bulk} (°C)
0	0	10	0	60
1	10	10	0	60
2	40	101,6	1,3551e+005	21,38
3	340	101,6	1,3551e+005	21,38

Figure 9 show the results obtained for an arbitrary thermal path along the radius of the alumina specimen: as for the previous analysis, the experimental and numerical results are in good agreement (difference of about 1°C until 150 °C).

This good agreement allowed therefore to validate the used code.

In addition, in Figure 10 it is represented the comparison between the measured and calculated temperature behaviours for a hot wire test with oven temperature of 50°C and 150°C.

The steady state is reached in the first case after 150 s while in the latter case after 300 s: this different time scale is conditioned by the time required by the oven to reach the temperature test condition.

It is worthy to note that the stationary condition in the numerical simulation is reached immediately due to assumed initial conditions (the thermal interaction is simulated with an effective heat transfer coefficient, see Table 1); while as regards the experimental data, stationary condition was obtained by varying the air flow rate, for this reason, the graphs behaviour have different times.

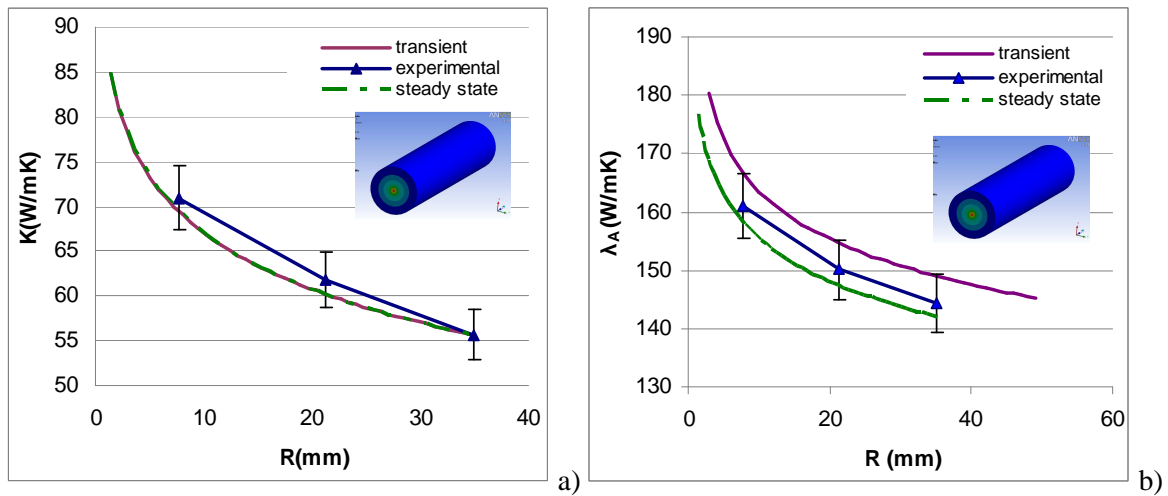


Figure 9 – Radial behaviour of alumina thermal conductivity: 50°C (a) and 150°C (b)

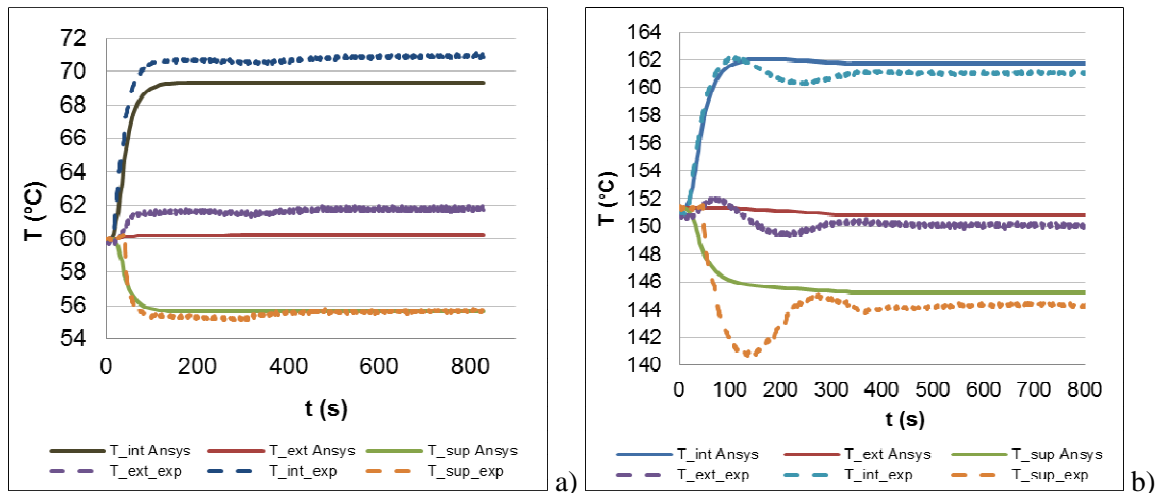


Figure 10 – Comparison between measured and calculated temperature: 50°C (a) and 150°C (b)

4. Conclusion

Breeding blanket material, in form of sintered block and pebble bed, is considered one of the most promising fusion blankets and worldwide efforts have been devoted to its R&D.

In this paper the thermal conductivity of the alumina, to be used as reference thermal conductivity in the test rig method, has been determined by performing hot wire tests at different temperatures. The experimental activity was carried out at the Lab. Scalbatraio of the Dep. DICI of the University of Pisa by using a dedicated device and an adequate DAS.

The thermal conductivity of an alumina specimen (of cylindrical shape) was determined at stationary conditions by means of the temperature gradient measured across the longitudinal direction of the specimen for at least 5 minutes. The tests were carried out in the temperature range 50÷400°C, with increment of 50°C. The results show that for an average temperature of 300°C, an average power of 217.1 W and a temperature difference between the internal and external thermocouple of 13°C, the thermal conductivity of alumina is equal to 9.41 W/m°C.

Numerical (post-test) simulations were also carried out to validate hot wire test results by performing both steady state and transient analyses.

The experimental results indicated that:

- 1) the thermal conductivity λ_A decreases along with the increase of the test temperature; the calculated maximum deviation resulted about 1.3% (experimental data have been interpolated with a third-order polynomial curve).
- 2) λ_A , experimentally determined, was compared to the literature value of the thermal conductivity: a very good agreement is observed (Figure 6) at 400°C, while for temperatures above or below 400°C it was not possible to make any comparison because of the lack of data available in the literature;
- 3) the comparison between the experimental and numerical results, in terms of radial behaviour of the thermal conductivity or radial temperatures, highlights a very good agreement with a discrepancy less than 5%.

The alumina thermal conductivity will be used as reference value for the application test rig method for the evaluation of thermo-mechanical characterization of ceramic pebble beds of interest for the design and analysis of fusion breeding blankets (activity currently ongoing).

Future experimental tests will be carried out increasing the temperature test condition up to 800°C in order to the required thermal characteristics to be used, subsequently, in the test rig method to measure the effective thermal conductivity of pebble beds.

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